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Master Thesis

A review on experimental methods utilized in map perception and cognition

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Μέλη Εξεταστικής Επιτροπής συμπεριλαμβανομένου του εισηγητή

Η διπλωματική εργασία εξετάστηκε επιτυχώς από την κάτωθι Εξεταστική Επιτροπή

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Παράβαση της ανωτέρω ακαδημαϊκής μου ευθύνης αποτελεί ουσιώδη λόγο για την ανάκληση του διπλώματός μου».

Ο Δηλών

Γεώργιος Σκουλάς

Ευχαριστίες

Ολοκληρώνοντας αυτή την εργασία, θα ήθελα να ευχαριστήσω όσους συνέβαλαν στην ολοκλήρωση των μεταπτυχιακών μου σπουδών. Καταρχάς ευχαριστώ τον επιβλέποντα καθηγητή της διπλωματικής μου εργασίας, κ. Βασίλειο Κρασανάκη. Οι συζητήσεις, οι συμβουλές και η συνεργασία μαζί του έδωσαν τον τόνο στην παρούσα έρευνα. Θέλω επίσης να ευχαριστήσω τα υπόλοιπα μέλη της τριμελούς επιτροπής, τους κκ. Ανδρέα Τσάτσαρη και Αναστάσιο Κεσίδη, των οποίων τα μαθήματα παρακολούθησα και ήταν πάντα ενθαρρυντικοί. Ακόμα, ευχαριστώ όλους τους καθηγητές του Μεταπτυχιακού Προγράμματος «Artificial Intelligence and Visual Computing» για την στήριξη και την πάντα πρόθυμη συνεργασία τους. Σε προσωπικό επίπεδο, θα ήθελα να ευχαριστήσω τη Φαίδρα Σταυροπούλου και τη Μαρία Σκουλά για τις πολύτιμες παρατηρήσεις τους κατά τη συγγραφή της παρούσας εργασίας. Τέλος, οφείλω ένα μεγάλο ευχαριστώ στους γονείς μου για την ανεκτίμητη και συνεχή στήριξή τους, τόσο ηθική όσο και υλική, καθ’ όλη την διάρκεια των σπουδών μου.

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ABSTRACT

This thesis explores the experimental methods employed by the cartographic community to derive quantitative data in map cognition and perception studies. From traditional tools such as questionnaires, reaction time and accuracy metrics, to modern techniques like eye and mouse tracking and neuroscience methods (EEG and fMRI), the spectrum of methods showcases the innovative evolution in understanding map user behaviors. Following this, research studies underscore the use of the aforementioned techniques in the cognitive process of map perception. Specifically, the subjects, the techniques employed in individual studies, and the results and conclusions drawn by researchers based on their experiments are discussed. A discussion is underway analyzing the studies, their subjects and methods, and outlining open questions for future research. This work also touches on potential issues arising from current research, which could form the basis for further investigation. The key conclusions and outcomes of each referenced study are noted, along with potential aggregated statistical data represented in table format, derived from these studies.

Findings highlight eye tracking as the dominant method due to its reliability and ease of use in analyzing map user-behavior and evaluating maps and geovisualizations. The method of mouse tracking has emerged as a dependable technique, while the functionality of questionnaires, as well as reaction time and accuracy metrics, has shifted to more supplementary roles. Conversely, techniques like electroencephalography (EEG) and functional magnetic resonance imaging (fMRI), though intricate, offer unparalleled insights into the spatial memory and behavior of map users. Moreover, as the world transitions from paper maps to dynamic digital formats, understanding map reading strategies across diverse platforms becomes essential. The design principles of maps, characteristics of map users, and map interfaces stand out as the most researched subjects in studies related to map perception. Innovations such as artificial intelligence (AI) and machine learning present promising opportunities, leveraging data from experimental methods to predict navigation decisions and potentially enhance map design. The emergence of Augmented Reality (AR) and Virtual Reality (VR) introduces a scope of immersive map interactions, suggesting that the future may see comprehensive studies comparing traditional maps to their AR/VR counterparts. In conclusion, the thesis encapsulates the cartographic community's engagement, from conducting in-depth research studies to developing tools and proposing innovative methodologies. The highlighted trend indicates a combination of experimental methods, signaling the potential for more integrated, multi-dimensional research in future cartographic studies.

Key words: Map, Map Perception, Map Cognition, Map Reading, Eye Tracking, Mouse Tracking, Questionnaires, Reaction Time and Accuracy Metrics, Electroencephalography (EEG), Functional Magnetic Resonance Imaging (fMRI)

1. Introduction

A map is a cartographic product that represents spatial and non-spatial information of the actual-world, by means of graphical symbolization. The basic objective of a map, no matter its type, is to communicate effectively and efficiently its information to the map user. The condition of the map communication is dependent on the map, on the map user and on the map reading process. The manifestation of the communication is achieved through the user's map reading and map cognitive progress. More effective and efficient map visualizations offer better and faster understanding. Research studies by the cartographic community aim to investigate the effectiveness of maps, their features, their elements and the characteristics of the map users. The examination of the aforementioned research purposes is being performed by implementing experimental methods in order to acquire qualitative and quantitative data for evaluation. The type of experimental research studies that aim to interpret and understand the map reading strategies, the attentive behaviors and the visual search of users on map products concerns the analysis of map cognition and map perception. The conclusions of this type of research studies offer the knowledge to design efficient map products that correspond to the needs of the user, the type of data, the conditions and the means, according to which the spatial information is communicated.

This diploma thesis aims to document the dominant experimental methods used by the cartographic community to obtain quantitative data in map cognition and perception studies. To achieve this, contemporary research studies were reviewed. From the extensive collection of articles and papers reviewed, 98 specific studies from the period of 2006 to 2023, focusing on map cognition and perception, were thoroughly examined. The research methodology involved online searches on scholarly literature platforms (*e.g.,* Google Scholar). While the bibliography of selected articles aided in further research, the emphasis was largely on studies from the past five years.

Building on this foundation, it's essential to understand how the broader cartographic community has previously approached and reviewed these issues. It's worth noting that this work not only complements other influential reviews but also utilizes them as primary sources for the research conducted in this thesis. The intentions of the study of Lobben *et al.* (2009), were to serve as a starting point for the implementation of the functional resonance imaging (fMRI) method in cartographic-specific subjects, related to improvement of maps and map reading. The study of Kiefer *et al.* (2017) included studies that were published until 2017 and implemented exclusively the eye tracking method for map cognition and map perception related-studies. Krassanakis & Cybulski (2019), presented an eye tracking literature review for the years 2009 to 2018, extending the previous research of Kiefer *et al.* (2017). Krassanakis & Cybulski (2021) presented a review of eye tracking, in order to observe and reveal existing trends, while offering a future perspective about the contribution of eye tracking analysis in the cartographic research field. Similarly, Fairbairn & Hepburn (2023), conducted a review about the state of the art and the contribution of eye tracking techniques in the field of cartography in order to expand the scope of its application and evaluation. Krassanakis & Misthos (2023), conducted a study presenting the advantages and the disadvantages and the procedures of the mouse tracking method while, highlighting its opportunities and future prospects.

The field of cartography, with its specific focus on map perception, has employed a range of experimental methods over the years. Researchers transitioned from traditional tools like questionnaires and reaction time and accuracy metrics to the now-dominant eye tracking method, and further expanded to advanced neuroscience techniques such as electroencephalography (EEG) and functional resonance imaging (fMRI). These evolutions in methodology have enabled deeper insights into map user behaviors and cognitive processes. As the field advances, the application of various methods reveals not only the changing nature of map related studies but also the innovative ways in which data is gathered and analyzed.

This analysis encompasses not just experimental studies but also dives into review papers, tools developed for analysis, and proposed methodologies that the cartographic community has brought forth. While the depth of this research touches on the advantages, disadvantages, and application methodologies of these experimental methods, it also delves into the broader subjects they have been applied to-from map design and visualizations to the increasing role of AI in cartography. One prominent observation is the shift in method preferences over time. While earlier research leaned heavily on reaction time and accuracy metrics, contemporary studies prioritize eye tracking, mouse tracking, and neuroscience tools, showcasing the evolution of the field. A deeper dive into this research will reveal specific findings, detailed analyses, and potential directions for future cartographic studies while exploring the implications of these methodologies and the advancements and the evolution the field is taking in understanding map user behavior and perception.

This thesis is structured to provide readers with essential knowledge necessary to understand the objectives of the research studies, the explored map-elements, the implemented methods and the findings. Initially, the core concepts of maps and the details of their primary features, elements, and types are presented. Following this, the applied experimental methods within the studies are analyzed, highlighting the metrics and procedures used to understand user behaviors during map reading. Then the reviewed studies are described by highlighting their goal, employed method, procedures and results. A detailed analysis of these studies follows, highlighting significant findings and conclusions. The thesis further offers perspectives on potential future research directions, complemented by comprehensive statistics presented in visual representations. The research concludes by summarizing its insights.

To summarize, the thesis is structured as follows:

- Introduction: This section introduces the aim and subject of the thesis.

- Cartographic Visualization: A presentation about what a map is and of what features and elements it consists. An analysis of the map types, measurements scales, visual, dynamic and sound variables and an induction to the concept of map cognition and map perception.
- Experimental Methods in Cartography: The analysis of the experimental methods used in map cognition related studies. The methods of Questionnaires, Reaction-Time and Accuracy, Eye Tracking, Mouse Tracking, Electroencephalography (EEG) and Functional Resonance Imaging (fMRI), are described along with the measurements and the derivatives for interpreting the map reading process of users.
- Cartographic Research Studies: This section presents the reviewed studies, detailing their subjects, aims, methodologies, experimental methods, participant counts, experimental designs, and conclusions.
- Discussion and Open Questions for Future Research**:** An open discussion and correlation of the examined studies; their results and their conclusions are analyzed. Future research topics and methodologies are expressed and possible aggregate statistics in the form of tables and diagrams are constructed.
- Conclusions: This section summarizes the conclusions and findings of the thesis.

Finally, in Bibliography the books, the published research studies and the articles used in this thesis are cited.

2. Cartographic Visualization

2.1 What is a Map?

A map is a visual depiction of the real world, presented in either analog or digital format (Bertin , 1967). It shows on “paper” the representation of a phenomenon or an object of the actual-world. “*Although there are many types of maps, one description can be adopted that defines all maps: A map is a graphic representation of the milieu ”* (Robinson & Petchenik, 1976, p. 16). The *milieu*, as Dent *et al.,* (2009) explain, includes both the cultural and physical aspects that make up the world. Also “*Maps are used to visualize geospatial data, that is the data that refer to the location or the attributes of objects or phenomena located on Earth*” (Kraak & Ormeling, 2010, p. 1). Thus, maps depict objects or phenomena from the real world. They serve as tools to convey essential information to users, guiding them in decision-making or enlightening them on specific subjects. Maps do more than just showcase real-world representations, they educate, inform, and assist users in making informed decisions (Longley, *et al.*, 2005). The geospatial-data consist of the information that is relative to the position, the attributes and the time-space of an object or phenomena (Kraak & Ormeling, 2010). The most well-known and traditional approach to map representation is paper-maps (Figure: 1) (Robinson, *et al.*, 2002). But with the technological advancement of the last 20-30 years the most modern approach consists of digital-maps that are presented on personal-computer (PC) screens (Figure 3), mobile smart-phones (Figure 4) and web-maps (Figure 2).

Figure: 1 Paper-Analog Map (Source:https://www.indiamart.com/proddetail/folded-tourist-maps-20697116148.html)

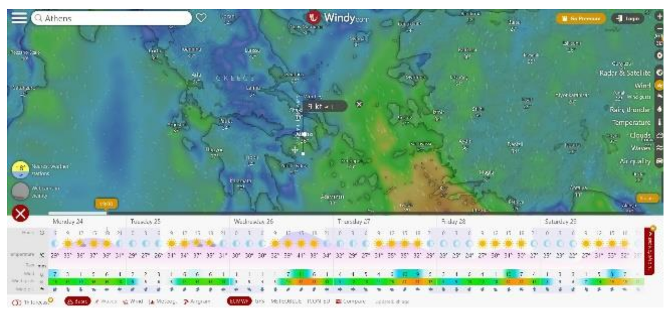


Figure 2: Windy, Weather-Web-Map (Source: https://www.windy.com)

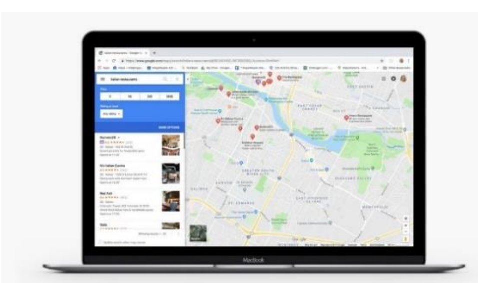


Figure 3: Portable Laptop Screen Map (Source:https://blog.mapspeople.com/google-maps-marketing-what-is-it-and-why-is-it-important)

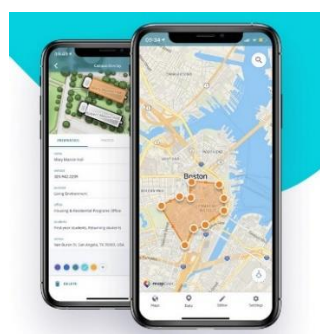


Figure 4: Mobile-Map (Source: https://www.maptiler.com/mobile/)

The representation of the actual-world that the maps provide is limited only to the intention and the specific phenomena the map-designer wishes to represent. *“Maps can satisfy a variety of needs”* (Dent, *et al.*, 2009) and can guide and navigate the map users. Generally, two major map subclasses exist. The first one is the general purpose-maps (Figure 5) and the second one is the thematic-maps (Figure 6) (Robinson, *et al.*, 2002). General use/purpose maps provide general information about the location they are representing. On the other hand, thematic maps represent *“the spatial distribution of a particular phenomenon”* (Robinson, *et al.*, 2002). It becomes clear that the design of a map entails the need for the representation of a phenomenon or object of the *milieu*.

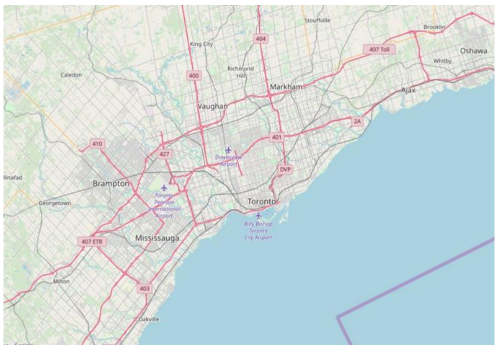


Figure 5: General Purpose OpenStreetMap Basemap (Source:https://www.e-education.psu.edu/geog486/node/641)

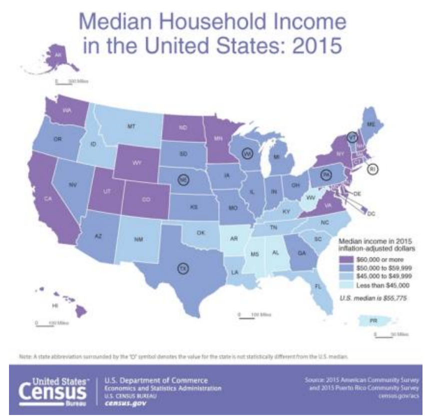


Figure 6: A Thematic Map (Source: https://www.e-education.psu.edu/geog486/node/641)

Having established what a map is, its potential representations, and its benefits, it's now essential to explain how a map is designed and the rules guide its creation. These procedures and standards are set by the scientific field of Cartography (Dent, *et al.*, 2009). As Dent, *et al.* (2009) explain in their Book *“Cartography Thematic Map Design”*: “*There is mapmaking that refers to all the processes of producing a map, whether the person is collecting data, performing the design of the map or preparing the map for distribution. Mapmaking is the process of designing, compiling and producing maps. Cartography on the other hand is viewed as a broader notion of mapmaking, for it requires the study of the philosophical and theoretical bases of the rules for mapmaking . It is often thought to be the study of the artistic and scientific foundations of mapmaking.”*. Therefore, cartographers are also map-designers.

The International Cartographic Association defines cartography as it follows (Dent, *et al.*, 2009, p. 5):*“The art, science, and technology of making maps, together with their study as scientific documents and works of art. In this context may be regarded as including all types of maps, plans, charts, and sections, three-dimensional models and globes representing the Earth or any celestial body at any scale.”*

2.2 Map Types

In the previous paragraphs we mentioned two different types of maps, those of general purpose and thematic maps. This differentiation was made based on the information presented and the aimed application of the maps' creation. There can be plenty of other criteria for differentiation in map types. The map types presented below are based on how the spatial data are presented on the map. First, a presentation of various types of maps and along, examples that illustrate their characteristics, accompanied by figures for clearer understanding.

2.2.1 Static Maps

Static-maps are the easiest to create (Kraak & Ormeling, 2010). As it has been made clear by now, maps can be tangible (printed) products or virtual – digital products. The static-maps can be designed easily in both of these forms. In the static-maps the cartographic symbolization of the geospatial-data remains constant during the map reading process. Hence, the elements of the map are constant and unmovable. Within the category of static-maps, different representations can be produced that aim to different applications. The type of the geospatial-data (qualitative, quantitative) and their measurement scales (nominal, ordinal, interval and ratio) dictate the cartographic symbolization and the representation of the map. Static-maps are commonly utilized in complex architectural environments (Lynch, 1960). They enable users to acquire knowledge about their current position, enhance spatial orientation, and aid in identifying potential routes (Klippel, *et al.*, 2010).

Some examples of static-maps are presented. A category of static-maps, flow-maps, can visualize quantitative differences using point symbols or flows/lines. Flow-maps “are using graduated or proportional symbol functions that are applied to the line attributes” (Kraak & Ormeling, 2010). Flow-maps essentially show the flow of the examined phenomenon from one location to another. Usually the lines of the flow-maps are using a more artistic approach to their visualization (Kraak & Ormeling, 2010). Figure 7 displays a flow-map illustrating the percentage of overall Chinese exports, with each line representing a destination city for these exports from China. The different colors assigned to each flow line correspond to the proportion of Chinese exports received by each respective destination city.

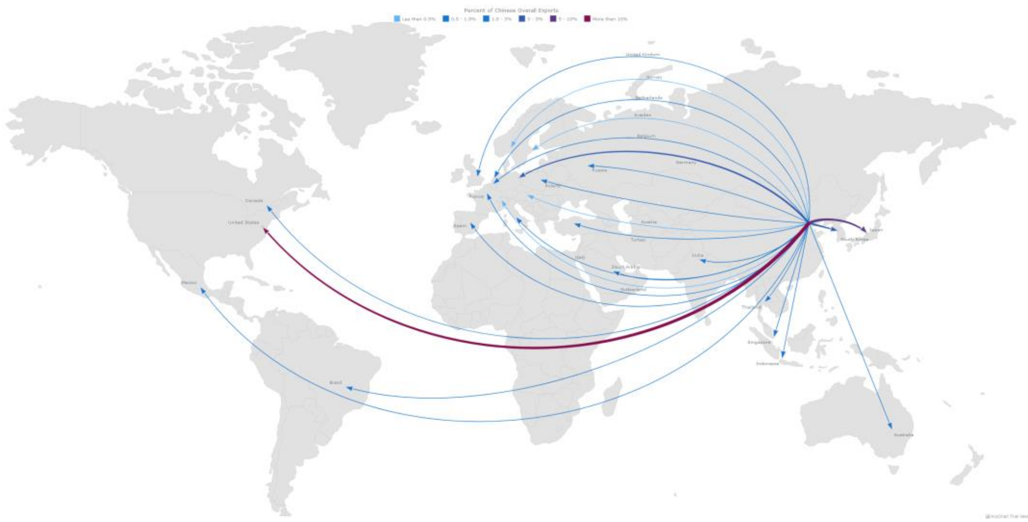


Figure 7: Flow Map of Percent of Chinese Exports (Source:https://www.anychart.com/chartopedia/chart-type/flow-map/)

Additionally, static-maps can visualize 2.5D information. A plane uses two dimensional data. Spatial data are represented by the x and y coordinates that correspond to their actual location on the world. The 2.5 dimension can be achieved by using isarithmic surfaces . *“An isarithmic map is a planimetric graphic visualization of the surface of a three dimensional volume”* (Kraak & Ormeling, 2010). Isarithmic maps consist of isolines. *“Isolines is a system of quantitative line symbols that attempt to portray three dimensional model displays that surface as continuous image depicting the undulations.”* (Kraak & Ormeling, 2010). Each isoline corresponds to a specific value of the data presented. The interval between the isolines corresponds to the interim *“distance”*. It’s important to note that the isarithmic mapping requires continuous surfaces to be depicted and not discrete sets of data (Kraak & Ormeling, 2010). When the data correspond to points such as elevation with contours, depth with bathymetric maps, the isarithmic maps fall into the category of Isometric-maps. When the data refer to geographical areas (polygons) then the isarithmic-maps fall into the category of isoplethic-maps (e.g population per km *etc*.) (Kraak & Ormeling, 2010). Figure 8 depicts the bathymetric map of the Gulf of Maine, showcasing the topography both above and below the sea-level in the examined area. Areas elevated above sea level are represented by a color gradient ranging from green to brown, with the color deepening as the elevation increases. Conversely, the depth beneath the sea level is indicated by varying intensities of dark blue, with deeper areas denoted by a more intense shade of blue.

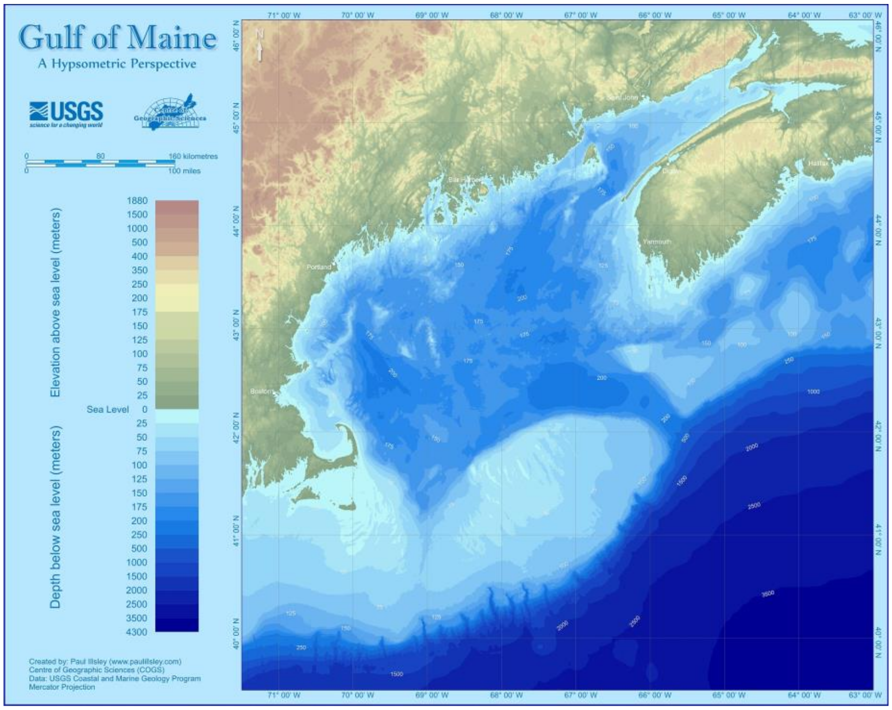


Figure 8: Bathymetric Map of Gulf of Maine (Source:https://www.paulillsley.com/Gulf_of_Maine/Gulf_of_Maine.jpg)

2.2.2 Animated Maps

Animated-maps provide the advantage of visualizing the spatio-temporal changes of the data (Kraak & Ormeling, 2010). They have the ability to show the changes on the specific location of a phenomenon in relation to time. Animated-maps can visualize more dimensions of a phenomenon. As we mentioned previously, geospatial-data in static mapping are able to visualize up to three dimensions, latitude, longitude plus one more dimension, for example elevation (with isarithmic maps) or the attribute values of the examined phenomenon. Animated-maps can offer all of the aforementioned features, with the added capability of displaying changes in attribute values over another dimension, such as time (Figure 9). That ıs just one of the aspects of the animated-maps. They can function as static-maps that are visualizing a specific location on the map with blinking symbols, to attract the attention of the map-viewer (Kraak & Ormeling, 2010). The advantages of animated-maps are best showcased on digital-maps. When referring to an animated-map's ability to depict spatially a phenomenon over time, the representation consists of a sequence of static-maps (Dent, *et al.*, 2009).

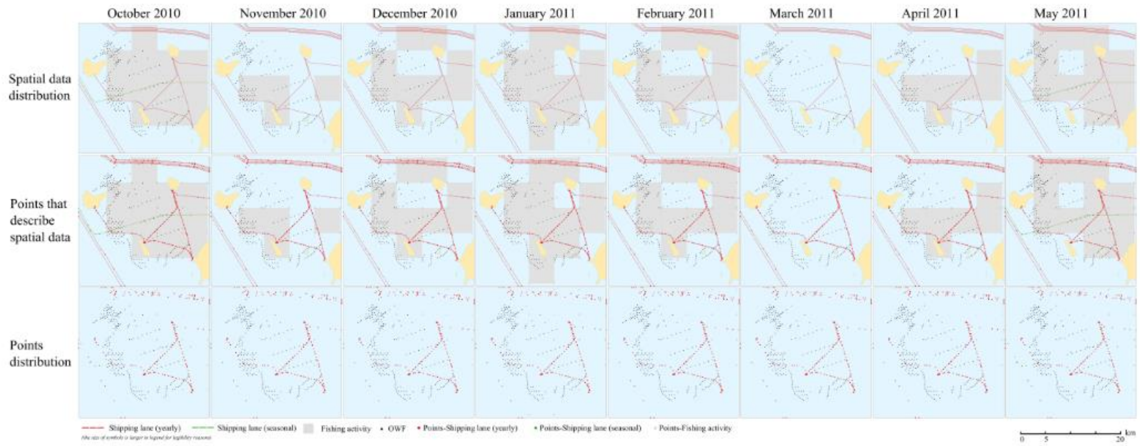


Figure 9: Data Visualization in Marine Space, Frames of Data Over the Time (Month) (Source: Krassanakis & Vassilopoulou, 2018)

2.2.3 Interactive Maps

Another type of maps based on the presentation of the examined object/phenomenon and map-viewer experience is the interactive-maps. Interactive-maps are not static-maps; instead, they offer users the ability to interact with them. This interaction includes for example zoom in, zoom out and pan on the map (Kraak & Ormeling, 2010). Additionally, some interactive-maps provide the ability to be clicked on, in order to identify features, to activate or deactivate specific layers or classes of a map and to view ancillary information about the visualized classes and features (Dent, *et al.*, 2009). The interactivity of the map user can be achieved only through digital types of maps (Dent, *et al.*, 2009). Both static and animated-maps can be simultaneously interactive, since they may provide an aspect of interactivity (Dent, *et al.*, 2009). The most well-known interactive-maps that are also familiar to the broader population are web-maps (Dent, *et al.*, 2009). Most of the web-maps provide some level of interactivity. Figure 10 presents *"Ventusky"* weather web-map, an interactive tool for weather forecasting visualization. This weather web-map application offers plenty of interactivity as it allows users to zoom in and out, select different weather parameters, and choose the time and date to get accurate forecasts.

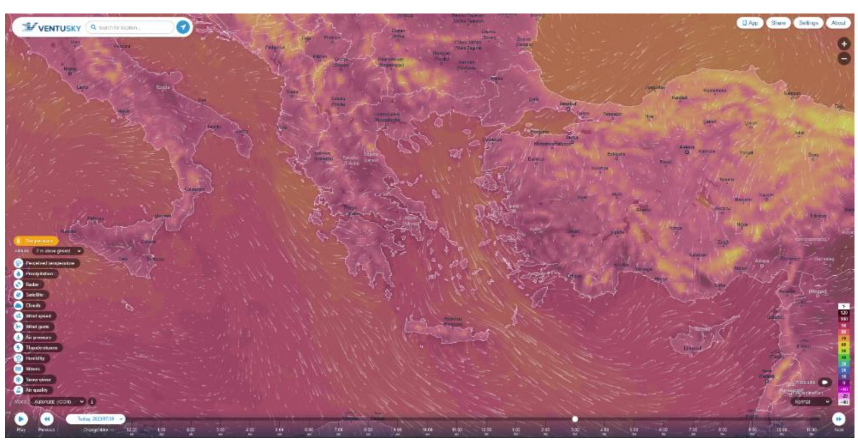


Figure 10: Interactive Weather Web Map Ventusky (Source: https://www.ventusky.com)

2.3 Cartographic Symbolizations

As mentioned, a map is a graphic representation of the actual-world. Having discussed the types of maps and their respective advantages, we will next delve into the variables of cartographic symbolization and the specific maps and spatial data they apply to. When designing a map it's important to visualize the geospatial-data as accurately as possible, while providing a clear impression of what it is visualized. The graphics used to achieve these purposes hold significant importance. As Bertin (1987), suggests *"Graphic representation constitutes one of the basic sign systems conceived by the human mind for the purposes of storing, understanding, and communicating essential information. As a "language" for the eye, graphics benefits from the ubiquitous properties of visual perception. As a monosemic system, it forms the rational part of the world of images."* Based on the data's types and attribute values, the cartographer must select the most efficient graphic elements to represent all these on a map. Jacques Bertin was the first to describe such variables in his book *"Sémiologie graphique : les diagrammes, les réseaux, les cartes"*, published in 1967. Bertin's study was focused on the sign systems and semiotics. Semiotics refer to the understanding of how an object can stand for another object. Consequently, this understanding can help cartographers to find the way in which a map symbol can describe an object or a phenomenon of the actual world and comes to mean something to the map user (Roth, 2017).

2.3.1 Measurement Scales

The map-attributes can be categorized into qualitative or quantitative (Kraak & Ormeling, 2010). There are four types of measurement scales for their values (Dent, *et al.*, 2009) (Figure 11):

- Nominal scale: Differences in qualitative data arise when attribute values vary in nature, without any indication that one aspect is more important than another, (*e.g.,* countries). (Kraak & Ormeling, 2010).
- Ordinal scale: Values are ordered without clear distinctions in the data. These differences are qualitative in nature. Attribute values can be sequenced in one specific manner because some are more significant than others (*e.g.,* 'small, medium, large settlement'). (Kraak & Ormeling, 2010).
- Interval scale: There are well-known numeric distinctions among the data, necessitating the definition of a metric unit. These differences are quantitative. Attribute values can not only be ordered, but the intervals between them can also be ascertained (*e.g.,* temperature) (Kraak & Ormeling, 2010).
- Ratio scale: There are well-known numeric differences within the data, and the attribute values possess an absolute (true) zero (*e.g.,* population) (Dent, *et al.*, 2009). Quantitative differences amongst data.

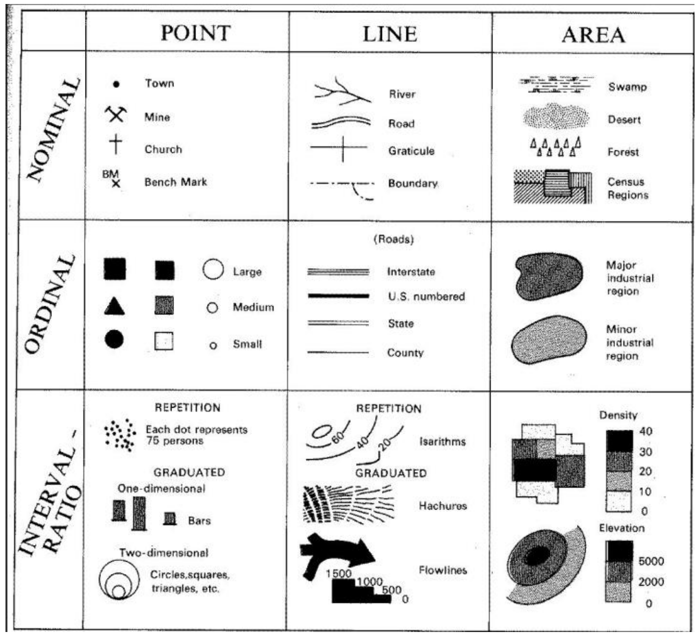


Figure 11: Measurement Scales of Data and Map Symbols (Source: https://people.geog.ucsb.edu/~kclarke/G176B/robinson.jpg)

2.3.2 Visual Variables

Map symbolization consists of the visual variables that are the basic tools for graphic representation on maps. Visual variables are components of the graphic-system (Dent, *et al.*, 2009). The cartographic data can be either zero dimensional and represented with points, one dimensional and represented with lines, two dimensional and represented as area, three dimensional and represented as volume, or finally four dimensional and represented over time (Dent, *et al.*, 2009). Manipulating the visual variables that correspond better to the examined geographical data can help create effective representations (Dent, *et al.*, 2009). Visual variables can be used to visualize qualitative and quantitative differences among the cartographic data (Bertin , 1967). Also, visual variables can be applied to different geometries such as points, lines and areas, different types of data (socioeconomical, statistics, natural phenomenon, topographical *etc.*) and types of measurement scales (nominal, ordinal, interval, ratio). The analysis, produced by Bertin (1967), on his research on the sign systems and semiotics, concluded to the definition of seven visual variables that can be adjusted to convey information (Roth, 2017). These visual variables are the followings:

- Position-Location describes the position of a map symbol relative to a coordinate system (Roth, 2017). Due to its nature, it is considered as an essential variable that takes visual primacy over the other variables (Roth, 2017). In cartography, location represents primarily the geospatial position that encodes information about the examined object/phenomenon. Position can be used to visualize both quantitative and qualitative types of data, hence it supports the representation of all the types of measurement scales, nominal, ordinal, interval and ratio (Dent, *et al.*, 2009).

- Size refers to the amount of space a cartographic symbol occupies (Roth, 2017). Larger map symbols have a tendency to correspond to an increase in the value of the examined attribute. Size is suited best for visualization of ordinal, interval and ratio scales, meaning it can't be used effectively to represent the nominal scale and qualitative differences amongst the geographical data (Dent, *et al.*, 2009).
- Color Hue refers to the predominant wavelength of the map symbol within the visible segment of the electromagnetic spectrum (Roth, 2017). As Bertin (1967), suggests, *"hue is the name we apply to a particular color"*. It is considered as one of the three variables associated with the perception of color (hue, value, saturation). It is best suited for representing the qualitative differences amongst the data (nominal scale) (Bertin , 1967). Hue is an acceptable variable for the depiction of data that belong to the category of ordinal measurement scale.
- Color Value refers to the relative amount of energy emitted or reflected by the map symbol (Roth, 2017). It is also considered as one of the three variables associated with the perception on color (Roth, 2017).Value variable is considered as the sequence of stages between light and dark (Dent, *et al.*, 2009).
- Texture describes the texture's spacing of a fill pattern within a map symbol (Roth, 2017). Best suited for ordinal data, texture is used in the area symbolization to emulate to their landscape's surface type, coarse or smooth (Dent, *et al.*, 2009).
- Orientation refers to the rotation or direction of the map symbol from the "normal" (Roth, 2017). The "normal" orientation is typically in relation to the map's neatline (Roth, 2017). It can be used to portray differences that apply to the ordinal scale. Typically, the orientation needs to be precise to the actual representation of map-symbols that have rampant structures (*e.g.,* building). On the other hand, more abstract approaches can be reviewed as long as they do not affect the effectiveness of the symbolization (Dent, *et al.*, 2009).
- Shape describes the external form of a map symbol. Although it fails to depict quantitative differences (ordinal, interval/ratio scales), it is considered crucial to the representation of qualitative differences amongst the data. The variable of shape can be used in a variety of approaches from more abstract to more compact and rampant shapes (Roth, 2017).

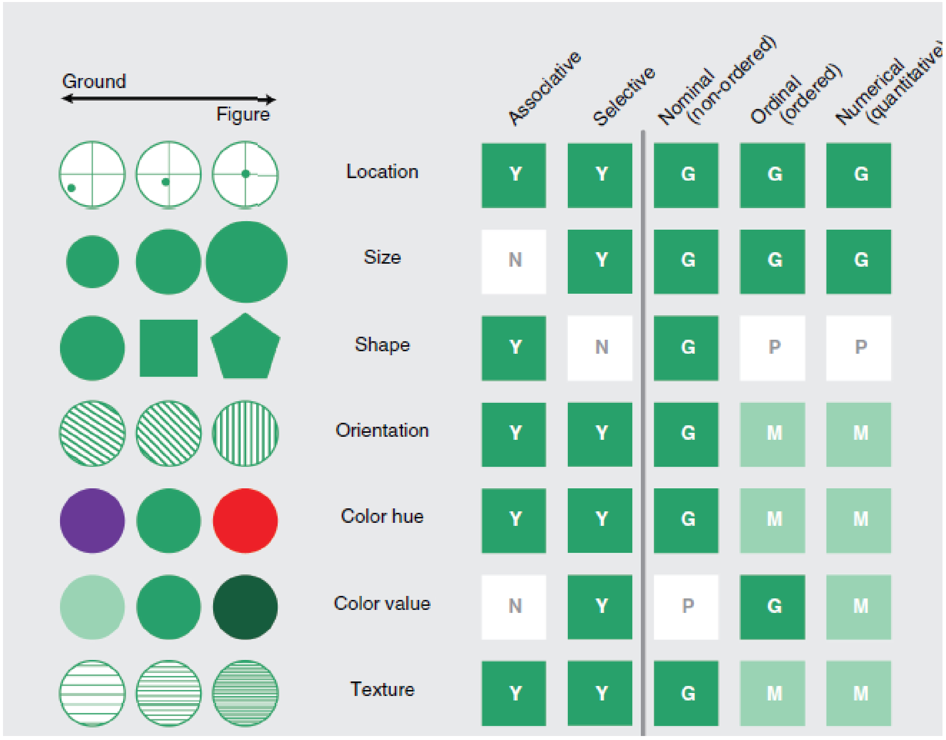


Figure 12: Visual Variables and Their Syntactics (Source: Roth, 2017)

These are the seven main visual variables Bertin (1967), introduced in his book "*Sémiologie graphique : les diagrammes, les réseaux, les cartes"* Since then, other cartographers have added and presented more visual variables that fall in the same principal as the above. MacEachren (1992), introduces additional visual variables such as color saturation, resolution of map symbols, transparency of map symbols and their crispiness. Just like technological enhancement, the visual variables need to be updated. Robinson (2002), introduced in 1995 the secondary visual variables, consisted of pattern arrangement, pattern texture and pattern orientation. The variables presented have a crucial role in the map making progress and visualization and their application is essential to all map types. They are equally important to all map types, either general, purpose, thematic, static, animated or interactive.

2.3.3 Dynamic Variables

In animated-maps, dynamic variables are used alongside the standard visual variables. The basic design tools of map symbolization are applied in animated mapping and the combination of the dynamic and visual variables is required. The dynamic variables, firstly introduced by DiBiase (1992), are consisted of the variables of duration, rate of change and order. Additionally in 1995 MacEachren (1995) in his book *"How maps work: Representation, Visualization and Design"* introduced the dynamic variables of display date, frequency and synchronization.

As DiBiase, (1992), and MacEachren (1995), suggest, the variables definitions are the followings (Figure 13):

- Duration describes the length of time, during which a frame or an amount of common frames is displayed. It consists of scene duration that describes the length of a period when no changes happen, the scene that refers to the amount of frames that no changes happen. Duration is best suited to represent quantitative differences amongst the data, hence, it is more effective on ordinal, interval and ratio types of measurement scales.
- Rate of change is described as the ratio of **m/d**, where: **m** = to the magnitude of changes between scenes and **s** = to the scene duration. These changes can be about locations or attributes values on a specific area. Furthermore, the variable of change can be either constant or not. Change is more effective on quantitative data types and the scale types of ordinal, interval and ratio, but it can be marginally effective also on qualitative data.
- Order describes the order in which the frames are displayed. The order can be chronological in a time series or it can refer to another logical connection. It is effective on ordinal types of data.
- Display date illustrates the date that refers to the displayed data. It is a reference between frames or scenes. Display date is used effectively on qualitative differences amongst the date, hence it is appropriate for the nominal scale.
- Frequency corresponds to the number of identifiable state per time-unit and it is directly connected to the variable of duration.
- Synchronization describes the temporal correspondence among the different time series. It is based on the variable of display rate.

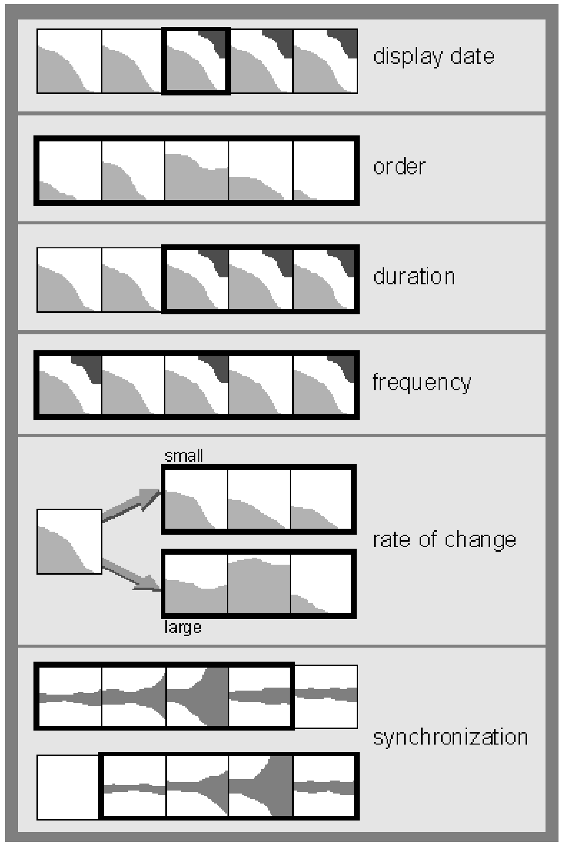


Figure 13: Dynamic Variables (Source:https://journals.openedition.org/cybergeo/509?lang=en)

2.3.4 Sound Variables

Abstract and realistic sounds can also be used in map creation (Krygier, 1994). Sound can be implemented in all the three categories of maps presented, static, animated and dynamic. Sound is an important sense that helps the better understanding of the environment (Krygier, 1994). Thus, using the element of sound on a map can lead to the better cognitive process of map reading by the user (Krygier, 1994). As with the visual and dynamic variables, there are features of sound that can also be adjusted and create more efficient representations on a map. The sound variables introduced by Krygier (1994), consist of:

- Location of sound in two or three dimensions. This variable is more effective when used for data that belong to the ordinal scale.
- Loudness represents the magnitude of a sound and is effective for portraying ordinal data.
- Pitch is the frequency of a sound. This variable is more suitable for representing data that belong to the ordinal scale as well.
- Register is the relative location of a pitch in a given range of pitches and is suitable for representing ordinal data.

- Timbre is the characteristic of a sound and is effective for nominal data.
- Duration is the length of time of a sound and is suitable for ordinal data.
- Rate of change refers to the proportion between sound durations and periods of silence over time, making it effective for illustrating ordinal data.
- Order is the sequence of the different sounds over time and is effective for ordinal data.
- Attack/Decay describes the time a sound takes to reach its peak or to fade away. It's an effective measure for ordinal data.

2.4 Map Perception and Cognition

Map perception and cognition are intricately linked to visual, sound, and dynamic variables, each playing a pivotal role in how we interpret spatial information. Combined with measurement data scales, these variables create a rich, multi-sensory experience that enhances users' understanding of geospatial features. Perception and cognition are connected to vision, one of the five senses of the human. The vision of an individual and the oculomotor events that follow to understand and interpret information of the surroundings require simultaneous and instantaneous processes performed by the brain (Żyszkowska, 2017). Research studies about perception are an established subject in both the fields of neuroscience and psychology. Perception and cognition follow vision. Through vision, the visual search, represented by eye-movements can be achieved (Żyszkowska, 2017). The abstract vision of an individual can be described as the process of eye movements wondering on the environment. The abstract vision can be converted to visual knowledge when attention on a specific visual element occurs (Krassanakis & Filippakopoulou, 2023). Perception is related to how the brain interprets the signals coming from our senses (Keskin, 2020). Perception as Żyszkowska (2017), suggests can be divided into three distinctive processes: perceiving, distinguishing and identifying. As Peterson (1994, p. 35), explains, cognition can be defined as: *" the intelligent process and products of the human mind includes such mental activities as perception, thought, reasoning, problem solving and mental imagery"*. Hence, visual cognition can be described as the function of the brain in perceiving the visual information of the environment (Krassanakis & Filippakopoulou, 2023). The perceived visual knowledge is recorded in the form of mental images (Krassanakis & Filippakopoulou, 2023). Mental images are directly connected to the memory of the brain. Based on that, the mental images are formed (Keskin, 2020). When an individual fixates on an object or performs intentionally or unintentionally a spontaneous visual search, their understanding of the surroundings is represented by the mental image the subject creates. This mental image is created mainly by two factors. The first factor is based on previous knowledge the brain has acquired and stored as memory in the brain (Krassanakis & Filippakopoulou, 2023). The second factor is achieved by observing and understanding the fixated target (Krassanakis & Filippakopoulou, 2023). Keskin (2020, p. 3), adds: "*Spatial Cognition can be defined as restructuring the space on a mental level and its assimilated reflection.*

Spatial cognition is related to both the physical environment and the abilities of individuals regarding sociocultural, economic and political characteristics of their daily life.”. Additionally, the environment either physical or of abilities of individuals forms a visual scene (Krassanakis & Filippakopoulou, 2023). Mental images are created by the brain when an individual performs an conscious or nonconscious visual search of a visual scene. The aforementioned process of understanding can be described as perception and spatial cognition. The memory is used by the brain in order to recall relative information about the objects and the shapes that are part of the visual scene (Krassanakis & Filippakopoulou, 2023). While many studies have researched the functionalities of the optical system, a lot of information is unknown to us about the process of the brain, in perceiving, capturing and interpreting the mental images (Krassanakis & Filippakopoulou, 2023).

The analysis of the procedures of cognition and perception can lead to understandings about the methodology and the elements of attention of an individual on a specific visual scene. As far as maps are concerned, they can be used in a visual scene as a stimuli and examine the cognitive processes of individuals, when using or performing specific tasks on maps. Hence, map cognition and map perception can be observed. The study of map cognition and perception on maps and map features can provide important information about the map elements, variables and symbolizations that stand out, compared to others, by creating attention, thus achieving visual knowledge valuable for forming mental images (Krassanakis & Filippakopoulou, 2023). The realization and identification of elements of maps that cause attention, in conjunction with the investigation of the map perception and map cognition, can assist in designing and creating accurate and effective map visualizations. The interpretation of map cognition, perception and attention can be achieved, by implementing various qualitative and quantitative experimental methods that use as a stimuli different map types, styles and map-related features. The experimental methods can contain questionnaires, reaction - time and accuracy, eye tracking, mouse tracking, EEG and fMRI. Map reading is a complex process, based on human vision and cognition. The map reader is required to interpret the visual representations portrayed on a map, in conjunction with their needs, knowledge, and experience (Clive, *et al.*, 2017). During map reading the elements that interact with each other are: the map user, the map and the established reading and attention conditions (Krassanakis & Filippakopoulou, 2023). The map’s design, along with the map user’s knowledge and the conditions of the map reading are all factors that affect map reading procedures (Krassanakis & Filippakopoulou, 2023). Montello (2002), explains: “*Map design can be thought of as mind design, the way a map is designed will influence the views of the world it stimulates or inhibits.”*

In the previous sections, basic elements of map creation, procedures, techniques, map-types, and map variables have been discussed. All these elements contribute to designing a final product of a map that aims to present and communicate to the reader clearly and accurately spatial and non- spatial information. Map-creation is based on the graphical design of visual symbols (Robinson, *et al.*, 2002). A plethora of map symbols can be used to describe a spatial phenomenon. The qualitative and quantitative aspects of geospatial data can be conveyed by linking the attributes of the specific data to the features of graphical symbols. By attributing to the symbols, coordinates (horizontal, vertical), they receive spatial status that refers to the position on the actual-World where the data occurred (Robinson, *et al.*, 2002). Similarities or differences of symbols designed on maps can be used to describe these effects on the data they represent (Robinson, *et al.*, 2002). For a map to be effective, it is important for the cartographer to select cautiously the symbols that are going to describe the spatial and non-spatial information. No matter how accurate position-wise and homogenous the data are, if the selection of symbols depicting them is not appropriate, the map will not be efficient enough and it will not be able to effectively communicate its information to the map reader (Robinson, *et al.*, 2002). Map symbols are used in order for the map reader to easily perceive the information rendered on the map corresponding to a phenomenon or object of the actual World (Robinson, *et al.*, 2002). Determining the map elements that affect the map reading and map perception is important for creating accurate and effective map-products. Map reading is a cognitive process.

According to Robinson, *et al* (2002), when creating a map, key objectives include assigning specific meanings or features to the map's discrete symbols. The layout of these symbols should be optimized to align with the map's intent. Cartographers should always consider the primary aim and application of the map when choosing graphical symbols. In cartography, multiple symbols and graphical methods can depict data, signifying that there isn't just one right answer. While there's some flexibility in choosing symbols, the cartographer has to keep in mind that many designing options are conventions, as conflicts may arise between conceptual and optical goals (Robinson, *et al.*, 2002). For instance, when oceans are depicted on a map, the areas closer to the shore are usually colorized with lower color values of blue compared to higher values for the areas further. The process of map creation is inherently linked to its intended purpose. A map is not just about the data it portrays but also the symbolization chosen to communicate that information. In cartography, the integration of experimental methods has become indispensable for gaining deeper insights into map perception and cognition. Eye tracking techniques provide a detailed understanding of where viewers focus when deciphering map information, revealing patterns and areas of interest. Similarly, mouse tracking can shed light on the user's navigational choices and interactions. Further, advanced neuroimaging techniques like EEG and fMRI can shed light on how the brain works when interpreting maps, giving researchers access into the brain's processes when engaging with different map variables and features. By taking advantage of these sophisticated tools, cartographers can refine their designs to align more closely with how users perceive and process geospatial information.

3. Experimental Methods in Cartography

Quantitative experimental research offers the ability to measure, quantify, analyze and count data and information during an experimental research, in order to verify or reject a hypothesis, discover trends and connections among data, techniques, methods *etc*. In cartography, experimental methods that are applied to assess map reading and cognitive process can be among others: Questionnaires, Reaction Time and Accuracy Measurements, Eye Tracking, Electroencephalography (EEG), Functional Resonance Imaging (fMRI) and Mouse Tracking (Figure 14). In the following paragraphs the aforementioned experimental methods and their basic elements are presented.

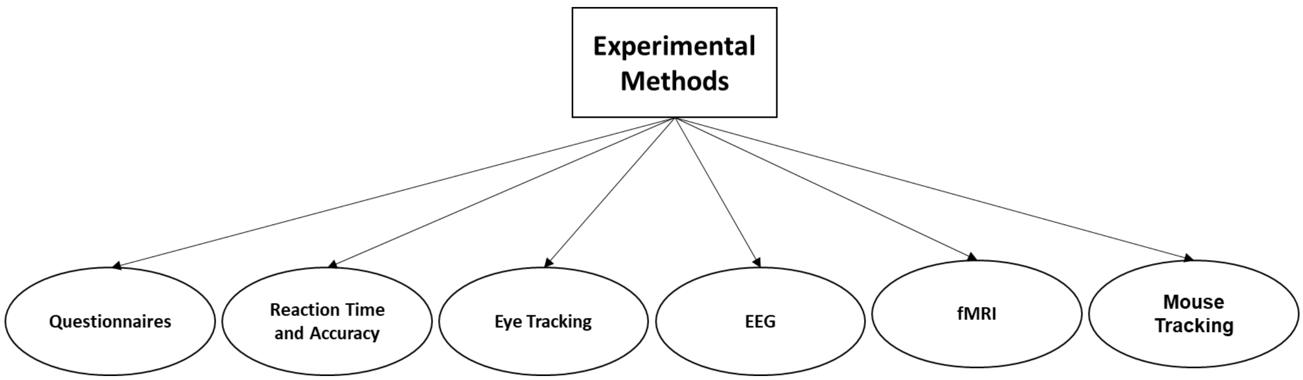
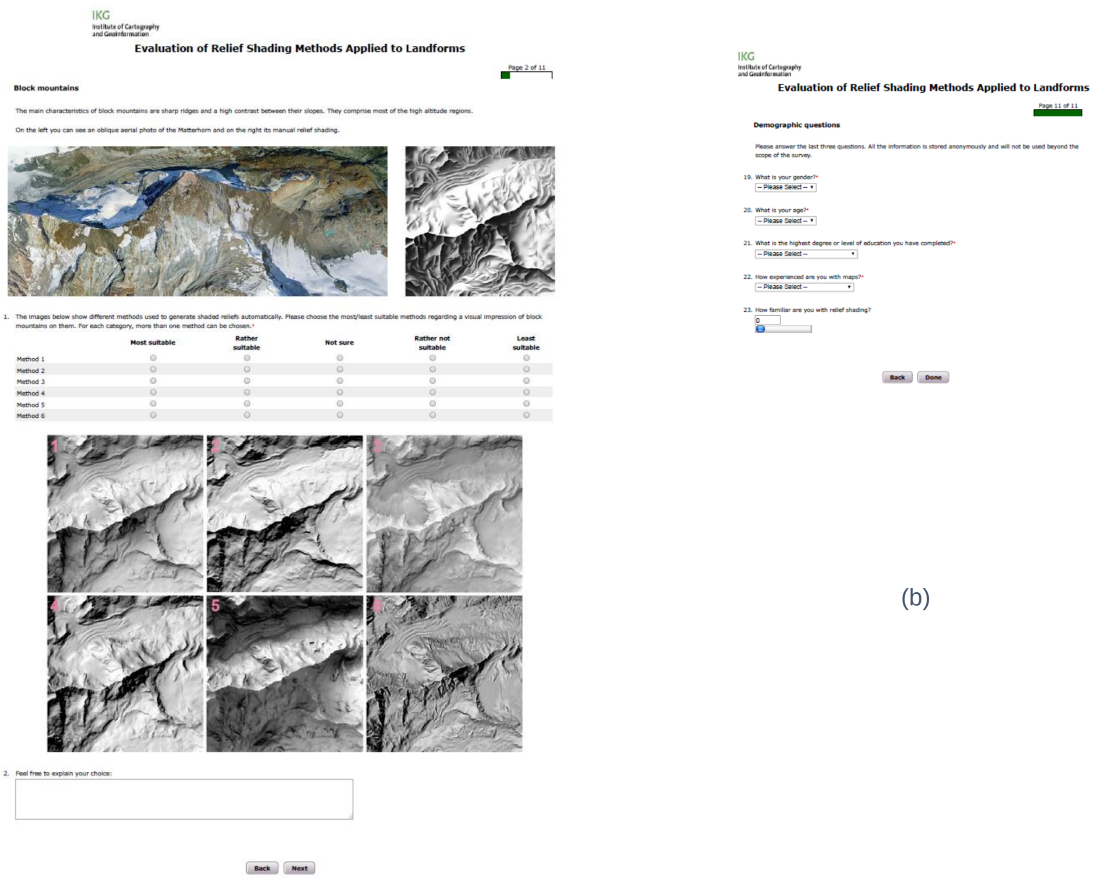


Figure 14: Experimental Methods Implemented in Map Perception and Cognition Studies

3.1 Questionnaires

One of the most typical experimental methods in cartography is the use of questionnaires (Krassanakis & Filippakopoulou, 2023). Depending on the subject of the study, filling-in questionnaires can provide both qualitative and quantitative data. The method of questionnaires for the majority of cartography and map cognition related studies is performed mainly online (Krassanakis & Filippakopoulou, 2023). Furthermore, questionnaires can be implemented as a review with or without the presence of the researcher (Krassanakis & Filippakopoulou, 2023). Questionnaires can be also classified based on the type of the answer. Closed - ended questions have predetermined answers of binary form (YES or NO), multiple choice form or scale form. Open – ended questions require the responders to describe in detail their opinion about the examined subject (Krassanakis & Filippakopoulou, 2023). The questionnaire method has been used by multiple research studies in map cognition related studies. Additionally, it has been implemented in combination with other methods, such as eye tracking, mouse tracking, EEG and fMRI. The online questionnaire of the study of Farmakis-Serebryakova & Hurni, (2020), is being used as an example (Figure 15). Participants were asked to rank (from "more suitable" to "less suitable") six relief shading techniques based on their suitability for nine distinct landforms and provide reasons for their choices. They were given an oblique aerial photo of the landform under consideration, accompanied by a representation using a manual relief shading technique. Figure 15 (a) displays this in relation to the "Block Mountains" landform. Upon completing the main questions, participants then provided information about their demographic details, as shown in Figure 15 (b)



(a)

(b)

Figure 15: Example of Online Questionnaire Implemented for (a) Comparing Different Relief Shading Techniques for Block Mountains and (b) Demographic Questions (Source: Farmakis-Serebryakova & Hurni, (2020))

3.2 Reaction Time and Accuracy Measurements

Reaction time is the measurement that many experiments use in the broader field of psychology, to determine cognitive factors in human's decision making process during a specific task on a stimuli. Accuracy refers to the effectiveness of the map user to solve the task correctly (Krassanakis & Filippakopoulou, 2023). Reaction time is combined with accuracy measurements for a comprehensive assessment. As Whelan (2008) and

Kosinski (2013), explain, reaction time (RT or response latency) is the amount of time required of a subject to complete a specific task. Luce (1986) and Welford (1980) have distinguished the reaction time experiments in three main categories . As Kosinski (2013) notes:

- Simple reaction time experiments require one stimulus and one response. For instance, tasks that require the participant to identify a specific symbol on a display, such as, ‘spot the dot’ and ‘reaction to sound’, fall into this category.
- On recognition reaction time experiments, multiple stimuli may appear (known as distractors) but only one of them is qualified as an accepted response.
- Choice reaction experiments require the participant to respond when an appropriate stimuli presents itself during the task. Usually, the stimulus sequence of appearance is random, in order for the participant not to learn a pattern and thus, anticipate the next stimulus. If the sequence of stimulus types is not random but follows a specific pattern then the Serial choice reaction in experiments is applied.

Reaction time measurement is referred to the time taken by a subject to complete a specific task and is not used under free-viewing condition experiments (Krassanakis & Filippakopoulou, 2023). As Donders (1868), and many experiments in reaction time until today suggest, simple reaction time compiles of the fastest reaction time, while recognition reaction time is faster than choice reaction but slower compared to simple reaction time. Choice reaction time requires the longest time of all (Kosinski, 2013). Simultaneously, reaction time is not only affected by the method of the experiment but it is also affected by the complexity of the response. More complex responses require more stored information thus, causing longer reaction time from the participant in order to acquire all needed information (Kosinski, 2013). Furthermore, the type of stimuli affects the recorded response time. Sound based stimuli produce shorter reaction time compared to light based stimuli (Kosinski, 2013). Age can affect response time, as Kosinski (2013), notes *“Simple reaction time shortens from infancy into the late 20s, then increases slowly until the 50s and 60s, and then lengthens faster as the person gets into his 70s and beyond”*. Kosinski (2013), cites a plethora of factors that influence response time, among others, arousal or state of attention, (including muscular tension), direct vs peripheral vision, fatigue, distraction, stress, *etc*. All of the above can have an impact on recorded response time.

The most common procedure for examining reaction time and accuracy data requires conducting an analysis of variance (ANOVA) on the sample mean (Whelan , 2008). Derivatives of such analysis can arise, such as, average, median, min – max and range. All these statistics can be used to interpret the effectiveness or accuracy of a stimuli. Whelan (2008), suggested that ANOVA approach for deducing and analyzing response time data lead to misinterpretation of the dataset. That happens because, as Whelan (2008) notes, ANOVA has low ability in capturing differences in the data. Response time data can be skewed and contain outliers. ANOVA data transformations can be applied to remove outliers, while the examination of the entire distribution can eliminate some of the restrictions cited and maximize the return from the obtained data (Whelan , 2008). The research study of Przech & Gołębiowska (2021), utilized reaction time and accuracy of responses to assess the efficiency of choropleth, graduated symbols, and isoline map representations. This study is further discussed in paragraph 4.1 Map Design and Cartographic Visualization Related Studies.

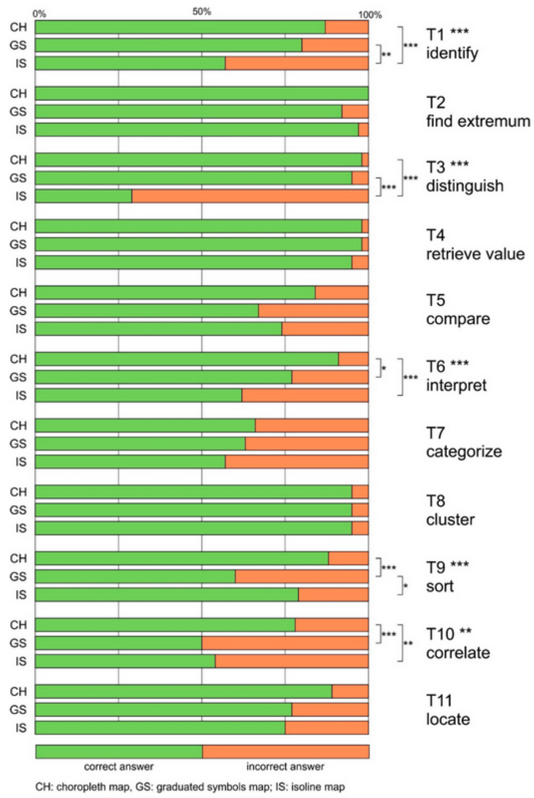


Figure 16: Example of Data Analysis Describing the Variations in Response Accuracy Among Participants per Task and Map Type (Source: Słomska-Przech & Gołębiowska, 2021)

3.3 Eye Tracking

One of the most unbiased and useful methods for exploring, studying and learning both perceptual and cognitive processes has been eye tracking (Figure 17) technology (Krassanakis & Cybulski, 2021). Understanding the cognitive activities of participants during specific tasks has been a main objective for researchers in various scientific fields such as psychology, *etc*. (Lai, *et al.*, 2013). Many methods have been implemented, such as think aloud strategies (vocalizing the internal thinking of a subject during a cognitive task) that often suffer from validity issues (Lai, *et al.*, 2013). Hence, a need for a more robust method arises. Kiefer, *et al.,* (2017, p. 1), explain that: *“Eye tracking allows us to measure an individual’s visual attention, yielding a rich source of information on where,* *when, how long, and in which sequence certain information in space or about space is being looked at."*

Figure 17: Eye Tracking Equipment, Tobii Pro Screen (Source:https://www.bitbrain.com/neurotechnology-products/eye-tracking/screen-based-eye-tracking)

Fitts *et al.,* (1950), were of the first to provide research around eye tracking applications, but not many research studies around that topic followed, mainly of weaknesses of the software and equipment used at the time (Keskin, 2020). Inaccuracies of recording the actual eye movements due to technical limitations, complexity in data extraction and interpretation were some of the limitations at the time (Keskin, 2020). Thanks to the technical advancement of eye tracking equipment and software for eye movements analysis these obstacles were able to be overcome (Keskin, 2020). Ever since Steinke (1987), provided the experimental applications and results of research studies around eye movements back in the 1990s and 2000s, eye tracking has been an important experimental method, providing fruitful and robust information about cognitive and perceptual processes (Krassanakis & Cybulski, 2021).

Today, cartography and spatial research in general are scientific fields where eye tracking techniques have been implemented successfully with wide use, providing significant results (Kiefer, *et al.*, 2017). A plethora of literature published in journals the last 20 years suggests that eye tracking can provide significant data. These data can be analyzed by cartographers in order to reject or support hypotheses in regard to the efficient design of maps, to the successful acquisition of spatial information and to understand how map readers interact with geographic information (Keskin, 2020).

Vision provides abundant information about cognitive and perceptual experience (Mahanama, *et al.*, 2022). Eye tracking succeeds in capturing the eye movements which represent the overt attention (Kiefer, *et al.*, 2017). Eye tracking offers a variety of recordings of human vision, gaze, eye and pupil movements (Mahanama, *et al.*, 2022). As Mahanama *et al.,* (2022), note on oculomotor events, the eye movement measurements consist of five basic eye and pupil movements, which are:

- The period during a specific time span that the visual gaze remains stable (at least 80 or 100 ms) is called a fixation (Keskin, 2020). Fixations could reveal the human's understanding of the visual scene at a specific moment (Keskin, 2020).
- Saccade refers to the quick eye movements that occur between two successive fixations (Keskin, 2020). Although the rate defers, the human usually performs on average 3 to 5 saccades per second (Mahanama, *et al.*, 2022).
- The smooth pursuit is in charge of maintaining a moving object in the fovea. A saccadic movement initiates the smooth pursuit by aiming the eye in the direction of the tracked object. Smooth pursuit shares the same measuring system since it performs similarly to saccadic systems in many ways (Mahanama, *et al.*, 2022).
- Blink is the spontaneous, intentional or unintentional reopening or closing of the eyelids (Mahanama, *et al.*, 2022).
- Ocular vergence is occurring when the eye movement is fixating on objects on different depth levels and planes, because of the binocular vision which dictates the opposite movements of the eyes. The movement can happen in either direction causing convergence or divergence (Mahanama, *et al.*, 2022).

Eye movement can be described as a sequence of fixations and saccades (Mahanama, *et al.*, 2022). Fixational eye movements does not mean that during fixations the eye movement remains still. Even during fixations there are small movements toward the targeted object. There are three categories of such movements: tremor, micro saccades and drifts. Their differentiated factor consists of frequency and rate of eye movement during fixations (Mahanama, *et al.*, 2022). Literature research for the eye tracking technique applied to cartography suggests that the eye movements that are mainly used are fixations and saccades based metrics, while micromovements of tremor, micro saccades and drifts do not affect the research object under consideration. Based on those five categories, the following three main specific analyses have been designed to interpret and accommodate these eye movements (Mahanama, *et al.*, 2022).

- Area of Interest (AoI) analysis is applied to examine eye movements by orienting eye movement to a specific visual regions. Instead of analyzing based on the whole visual field of view, a specified region is selected. This analysis is useful for attention based research such as user interface, marketing *etc*. (Mahanama, *et al.*, 2022).
- Heatmap analysis is applied for studying the spatial distribution of the fixations and saccades based on the entire visual scene (Krassanakis & Kesidis, 2020). It is best used for individual analysis of eye movements of participants, in per user designed tasks. The aggregation of the results of such tasks can be used for further analysis. This technique allows the detection of the quantity and quality of areas of visual

attention that the participants had on a specific visual stimuli, such as image, map, graphic *etc*. (Mahanama *et al*., (2022); Krassanakis & Kesidis, (2020)).

- Scanpath analysis represents the sequence of fixations and saccades during a specific task. The designed path describes the sequence of the participant's eye movements during that task (Mahanama, *et al.*, 2022). The fixation is usually symbolized by a node and its size is relative to the duration of the fixation (bigger radii for longer times and smaller radii for shorter times) scene (Krassanakis & Kesidis, 2020). That way the detection of both the sequence of movement and the duration of the fixation can be measured (Krassanakis & Kesidis, 2020).

Moreover, further analysis can be applied to the eye technique method. The analysis is expressed in measurements that are derived by fixations, saccades and the analysis of such movements. As Mahanama *et al.,* (2022), explain, these measures for fixations are:

- Count that represents the number of fixations during a given time period on specific AOI or an entire stimuli.
- Duration is the time period of a fixation, meaning the eye is staying still on a target. The duration corresponds to the cognitive process on the targeted stimuli (Keskin, 2020).

Also, according to Mahanama *et al.,* (2022), the measures for saccades are:

- The amplitude of a saccade represents the distance covered during a rapid eye movement. Expressed in angular degrees or pixels (when referring to images), it is defined as the Euclidean distance between two consecutive fixations..
- Direction of the saccade on a stimuli.
- Latency refers to the time interval between the introduction of a stimulus and the beginning of a saccade.
- Rate (also known as saccade frequency) denotes the number of saccadic eye movements occurring within a given unit time.

The visual search measures (Mahanama, *et al.*, 2022) are:

- Scanpath similarity. Lines and nodes represent saccades and fixations accordingly.
- Time to first fixation on AOI is the timed period between the presentation of the stimuli and the first fixation.
- Revisit count is the number of the gaze returning to a specific AOI.
- Gaze transition matrix describes the transition probability from one start to another.

The basic procedure of analysis for the aforementioned measurements in general includes metric's analysis based on first order statistical features such as min, max, mean, median, *etc*. and not on more advanced analytics (Mahanama, *et al.*, 2022). Many other derivatives of smooth pursuit, blinks and ocular vergence can be used (Mahanama *et al.,* (2022); Lai *et al.,* (2013)), but as resulted by the literature research, the metrics presented are the most common to encounter on research studies about perceptual, cognitive process and spatial distribution on maps. A typical process about the procedures taking place of the application of the method of eye tracking can be derived by examining the research studies implementing it. Studies that included eye tracking-based-problem-solving-tasks were mostly supervised by a technician or a researcher (*e.g.,* Beitlova *et al.,* (2020)) and occurred in a controlled environment (*e.g.,* laboratory based). A typical task-based-experiment methodology contains:

- An introduction of the participants to the tasks, the task's aim and familiarity with the environment.
- Calibration of the eye tracking equipment.
- Display of the respective task on a monitor for a brief moment hence the participants can read and understand the required task.
- Calibration on the monitor of the participant's eye movements trajectory, usually to the center of the screen. This typically is achieved by presenting on the monitor a fixation cross for a brief time (*e.g.,* 600 ms) in order for the participant's eye movements to fixate on the location of the cross (usually on the center of the screen).
- Presentation of the visual stimuli (map) thus, the participant can examine and find the solution to the task. The stimuli could be displayed for a limited period of time or not, depending on the task design. If more visual stimuli were required for each task the calibration of the participant's eye movements would be repeated before displaying the next stimuli.
- Conclusion of the task once the participant answers either by mouse clicking or by verbalizing their decision. Again, the form of the answer is relevant to the task design.
- Repetition of the process for any additional tasks.
- Possible completion of questionnaires prior or after the experiment.
- Interviews usually occur after the experiment's completion.

In general, the design of the experiments dictates the procedures that are going to be followed but usually the aforementioned process is observed. Other studies require by the participants to perform a free view of a visual stimuli, not bound to a specific task (*e.g.,* He *et al.,* (2023)). Eye tracking methods can be implemented individually and offer an analysis and data. Many studies prove that claim (Kiefer, *et al.*, 2017).

3.4 Electroencephalography or EEG

As already mentioned, eye tracking as a technique can be used in conjunction with traditional methods such as response time capturing. It can also be combined with more sophisticated and complex methods, such as Electroencephalography or EEG (Figure 18). At the time of this thesis, a small amount of studies has implemented EEG as a method to obtain quantitative data in the cartographic field. As Keskin (2020, p. 12) explains, *“EEG records the electrical activity along the scalp produced by firing of the neurons in the brain with high temporal resolution”*.

EEG is a non-invasive method. Using this method, electrodes are positioned on specific areas of the brain, capturing instantaneous recordings that are then processed by a computer (Keskin, 2020). EEG is difficult to apply in order to answer questions about high spatial resolution, since it reflects a variety of brain activities from various areas of the brain and various distances from the electrode (Keskin & Ooms, 2018). However, EEG offers a deeper insight about behavioral and cognitive processes of the human (Keskin & Ooms, 2018). EEG has been applied in a variety of medical, sports and marketing related research studies but it has also been used for analyzing the response of the brain to a visualization, display or image (Keskin, 2020). During this type of analysis, the recorded EEG that corresponds to the specific periods during which the participants received the event, is called ERP (event related potentials, activity time locked to an event) (Keskin, 2020). ERP is the part of EEG recording that is selected and offers the most information about the cognitive load, rather than just analyze the whole EEG recording (Keskin & Ooms, 2018). As Keskin (2020), explains *“EGG signals represent oscillations observed across a wide range of frequencies which are commonly divided into distinct frequency bands.”* Therefore, EEG aims to discover how brain activity performs during spatial and map related tasks (Keskin, 2020).

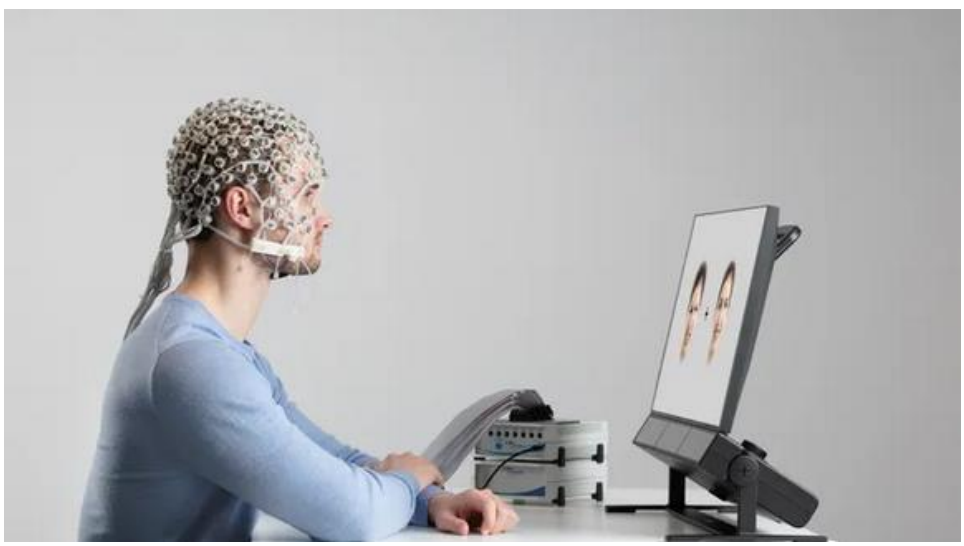


Figure 18: Eye Tracking and EEG (Source:https://www.tobii.com/products/software/behavior-research-software/tobii-pro-lab/multimodal-research-solutions)

Cognitive process entails both overt and covert attention (Keskin, *et al.*, 2020), which are fundamental cognitive functions and directly affect perception, memory and learning (Keskin, *et al.*, 2020). The factor of attention in cognitive process refers to how the brain comprehends the big amount of data presented to it and how it chooses to focus on specific information (Keskin, 2020). According to Keskin (2020, pp. 13-14):

- *“Overt attention is defined as selectively processing one location over others by moving the eyes to point at that location.*
- *Covert attention is defined as paying attention without moving your eyes.”*

While overt attention can be easily examined by eye tracking methods through understanding of fixations and saccadic eye movements, covert attention is more connected to the psychological and mental factors caused by the neuronal activity of the brain. The recoding of such instantaneous activity can be achieved by techniques such as EEG and fMRI (Keskin, 2020).

EEG as a method offers an abundance of data to analyze and combine with data collected by more traditional methods such as eye tracking, in order to draw solid conclusions and accept or reject an experiment's hypotheses. Nonetheless, designing an experiment based only on EEG or even combine EEG with eye tracking can have challenges (Keskin, 2020). Both technical and organizational issues may arise. The technical issues are referring to the calibration and synchronization of the required EEG and eye tracking equipment. The quality of the occurred measurements as well as their accuracy and efficacy are variables that need to be taken under consideration when designing such experiments (Keskin, 2020). Organizational problems are referring to the overall design of the experiment. The research's objectives need to be clearly defined. Considerations include the number of participants and their specific expertise or attributes. Decisions about the type of stimuli or tasks, as well as electrode placement and the specifics of brain activity recordings, are also paramount. These should be some of the aspects the researchers need to consider before taking any action in regard to the experiment’s design while keeping in mind that behavioral and cognitive data most possibly will differ amongst participants (Keskin & Ooms, 2018). In addition, it should be decided beforehand, which psychological measures of EEG, eye tracking and behavioral data (reaction time, questionnaires, *etc*.) are going to be used that best describe the cognitive load and what the analysis of those measurements should be (Keskin, 2020). A well designed and executed experiment is essential for the acquisition of meaningful, accurate and understandable information about the cognitive process of decision making and attention (Keskin, 2020).

3.5 Functional Resonance Imaging or fMRI

Functional Resonance Imaging or fMRI (Figure 19) is a quantitative experimental method that can be used in cartography for assessing map cognition and behavioral aspects of humans in map reading process. fMRI is considered as a foundational technique in cognitive neuroscience (Logothetis, 2008). According to Keskin (2020), *“fMRI measures neural activity indirectly by using blood oxygen – level dependent (BOLD) signal.”* BOLD constitutes a basis in human neuroimaging (Logothetis, 2008). fMRI provides an image of the brain activity with high spatial resolution of approximately 1 mm, by measuring the oxygen consumption of the activated brain area (Keskin, 2020). Furthermore, it can assess the metabolic activity of the whole brain changes (Keskin, 2020). Since fMRI images show changes in blood flow in the human brain, a region of the brain with a higher fMRI signal has more brain activity (Dong, *et al.*, 2023). fMRI is a non-invasive method. Specifically, fMRI offers insight as to where the brain activity occurs while a subject is processing information or carrying out a task (Lobben, *et al.*, 2009). fMRI does not provide exact information about how the subject is thinking, since the fMRI signal cannot discern differences between distinct brain regions or to differentiate tasks within a single brain area (Logothetis, 2008). fMRI is at the moment the best possible method to gain insight to the brain's functional organization (Logothetis, 2008). Even though literature related to cartography can be limited (Lobben, *et al.*, 2009) many other scientific fields are already using fMRI, such as cognitive psychology, behavioral economics, marketing *etc*. (Lobben, *et al.*, 2009).

Figure 19: fMRI Equipment (Source: https://www.uib.no/en/rg/fmri)

Lobben, *et al.,* (2007) encourage the interdisciplinary collaboration of cartographers and psychologists to perform research studies in the area of map reading using fMRI. They note that, even though many cartographers' questions may be already a subject of research for psychologists, rarely do the experiments include maps (Lobben, *et al.*, 2007). Many constructs have been a subject of research such as, visual search and spatial attention, object rotation and navigation by psychologists while using non map images (Lobben, *et al.*, 2007). Therefore, they indulge the use of fMRI in map reading and cognitive experiments as important information that can be obtained regarding this matter and help both scientific fields to understand and interpret the cognitive load during map reading process.

Similar to EEG, fMRI can be implemented individually or cooperatively with other more traditional methods *e.g.,* eye tracking, response time metrics, sk*etc*h maps and questionnaires. Literature research proved that fMRI has been used seldomly or tentatively in cartography and map reading, even though its contribution is acknowledged (Keskin (2020); Lobben *et al.,* (2009)). It is understandable that designing an experiment based on fMRI, just like EEG, can be proven challenging, because of the required equipment, data analysis, compatibility, transformation and preprocessing. Both Lobben, *et al.,* (2009), and Keskin (2020), advocate the use of this method since it can offer the chance to examine map reading processes differently and to extract aspects that are testable but specifically cartographic.

3.6 Mouse Tracking

Mouse tracking is a relatively new technique applied in a variety of sciences that examine the cognitive process of humans. Mouse tracking analyzes the mouse movements of a human occurring over visual stimuli (Figure 20). In addition to that, the path the cursor creates to complete a specific task along the coordinates (x,y) of the cursor during that path can be stored for further analysis. Mouse tracking was first introduced by Spivey *et al.,* (2005), as a technique applied in the field of language processing over almost 20 years ago (Freeman & Ambady, 2010). In that experiment, participants were tasked with moving the computer mouse from the center-bottom of the screen to either the top-left or top-right corners. They had to select the word that matched the shown image, all while the cursor's movements were being tracked and recorded (Freeman & Ambady, 2010). Since then, mouse tracking has vastly developed and been used for a plethora of appliances in experimental psychology and cognitive sciences (Kieslich, *et al.*, 2020).

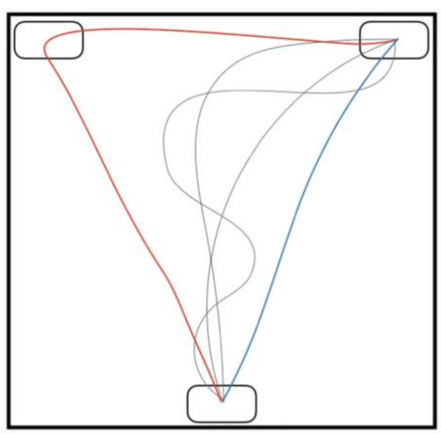


Figure 20: Shape of the Mouse Tracking Trajectories Underlying Distinct Decision Processes (Source: Maldonado, 2019)

Mouse tracking is used essentially to record the mouse trajectories of the human behavior on a visual stimuli during tasks (Kieslich, *et al.*, 2020). The ability to perform such analysis and collect that data offers the opportunity to the researchers to examine the cognitive processes in decision making in real time (Kieslich, *et al.*, 2020) . In most common mouse tracking tasks, participants are requested to select between two options displayed on a screen as buttons that may correspond to a visual stimuli, while the movement of the cursor is constantly recorded (Kieslich, *et al.*, 2020). The movement of the cursor is related to the activation of the making process towards the selection of an option (Kieslich, *et al.*, 2020). As Kieslich, *et al.,* (2020), notes, the curvature of the trajectory indicates the amount of attraction to the specific option. Furthermore, according to Kieslich, *et al.,* (2020), mouse trajectories offer two significant opportunities in the fields of experimental psychology:

- Mouse trajectories provide information about the conflict of a participant during the decision making of the most attracted option.
- Mouse tracking offers the ability to "assess the temporal development and resolution of this conflict during the decision process" (Kieslich, *et al.*, 2020).

Amongst the experimental methods in cartography presented in this study, Mouse tracking offers a more simple, affordable and less sophisticated technique (Demšar & Çöltekin, 2017). Additionally, mouse tracking based experiments can be performed simultaneously by many participants, while eye tracking or more sophisticated methods require movement data to be collected by one participant at a time (Demšar & Çöltekin, 2017).

As many research studies have proven there is strong correlation and similarities between mouse and eye movements, especially for conducting visual search experiments in the fields of cartography (Krassanakis & Kesidis, 2020). As Demšar & Çöltekin, (2017), suggest, mouse movements compared to eye movements are significantly slower and relatively smoother and more continuous. These differences make the comparison very difficult of the two trajectories of mouse and eye movements (Demšar & Çöltekin, 2017). On the one hand, mouse movement is usually performed under conscious actions, while on the other hand, eye movements are often executed unconsciously unless a specific stimuli dictates so (Demšar & Çöltekin, 2017). Nonetheless, eye and mouse movements share some common characteristics. As Demšar & Çöltekin (2017), indicate:

- Gaze and mouse tracking is represented by trajectories although of different features.
- The movements and trajectories of both eye and mouse are performed simultaneously and share the same theoretical space (visual stimuli).
- Because they share the same visual stimuli both movements are executed based on the same cognitive process.

As already mentioned, mouse tracking is a relatively new method that is still getting explored both concerning its capabilities and its appliances to the various fields of research. Based on the data acquired by the mouse tracking method, visualization techniques can be applied to assist further the study. Such visualizations can represent firstly mouse trajectories as lines on the visual stimuli, secondly duration diagrams which represent the stationary behavior of the cursor during the searching process of a map user, thirdly curvature diagrams which present the curvature changes of the data, and fourthly grayscale heatmaps, *etc*. (Krassanakis & Misthos, 2023). As noted in their paper, Krassanakis & Misthos (2023), list the advantages and disadvantages of the method. As advantages, the simplicity of the method, the suitability for research studies based on task oriented experiments under different conditions (remotely or not) on groups of participants with different characteristics are noted. Furthermore, mouse tracking offers adequate information for understanding the map user behavior, while being a method that can easily be combined with other experimental methods such as eye-tracking, EEG, *etc*. (Krassanakis & Misthos, 2023). The disadvantages of the method mainly focus on the lack of appliance on non-digital, printed maps and touch screen displays, while the method is described as unsuitable for free viewing exploration studies and for tracking the gaze position (Krassanakis & Misthos, 2023).

Hehman *et al.,* (2015), introduced new techniques of mouse tracking analytics for enhancing research studies in psychological sciences. They presented the theoretical background of the method, while suggesting many methods of mouse tracking data analysis. The proposed methods included the measurements and analysis of mouse trajectory deviations, velocity, acceleration and the temporal analysis of the mouse movements. Another presented technique evaluated mouse trajectory complexity with spatial disorder analysis. Additionally, they noted that, the extraction of distinctive and significant elements from mouse tracking data that represent behavioral aspects of the individuals could be determined by analyzing and comparing mouse trajectories of smooth or abrupt characteristics. They concluded by highlighting that principal component analysis (PCA) of mouse tracking data could provide significant and meaningful results.

Maldonado, *et al.,* (2019) examined the efficacy of the method in studies of the dynamics of cognitive processes. The researchers performed two experiments, the first one was designed in order to trigger a flip in decision and the second one was designed with more classical approach of linguistic negation. The task had the participants perform a truth value judgment task based on world known knowledge. They had to decide whether a sentence was either true or false and select the appropriate answer on the top left or right corners of the screen. Two patterns were implemented. During the first pattern the frame color on the screen remained stable, but during the second pattern the frame color of the screen switched once, thus resulting in revision of the initial decision. From the experiments it was concluded that in order to detect decision changes the mouse path as a variable is more important compared to temporal data such as acceleration and speed.

Kieslich *et al.,* (2020), investigated three different factors and the consequences they have in designing experiments based on mouse tracking methods. The research was presented since no standards or guidelines have been established for performing mouse tracking experiments. Through various experiments the design factors of response time, the starting procedure and the mouse sensitivity were examined. During the various experiments, the typical mouse tracking procedure described above was followed. The research resulted that these factors can have a significant influence both on the trajectory curvature and shape. The findings of the study led the authors to imply that the specific design of the study should be carefully taken into account when analyzing mouse tracking data and organizing mouse tracking research in order to test theories.

Finally, many toolboxes have been developed by the scientific community that aim to assist the methodologies of mouse tracking in map perception research studies. The tools can provide different applications, mouse tracking recordings, automated analysis and visualizations of the recorded mouse movement data. The subject of toolboxes and analysis tools is further discussed in Paragraph, 4.4 Analysis Tools.

4. Cartographic Research Studies

Over a span of 17 years, from 2006 to 2023, a total of 98 studies related to map cognition and perception were closely analyzed. The methodology employed for this extensive review involved rigorous online searches through reputable engines like Google Scholar. This research process was initiated with the use of specific keywords tied to the thesis's subject, such as "map perception", "map cognition", "cartography and experimental methods", and "eye tracking and maps" to name a few. Beyond the primary studies, the bibliographies of selected papers served as a rich resource, directing further exploration into relevant research. The same approach was followed when diving into well-known academic journals. Institutions such as ResearchGate, PubMed, Elsevier B.V., Taylor & Francis Group, Scopus, and MDPI AG (Multidisciplinary Digital Publishing Institute) were vital in this research process. It's noteworthy that while the timeline of studies str*etc*hes back to 2006, there was a concentrated focus on publications from the last five years. This comprehensive review encapsulates various works, including articles published in scientific journals, papers from conference proceedings, contributions to scientific workshops, and insights from Ph.D. and master's theses. The studies, depending on the examined field were classified into eight conceptual categories (Figure 21):

- Map design and visualization
- Map-interfaces
- Characteristics of map users
- Reviews
- Proposed methodologies
- Analysis tools developed
- Artificial intelligence (AI) in cartography
- Other applications.

For every research study the aim, the subject, the methodology and the results are presented. The acquisition and interpretation of the obtained data is performed by implementing experimental methods such as questionnaires, response time and accuracy, eye and mouse tracking and the more sophisticated EEG and fMRI.

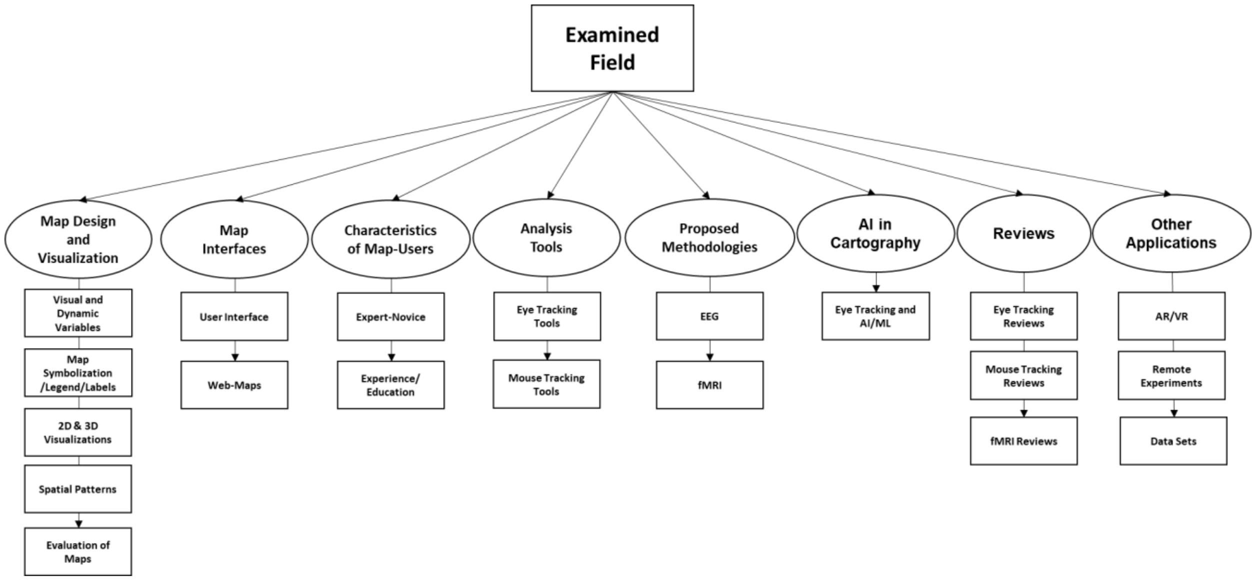


Figure 21: Examined Field of Reviewed Papers

4.1 Map Design and Cartographic Visualization Related Studies

One of the most well documented, examined field in cartography is the map designing factors and visualizations. Cartographers aim to design better cartographic products while implementing the most effective methods of graphical visualizations. To achieve this, reviews have been conducted on studies that empirically investigate the effectiveness and efficiency of various map products. More specifically the studied topics are related to the effectiveness of visual, dynamic and sound variables, the map symbolization, the map features such as legend and fonts, types of maps and the evaluation of new or existing map products.

Garlandini & Fabrikant (2009) examined the effectiveness and efficiency of four visual variables, meaning the size, the color, the hue and the orientation for 2D digital and animated map designing by eye tracking. The experiment of the study was performed in a controlled environment that employed a bottom-up and flicker approach in combination with eye measurements. The participants, 20 in total, had to identify when, where and how a visual change occurred on the examined map. The visual changes of the maps were designed based on the four variables at study. As the analysis of the results showed, the variable of size had the most efficient and effective behavior, while the variable of orientation was the least efficient and effective.

The examination of the visual variables of color hue, size and frequency on the usability of animated-maps, by eye tracking technology was studied by Dong *et al.,* (2014). Eye tracking data along with quantitative metrics, as accuracy for effectiveness and response time for efficiency, were recorded during tasks. An animated dynamic map representing the traffic flows of Hong Kong's main roads over twenty-four hours was designed and used in two different display sizes, a smaller and a larger one. On this map the visual variables of color hue, size and frequency were altered on different graphical elements creating various versions. A total of 30 participants took part in a task where they were required to identify the location of maximum flow and monitor its changes over time. Through the analysis of usability metrics and eye movements, it was determined that red, yellow, and aqua are more effective compared to other color hues. The size of line width is more accurate and effective than the color hues and the usability of frequency was not proportional to the playback rate of the animated map. On the larger display's size the map's higher frequencies were more effective, whereas on the smaller display's size the map's lower frequencies were more effective.

Krassanakis *et al.,* (2016), performed an experimental cartographic study (Figure 22) with the goal of determining the minimum duration threshold that the central vision needs in order to detect a moving point symbol on a map's background. Backgrounds containing discriminant levels of information were used to investigate the threshold and the assessment occurred through analysis of eye movements. The calculated threshold was close to 400 msec., as originated from the eye tracking data analysis. The result of this study offers a designing principle that can be applied on dynamic variables used on animated and interactive-maps.

Figure 22: The Map Used in the Experimental Research Study (Source: Krassanakis, et al., 2016)

Łucjan & Wojtanowicz (2018), performed an empirical study on animated maps to examine the scene transitions. They evaluated the impact of smooth and abrupt transition and collected data about the differences of the two methods in scene transition, in order to examine the influence of these variables on the cognitive process and effectiveness of animated maps. More specifically, three levels of scene transitions were examined, smooth, abrupt and abrupt with decay. Participants (students aged 13-14) were separated into three groups, each one corresponding to each level of scene transition. The tasks required by the map users to identify various vector elements (points, lines, polygons) on an animated map that represented fictional information which was designed for the study. The statistical analysis of the data included the accuracy of the answers, assessments of the wrong answers, and their derivatives. It was concluded that the scene transition variable indeed influences the interpretation of the represented discrete information. Animated-maps with smooth transitions were found to be less effective compared to those with abrupt and abrupt-with-decay transitions.

Elements of maps such as map legend for presenting information are a subject that many cartographers have researched. Brychtová (2015), researched the impact of color distance and legend position in choropleth map's readability by implementing eye-tracking. The conclusion of the study revealed that the position of the map legend did not affect the overall readability and effectiveness of the choropleth map, while the positive relationship of increased color distance on choropleth maps was noted. The study of Gołębiowska (2015), aimed to explore the role of the legend in interpreting thematic maps. Using a combination of usability metrics such as response time, accuracy, map user preference and the thinking aloud method, participants were tasked with using two thematic maps, each with a distinct legend layout (Figure 26). Although there were no significant differences in response time and accuracy between the two layouts, participants showed a preference for simpler or more familiar legends. Analysis of participants' verbal feedback uncovered varied legend comprehension patterns based on design and highlighted four primary problem-solving strategies. The research culminated in the formulation of principles for legend design.

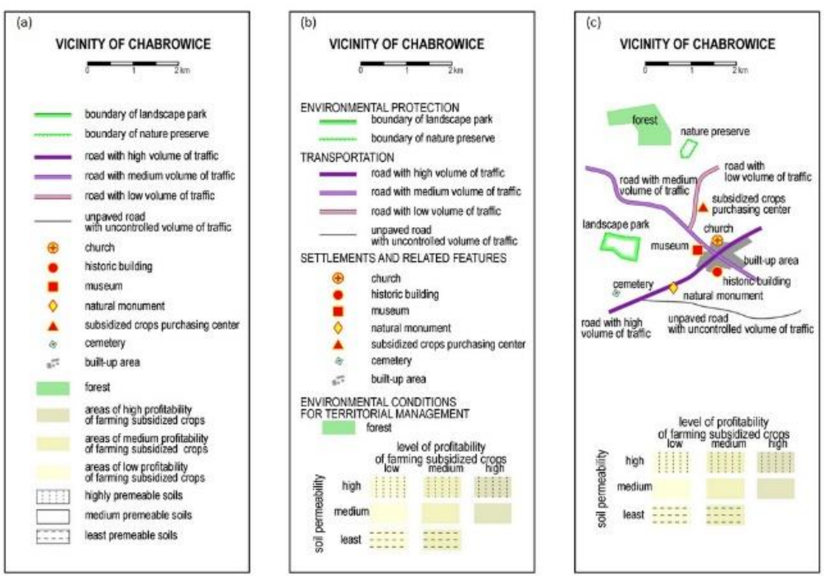


Figure 23: Examples of Types of Legends Used in Research Study ((a) List Legend, (b)Grouped Legend, (c) Natural Legend) (Source: (Gołębiowska, 2015)

The examination of map elements is a subject cartographers may investigate. For example, Brychtova & Coltekin (2016), using eye-tracking, concluded in their study, that the medium labeling font size that equals to "11 pt." is the most efficient to use on maps. Çöltekin *et al.,* (2017) evaluated the color organization in legend designs of soil-landscape maps implementing eye-tracking analysis. Two legend designs (Figure 24) of soil-landscape maps were examined to determine their efficiency via four map user related tasks. As it was suggested, soil maps are a challenging category of maps for reading and understanding, mainly because of the overwhelming information presented to the map reader. Hence, the understanding of the effective designing of such maps is of high importance. Two legend designs of the same map were studied, the first ordered the categories alphabetically and the second more uncommon technique ordered the categories based on color, using the *“Munsell color space”* method. In total, 20 participants of geography related fields, were required to complete four soil – map related tasks, during which their eye movements were recorded. The four tasks required by the participants to locate, identify, associate and compare information on the map. The used metrics for evaluation were the accuracy and response time of tasks, along with the eye movement’s analysis of scanpaths, the transitions between map legend, the legend AOIs and the qualitative analysis. As resulted by the analysis, Çöltekin *et al.,* (2017), noted that the accuracy of both legends was subpar, with participants' preference for the type of legend being evenly divided: 50% favored the alphabetically ordered one, and the other 50% leaned towards the color-ordered version. Regardless of the legend design, the majority of the participants failed to answer correctly two out of four tasks. The tasks were designed to locate and identify information on maps and log the lowest accuracy and longest reaction times. Based on the analysis of recordings and the level of expertise of participants, the authors noted that the prior knowledge on the examined field could dictate the performance on the two types of legends and tasks. Furthermore, the authors highlighted that experts could be highly prepared to follow methods they were accustomed to, such as the more traditional alphabetical ordering, whereas beginners might benefit from a perceptually driven design, such as color ordering. Simultaneously, they admitted that some tasks were challenging to solve. Despite the legend type or task, Çöltekin *et al.,* (2017), supported in their research that the perceptual complexity of soil maps is very high and requires caution when designing that type of map.

Figure 24: Alphabetical-Ordered (Left) and Color-Ordered Legend (Right) Legend Designs of Soil-Landscape Maps Used in Experimental Research Study (Source: Çöltekin, et al., 2017)

The symbolization of flow maps was studied by Dong *et al.,* (2018). The researchers explored the usability of flow-maps using eye tracking techniques and questionnaires. The authors examined and compared the impact of various flow symbolization, such as the type of flow (straight or curved), the thickness and the color-gradient of flow on map usability. The used eye-movement metrics were fixation count, percentage of fixations in AOIs and time to first fixations. Trial duration and accuracy metrics were used to describe the average time of completing the task and the accuracy of the answers accordingly. The participants, 40 in total, participated in the study by answering three questions after the stimuli was presented to them in a free of distractions environment. It was noted that the combination of flow maps with curved lines and the use of color-gradient to indicate volume was significantly more effective. Liao *et al.,* (2019), investigated the impact of map's label density (Figure 25) implementing eye-tracking and questionnaire methods, in order to assess the visual complexity of the maps. Participants had to identify on maps landmarks of point features and rate the map's complexity and legibility. Participants repeated this process on two different experiments. During the first experiment called "controlled experiment", the map that served as a stimuli was designed specifically for this study and all the variables were constant except label density. In the second experiment, the same process was conducted but instead of a specifically designed map, a stimulus of an actual map was used. This methodology was followed in order to confirm if the trends of the first experiment were applicable also to real maps. The results showed strong correlation amongst label density, perceived map complexity and response time. Response times tended to increase as the label density got more complex. Interestingly enough the authors discovered an inverse correlation of the two experiments between label density and the eye-tacking metrics of fixation-duration and fixation-frequency. On the one hand, the maps of the controlled experiment revealed that the increase of label density resulted in longer fixation-durations thus decreasing the fixation-frequency. On the other hand, the eye-tracking data of the experiment which used the real map revealed that the increased label density resulted in decreased fixation-duration and increased fixation-frequency. The conclusion of Liao *et al.,* (2019) was that these ambiguous results indicated that eye movement measurements might not be the best indicators of map complexity, and further research is required.

Figure 25: Label Density (a) Level 1 and (b) Level 10 of Sample Trial Maps Used in Study (Source: Liao et al., 2019)

Similarly, an empirical study of road networks (Figure 26) was performed by Liu *et al.,* (2019). The impact of different road network patterns on spatial cognition, was studied by implementing fMRI. Visualizations of regular and irregular road network patterns were presented using Google Maps as the backdrop. Nine participants were tasked with orientation and shortest route selection exercises. The fMRI analysis indicated that individuals navigating irregular road networks faced challenges in orientation tasks. However, for shortest route selection tasks, participants showed comparable levels of difficulty in both regular and irregular road networks.

Figure 26: Experimental Area (a) for Irregular and (b) for Regular Road Network (Source: Liu, 2019)

Korycka-Skorupa & Gołębiowska (2020), explored the impact of numbers used on thematic maps. The study presented an empirical study that examined the influence of the usability of numbers, by comparing the representation of quantitative information using numbers to proportional map symbols in typical map reading oriented tasks. The tasks design aimed to compare and observe the map user's behavior in reading quantitative information represented by the following three different methods, the use of numbers with fixed size, the use of numbers that their size changes compared to the change of the value of the phenomenon and the use of proportional symbols, specifically rectangles. The nine tasks required by the participants to identify and compare values of the represented phenomenon in 27 (9 maps per method) maps of a fictitious area that contained quantitative information about tourism. The maps contained a single variable, a redundant single variable and two variable representations. The data of analysis consisted of the response time to complete the tasks, the accuracy of response, and their derivatives. The implementation of numbers as a representing method had higher accuracy and response times in single and two variable visualizations compared to proportional symbols. No differences between representations of fixed size numbers and proportional size of numbers were observed. From this conclusion, it was suggested that, in certain cases, using numbers instead of proportional symbols might be more effective and preferable.

Stachoň *et al.,* (2020), studied the visual search on maps by eye tracking. The experiment required the participants to identify and select a target symbol on topographic maps. The map symbols differed in shape and hue. Blue was used for transportations objects, yellow for cultural objects, black and white for other objects and red for one hospital object, while the shape of the symbols corresponded to the objects they represented. The symbols were unlabeled, and the study's objective was to examine the influence of the pop-out effect and the relative positioning of the target symbols. Eye tracking data, trial duration and accuracy of responses were collected during the tasks. The results revealed that colored symbols were detected faster than the black and white symbols. As a result the impact of pop–out effect can be safely interpreted. The map users required less time to identify red symbols, therefore their dominance compared to other symbols was proven, followed by blue, yellow and finally black and white. The relative position of the target symbols impacted the visual search of the map users, meaning that the symbols located on the center and on the center of the upper part of the map were identified faster.

Gröbe & Burghardt (2020), proposed the visualization of micro diagrams for representing categorical point information sourced from location-based social media platforms, as these datasets are used more frequently by a number of applications. It was noted that the standard visualization for such data typically derives from point maps. Although it was admitted that this type of visualization is ideal with a limited amount of data, particularly with data that contain categories, this method has the disadvantages of cluttering and overlapping. The proposed micro diagram method is using diagrams that present the percentages of each category and their spatial distribution. Aggregation of the point data in regular grid structure and selection of the diagram-type that represents the data and their categories is implemented for the visualization of the micro diagram. Gröbe & Burghardt (2020), offered an insight about the application of the method and the variables that need to be taken under consideration when designing micro diagram representations for the most efficient result, such as diagram type, scale and color. Authors performed a case study where participants participated in four tasks of increased difficulty. The tasks required by the participants to estimate and identify categories using maps based on both point method and micro diagrams. The study's findings revealed that participants found it easier to determine the dominant category and the proportion of a category when using micro diagrams. Generally the reading of values was easier for the map users compared to point-method visualizations.

Karsznia *et al.,* (2021), sought to examine the correlation between spatial pattern recognition on an equal area unit map and the size of hexagonal enumeration units, measured in pixels. The aim was to determine the optimal range of sizes where spatial patterns are clearly visible, recognizable, and comprehensible to map users. The study involved 488 participants, the tasks designed to measure response time, preferences, and expected responses (Figure 27). Results indicated that enumeration unit sizes of 26, 52, and 104 pixels were generally preferred for indicating patterns. In contrast, maps with unit sizes of 1664 and 3328 pixels were viewed as less effective. Some anomalies were observed, underscoring the challenge in definitively determining the ideal unit size and emphasizing the need for further detailed research.

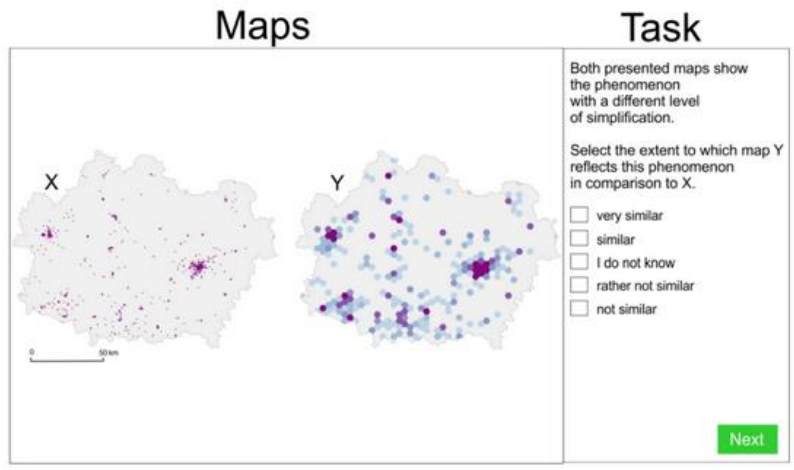


Figure 27: Layout of Task and Maps Implemented in the Experiment (Source: Karsznia et al., 2021)

Pappa & Krassanakis (2022), examined the pre-attentive effect on maps using mouse tracking remotely. For the recording and the analysis of the data, the study utilized the MatMouse software (Krassanakis & Kesidis, 2020) . In a task oriented experiment the participants were required to locate a target symbol amongst various other symbols, but this specific target symbol might not have been contained in the examined map. Various target symbols were used. The location of the target symbols was also varied between central placement on the map and peripheral placement. Four different maps served as a background for the design of the visual stimuli. While the participants were solving the task, the reaction time until they found the target symbol and the mouse coordinates was recorded and used for the analysis. The results of the study suggested that the pre-attentive feature has the same effect on all used target symbols, while the reaction time was influenced by the level of detail on the cartographic background.

Cybulski & Krassanakis (2022), examined in an experimental study the effect of map label language and position of target symbols in visual search of map users. The tasks required by 38 participants to identify on various maps various point symbols. The symbols' relative location was different from map to map and from peripheral to central based presence. The map label language of the point symbols was different between maps, having a map label in the native language of the participants (Polish) and a map label in a language no participant could understand and speak (Chinese). The data were acquired by eye-tracking methods, as the eye movements of each participant were recorded during each task. he study uncovered that when detecting target symbols in a language they did not speak, participants showed a preference for the peripheral location over the central one. Conversely, when the target symbols were in the participants' native language, they favored the central location. This behavior suggests that participants would focus on the native language label after identifying the target symbol, but would not do the same for labels in a language they did not speak after recognizing the target symbol. Another reading behavior of the participants was that when searching for a point symbol in either of two locations (peripheral or central) their visual attention focused on the corresponding zone. These results, as the authors noted, demonstrated that the location of cartographic symbols plays an important part in the visual search process.

Map symbolization was also studied by Kapaj *et al.,* (2023). They compared the efficiency of abstract 2D and realistic 3D building techniques of landmark visualizations on mobile maps (Figure 28). Navigator experts participated in a real world navigation task that required them to follow a route and identify landmarks along the way. The navigator experts used a mobile map and were divided into two groups, one group for each landmark visualization style examined. The gaze-behavior of the participants was recorded during the real-world-task. The analysis of the results highlighted that although the participant's spatial learning was improved when they focused their visual attention on the environment, no difference was observed between the two landmark visualization styles in terms of spatial learning.

Figure 28: Landmark Desing (a) Abstract 2D and (b) Realistic 3D Representation of Building Used (Source: Kapaj et al., 2023)

Visualization techniques of spatial information is another subject cartographers studied. Specifically, comparisons of 2D and 3D visualizations of maps with the purpose of examining the effective application field of each technique. The eye tracking approach was implemented also by Popelka & Brychtova (2013), to compare 2D and 3D terrain visualizations. The participants were required to complete tasks after viewing 2D and 3D terrain visualizations and complete questionnaires about their preference and whether the visualizations were understandable or not. No specific preference of either 2D or 3D representations was highlighted by the maps-users, whereas the analysis of the scanpaths proved that different map reading strategies on 2D and 3D visualizations are employed. Similarly, in the study of Popelka & Doležalová (2015), both eye-tracking and questionnaires methods were used. The participants of various levels of expertise first completed a questionnaire and then they were required to identify and locate a requested symbol on digital 2D and 3D city maps while their eye movements were recorded. The outcome of the study highlighted that no differences in symbol's searching were noticed, regardless of whether the 3D effect was present or not. Using an eye-tracking approach in the study, Dong & Liao (2016), determined whether the photorealistic 3D representation can facilitate map reading and navigation in digital environments. The experiment took place in a controlled environment and was performed by using a widely used digital environment (Google Street View) that offers the visualizations. The participants were separated into two groups. One group performed the task by using the 2D visualization and the other by using the 3D photorealistic visualization. On the one hand, the results indicated that as far as map reading is concerned, the participants were less effective and efficient on the 3D representation compared to the 2D. On the other hand, on 3D representations the map users performed more efficiently in self organization and orientation procedures. In the study of Liao *et al.,* (2017), the comparison of 2D maps and 3D geo-browsers was explored using eye-tracking techniques. The result of the study showed that the response time of map users was faster on 3D geo – browsers and that the 3D visualization was preferred for higher level of difficulty tasks.

The efficiency of various map types and their visualizations is explored by many researchers. Choropleth map is a type of map that its applicability, its methods of representing geo spatial information and its purpose are attracting a lot of interest by the cartographic community. In an effort to analyze the effectiveness of various 3D thematic cartographic methods, Popelka (2018), performed an eye-tracking experiment for the evaluation of prism and illuminated choropleth maps compared to simple choropleth maps. The findings demonstrated that even though prism maps yielded higher answer accuracy compared to basic choropleth maps, participants took longer to complete the task and provide correct answers. Additionally, the illuminated choropleth maps received a greater proportion of correct responses than the basic choropleth map versions.

Schiewe (2019), examined through the implementation of questionnaires, the impact to visual perception of spatial patterns in choropleth maps. The studied spatial patterns corresponded to three variables of choropleth designs (Figure 29). The study observed the effects of the three following biases, the dark is more biased, the area -size bias and the data classification. The designed tasks demanded by the participants (260) to detect and identify specific features on a choropleth map in regard to the examined subjects. As far as the dark is concerned it is more biased, the hypothesis of the author was that without a legend provided the map user would associate the darkest color hue with the largest data value. For the second bias, the hypothesis was that without a legend the map users would often miss very small areas with global extreme values. For the third bias, the hypothesis was that no matter if a legend is provided, the map users would tend to classify spatial patterns according to the related color intensities. The used tasks and choropleth maps were designed according to the studied hypotheses. After completing their tasks, the participants answered a questionnaire related to their level of expertise, their level of map familiarity and the confidence level about their answers. The analysis of the data obtained, consisted of statistical analysis of accuracy of answers, user/usage characteristics and correlations of the above. The results of the analysis supported all of the hypotheses made by the authors and no significant differences occurred. The authors suggested that further research about successfully detecting spatial patterns needs to take place, as they proposed future subjects of study.

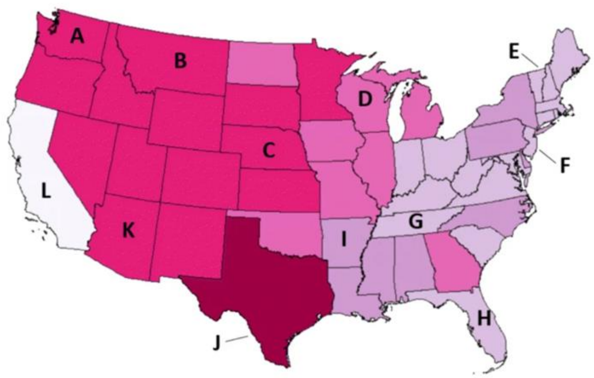


Figure 29: Design of a Choropleth Map Used in One of The Task of the Study (Source: Schiewe 2019)

Thematic maps highlight different aspects of the data they represent, assisting various user tasks. The research study of Słomska-Przech & Gołębiowska (2021), involved 366 participants and compared the efficiency of three map types, all based on the same data. The study aimed to evaluate the effectiveness of choropleth, graduated symbols, and isoline maps (Figure 30) in assisting users with basic tasks. Performance was measured using answer accuracy, time taken, and perceived difficulty. A total of eleven tasks were completed. Participants were split into two main groups. Each of these groups was further divided into three subgroups, corresponding to the map types being tested: choropleth, graduated symbols, and isoline. Results favored the choropleth map, both in terms of performance and user preference. While the choropleth map stood out, creating it properly poses challenges. It's vital to recognize that the field of thematic cartography offers diverse options, and reliance shouldn't be solely on one map type, despite its advantages.

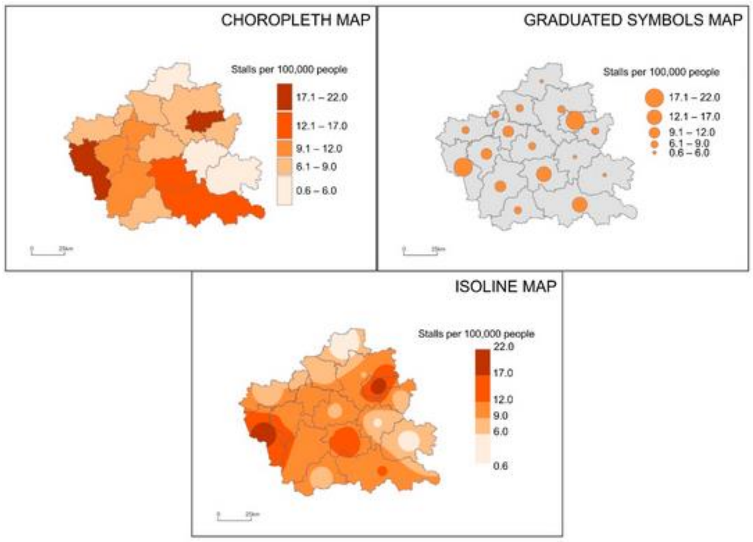


Figure 30: Examples of Different Map Types Used in Tasks (Source: Słomska-Przech & Gołębiowska 2021)

Cybulski (2022), studied the effects of temporal trends in spatial pattern on animated choropleth maps, using eye movement measurements as an evaluation method. This study used fifteen animated choropleth maps with various temporal trends and spatial patterns in order to examine their effectiveness, by requesting from the participants to accurately identify them on each map. The animated-maps represented the unemployment rate over twelve months. The spatial pattern of the choropleth map differed among radial, clustered linear, grid, peripheral or dispersed. Cybulski (2022), noted that the successful trend and pattern identification was dependent on the user's visual map reading strategy and the pattern itself. Rather than spatial patterns, animated choropleth maps were better suited for displaying temporal trends. Implementing techniques that facilitate effective visual searches, such as highlighting, cartographic redundancy, or interactive tools, may be necessary, given the difficulty of correctly recognizing spatio-temporal relationships.

In addition, the choropleth map has been used as a means to evaluate the value of other types of maps. Jia *et al.,* (2023), examined the effectiveness of cartograms (Figure 31) for conveying quantitative information using eye-tracking. The effectiveness of rectangular cartograms in representing quantitative information was examined through task-driven eye-tracking cognitive trials. The effectiveness of the cartogram was determined by comparing it with an unclassed choropleth map. The tasks were designed to locate, compare, find extremum and estimate information between the choropleth map and the corresponding rectangular cartogram, while the eye movements of the participants were recorded. In total, 90 participants completed the tasks, during which fixation, fixation durations, saccades, as well as the accuracy and duration of the responses were measured. The results of the study showed that the accuracy of the tasks was higher on the rectangular cartogram compared to the choropleth map and as the tasks got more complicated the users exhibited more patience when reading the cartogram. Compared to an unclassed choropleth map, the study showed that a rectangular cartogram had regular and uniform shapes and simple boundaries, making it easier to compare quantitative data. It was noted that additional tasks, a larger sample size of participants, and further eye-tracking analysis are required to draw more generalized conclusions.

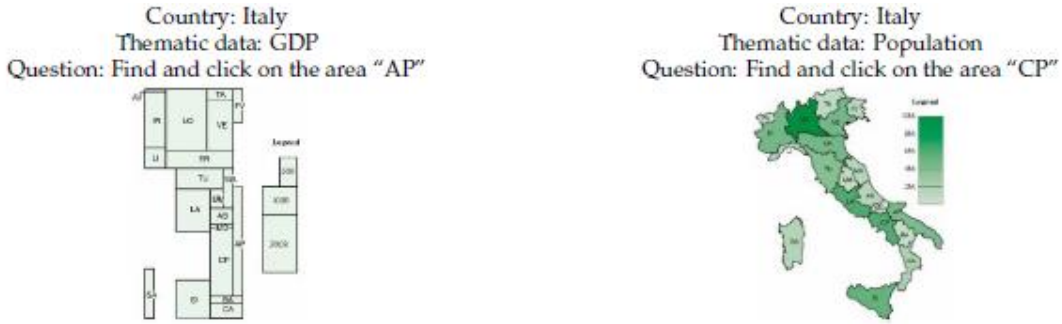


Figure 31: Paradigm of Cartogram and Choropleth Map of Italy Used in Locate-Based Task (Source: Jia 2023)

Besides the development of new methods of graphical visualizations, cartographers also study the effectiveness of existing cartographic products that are used by map users on a daily basis, such as educational atlases, *etc*. The study of Bugdayci & Bildirici (2016), consisted of an extended research, analyzing the cartographic design and visualization of 22 atlases used in courses of geography and social studies in Turkey. The authors examined a plethora of map features, such as cartographic generalization, fonts, colors of legend, graphic symbols and methods used to represent geospatial information on maps. The researchers noted the advantages of printed maps compared to digital in the learning process. Finally, the authors suggested improvements of the atlases that can assist the learning procedures for map reading and understanding. Identical conclusions were provided in the study of Paresadko & Baltabaeva (2017), who examined the school atlases used in Turkmenistan. The results of the study indicated that the atlases used have inaccuracies, are outdated and obsolete and mentioned the need for designing new ones. A map evaluation of a different type was performed by Burian *et al.,* (2018). The authors evaluated the quality of urban plans (Figure 32) in the Czech Republic using eye-tracking analysis. The participants had to complete specific spatial tasks on urban plans while their eye movements were recorded. Various urban plans of different areas that share similar graphical representations, layouts, scale and map features were selected. All maps were static and in digital form. Six tasks had to be completed by 26 participants, 20 novices and six experts in urban plans. The tasks required by the participants to identify specific map vector features on the given map. The metrics used for analysis were the response time and the accuracy of tasks, the fixations, the fixation duration and the fixation count. The authors concluded that the quality of symbols, the map legend and the level of experience of map users influenced their understanding of the urban plan. Moreover, they noted that the selection of appropriate symbolization and arrangement of the map legend could have an immense impact on the effectiveness and successful communication of the map. On urban plans with ambiguous symbolization, the participants needed more time to complete the task and more fixation count of longer duration, while more incorrect answers were reported. Simultaneously, Burian *et al.,* (2018), observed that many factors influenced the accuracy of the answers with prior knowledge and experience being two of them.

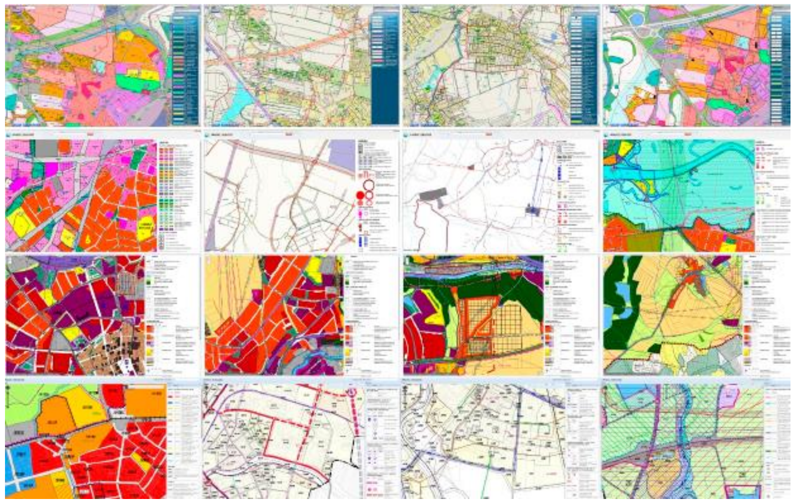


Figure 32: Overview of Selected Urban Plans (Source: Burian 2018)

Netzel *et al.,* (2017), examined the individual's effectiveness of rectangular cartograms in representing quantitative information was examined through task-driven eye-tracking cognitive trials. Specifically, the authors examined the impact of the color vs grayscale maps, the map's complexity in three different levels and the task's level of difficulty on map reading. Participants were tasked with choosing a route from a starting point to a destination and noting the number of transfers required along that route, all while their eye movements were being monitored. The metrics of eye-tracking consisted of fixations, fixation duration, saccades and scanpaths. The scanpaths of all participants were clustered in order to group participant's reading behaviors that shared common characteristics. Furthermore, the analysis revealed typical reading strategies of the individuals, such as directly tracing a path from the beginning to the desired location. Moving back and forth between the start and target location was a common method by which participants double-check the accuracy of their selection, meanwhile the variable of color vs gray was independent to the selected strategy. Burch (2018), performed an empirical study through eye-tracking in order to identify the map elements of metro maps visually attended. The results revealed that the participants always focused their visual attention on the map legend as they used it in order to interpret the map symbols and understand the map information. Additionally, key map symbols were visually attended such as, map legend, labels, airport signs, metro lines and stations, end of metro route destinations and interchange points. The color code and grayscale metro maps were similarly visually attended.

The conclusions of the study of Bugdayci & Bildirici (2016), about the improvements of atlases come in agreement with the research study of Beitlova *et al.,* (2020). The authors studied the different strategies in map reading of thematic maps between the students and their geography teacher implementing eye-tracking. This study aimed to answer whether the students could learn by using existing school atlases or not, if the atlases' design was sufficient and understandable by them and if the teacher's reading process compared to students' had any differences. In total, 30 students (of age around 18) and their geography teacher, were required to complete ten tasks. Each task included one of nine thematic maps found in atlases, used in teaching courses. During the tasks, recordings of the eye movements of the participants took place. The used metrics were of both qualitative and quantitative form. The quantitative data consisted of accuracy of answers, fixations, fixation count and duration, saccades and scantpath. Beitlova, *et al.,* (2020) noted that the results verified that the students could indeed learn from the existing maps, as the average correctness was above 70%. However, the poor graphical visualizations of symbols and the map legend's design made it difficult for the students to read and understand the map, as proven by their longer durations in fixations. Finally, the scanpath comparison of the students and their teacher presented a difference in the map reading process. While the students first read the legend and then attempted to answer the task, the teacher rarely looked at the map's legend and mainly used her knowledge to answer each task.

Farmakis-Serebryakova & Hurni (2020), performed an online survey to examine and compare the different relief shading techniques applied on landforms. The authors evaluated analytical hill shading methods against a set of landforms. In the online survey in form of questionnaire, the participants were presented with nine landforms (Figure 33). They were also presented with oblique views and their representation in both manual relief and analytical relief shadings, in order to be compared. The participants had to describe the six analytical relief shadings methods (clear sky, hill shading with North NorthWest (NNW) illumination, texture shading, cluster shading, clear sky with vertical exaggeration, multidirectional oblique weighted (MDOW) as the most, the least, the rather and rather not suitable, compared to the manual relief shading and oblique views. In the survey the level of expertise was taken under consideration as the experts' answers were evaluated and weighted differently compared to other levels. The results and analysis of the responses indicated that clear sky models performed well enough to most landforms, especially in mountain and valley types. However, the cluster shading performed well on areas described as mountains and hills, but not so-well on valleys. Based on the responses, most landform types were represented with an excess of information through texture shading and MDOW. The aspect tool was best suited for landforms described by glaciers. Alluvial type of landforms had the best results represented by the standard relief shading with custom lightning direction.

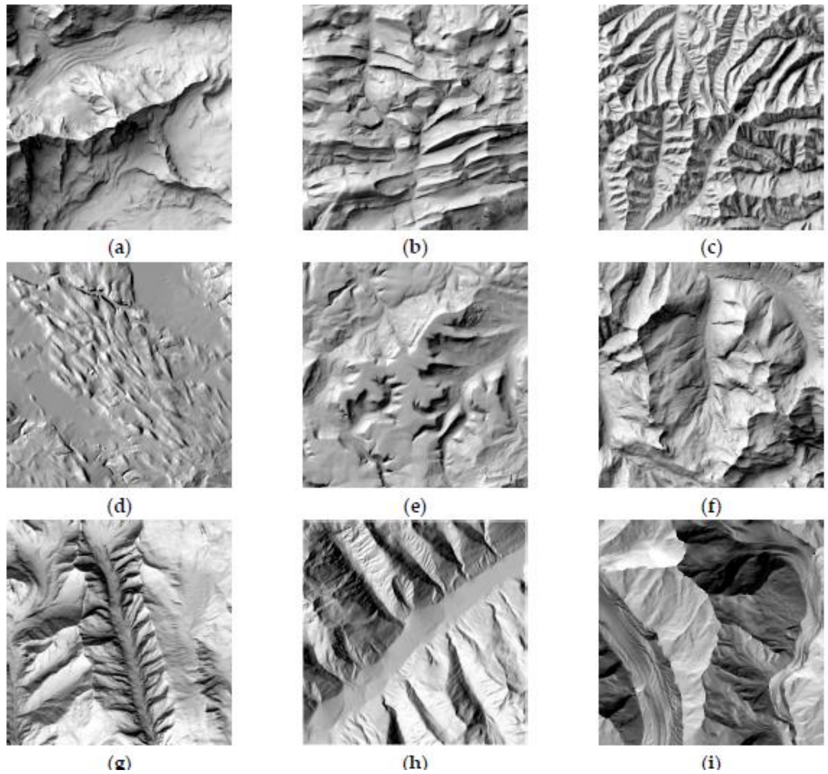


Figure 33: The 9 Relief Shading Methods: (a) Block Mountains, (b) Folded Mountains, (c) Erosion Processes, (d) Cluster Shading for Drumlins, (e) Plateaus, (f) V-Shaped Valleys, (g) Clear-Sky Model with Custom Illumination, (h) Standard Hillshading with Custom Illumination and (i) Aspect Shading for Glaciers (Source: Farmakis-Serebryakova & Hurni 2020)

Similarly, based on Landscape Rating Index (LRI) metric, Tzelepis *et al.,* (2020), investigated the influence of multidirectional hill-shading on perceived visual complexity by implementing eye-tracking and expert judgment procedures. Three different hill-shading methods were used to produce geovisualizations, a standard method of ideal diffuse reflection, a multidirectional oblique weighted (MDOW) method and a combination of the above. The LRI for the measured eye-tracking metrics (ETMs) was implemented for the evaluation of the data. In total, 15 participants observed the stimuli containing the visualization of earth's surface represented by the examined methods of hill-shading, unbothered by external factors for a period of approximately ten seconds, while capturing their eye movements. The conclusion of the study showed identical perceptual behaviors on the implementation of hill-shading with more than one light source, thereby maximizing the benefits of multidirectional illumination.

4.2 Map-Interfaces Related Studies

The technological advancement has formed new ways to access and use maps. Some manifestations of that aspect are web, digital and interactive maps (Figure 34). Therefore, studies that focused on effective designing and evaluation of map interfaces have emerged. Çöltekin *et al.,* (2009), explored the effectiveness of various interface designs on interactive maps, using usability metrics and eye-tracking technology. They proposed a combination of traditional metrics and eye-tracking analysis to determine empirically the satisfaction and the efficiency and effectiveness of interface designs on interactive maps. The study examined the overall performance of two interactive online map interfaces, *“Map Maker service of the National Atlas of the U.S.A, Natlas”* and a thematic map by *“Carto.net”* . The two maps included the same information, although their approach differs to the interactivity, visualization and representation of spatial information and of graphical interface. In total, 30 participants, were asked to perform three typical map related tasks, while their eye and mouse movements were recorded. Participants were required to determine if they could identify and establish a correlation corresponding to socioeconomical indexes and vice-versa. These metrics are the response time and the accuracy of response. Interviews about the preference of the interface and of the map were collected. Additionally, during every task, eye-tracking metrics such as fixations and gaze plots of specific AOIs of the participants were recorded. Çöltekin *et al.,* (2009), concluded that the participants tended to prefer the *“Carto.net”* interface more than the “*Natlas”*, even though the second was based on more accurate metrics. The findings of Çöltekin *et al.,* (2009), ‘s study indicated the designing problems for both interfaces. Furthermore, it was suggested that the eye movement analysis (fixations and fixation duration) assisted to identify certain design problems on specific buttons and areas of both interactive maps. Finally, it was admitted that a plethora of data can be acquired by eye-tracking analysis to aid the understanding of cognitive processes in map reading of humans.

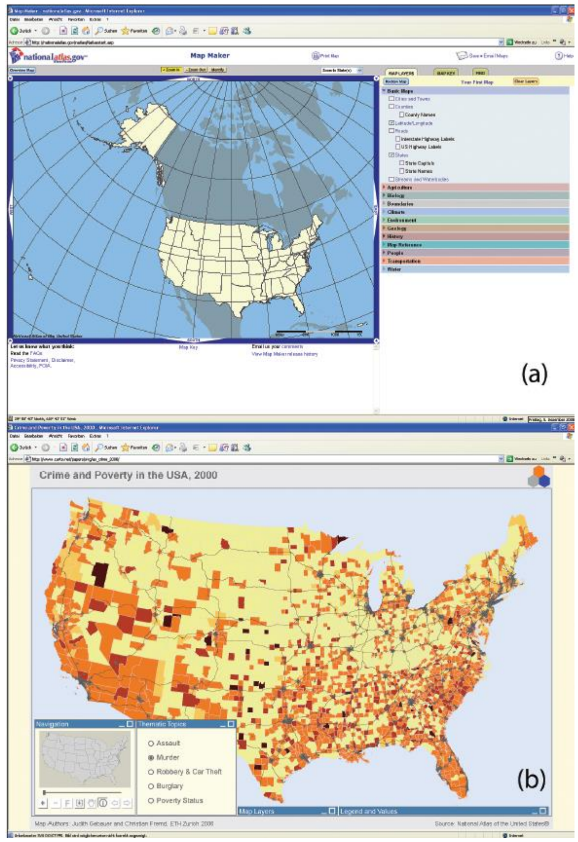


Figure 34: Interactive Maps (a) Natlas and (b) Carto.net (Source: Çöltekin et al., 2009)

Similar conclusions were highlighted by the study of Wilson *et al*., (2010). A system called MAPPER was used to produce personalized maps. The focus was on determining whether the overall performance of map users improved when using personalized interactive maps as opposed to non-personalized ones. The participants were divided into four groups, each group was assigned with specific themed map layers. Each participant of each group had to complete 15 tasks, relative to the thematic group in which the map user was placed. The tasks were designed according to the content of layers that each group was assigned to. For each group, one participant was assigned to complete all tasks with non-personalized maps, meaning all the layers and their spatial information were enabled and active on the interactive map. The other participants were able to personalize their maps according to their preference. The obtained data were referring to the time of completion and accuracy of responses. The analysis of the data highlighted that the participants were indeed more efficient using personalized maps and they required less time to complete map related tasks.

Manson *et al.,* (2013), implemented eye-tracking and mouse metrics to examine the design and usability of Web Mapping Navigation. Manson *et al.,* (2013), examined the efficiency and usability of four interactive functionalities offered on web map navigation. The tools consisted of pan zoom, double clicking, zoom by rectangle and wheel zoom. Participants underwent a short training session as part of the research, by performing eye and mouse tracking recordings on web mapping tasks designed to test the four tools and by answering questions in a follow up survey. The results indicated several differences between the four interfaces created based on the four tools. The participants preferred the interface designed based on the standard of rectangle zoom, followed by wheel zoom. Far less participants showed preference to the interface built based on pan zoom and click zoom.

Similarly, Chen (2017), examined the effectiveness and efficiency of three map interfaces for multi-touch tabletops. These different map interfaces were selected based on well-established digital map applications and research studies. Hence, the functionalities of the map interfaces consisted of gesture based, widget based and hybrid functionalities. In the study's experiment, participants were required to locate landmarks and determine routes between points of interest using different map interfaces. The tasks were designed to examine how the spatial awareness of the participants was influenced by the actions of zooming and routing between various points of interest, while using the map interfaces. Both qualitative and quantitative metrics were implemented. The qualitative data were obtained by questionnaires, where the participants described the degree of usability of the interfaces. The quantitative measurements and metrics recorded were the trial duration of the tasks and the time spent on panning and zooming either by widget commands or hand gestures. The analysis of the data revealed that the hybrid interface performed better, that the widget based interface caused less fatigue to the map users because of less hand movements but more tapping operations and that the gesture based interface was easier to learn but more hand movements were required by the users.

Popelka *et al.,* (2019), studied the advantages and disadvantages of weather web maps, utilizing eye-tracking technology and think aloud protocol (Figure 35). In this study both qualitative and quantitative metrics were implemented to examine the reading process of the participants on weather web maps. Five different web portals, containing meteorological content, were selected and used in tasks designed to take advantage of both the dynamic and the static graphic features of the web weather maps, by 34 participants. The study was separated in two procedures, one procedure of the study was responsible for implementing the eye-tracking on the static features of the web weather maps and the other procedure was responsible for studying the dynamic elements using eye-tracking. Accuracy of the answers, trial duration, fixation, fixation count and scanpath length were some of the metrics measured and used for interpretation. It was noted that since the data on the web's weather maps were continuously updating, the correct answers varied among participants. Additionally, the recorded method for eye-tracking, the dynamic features and the analysis of the gathered data were time consuming. The results of this study, showed that the map users were using the web maps in their simplest form, without searching for any further functionality or provided tools. The element of interactivity of the map was not an obstacle in the user experience unless it was overflowed with information and/or functionality.

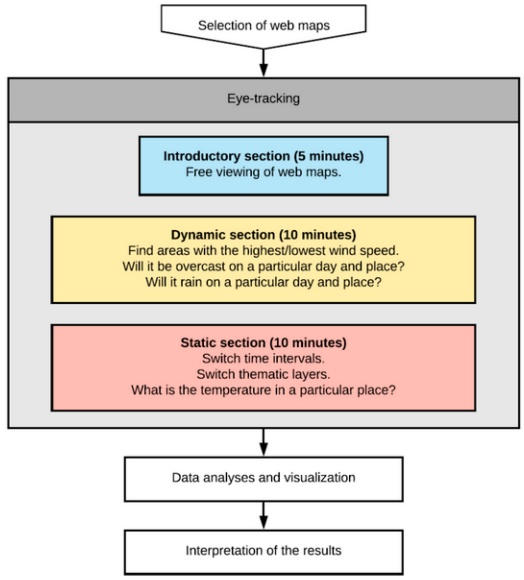


Figure 35: Design of Experiment (Source: Popelka et al., 2019)

Similar conclusions that were highlighted by the study of Wilson *et al*., (2010), were also noted by the study of Cybulski & Horbiński (2020). They examined the differences of the user's experience on two Graphical User Interfaces (GUI), employing eye-tracking methods. In particular, the examined GUI element involved the efficiency of the arrangement of buttons based on Google Maps and OpenStreetMap. In this study an interactive multimedia map was created in a simulation environment based on the two models. The eye-tracking captured the behavior of the interactivity that offered the two models. The buttons of the GUI served six functionalities such as zoom in, zoom out, search, change layers, geolocation and route. In total, 20 participants were divided in two groups of ten and they completed three tasks using the GUIs buttons. One group completed the tasks on the GUI based on Google Maps and the other group completed the tasks on the GUI based on OpenStreetMap. All the participants completed a questionnaire to determine their level of experience on the two GUIs. The parameters to determine the efficiency of the GUIs were the duration of the task and the time started after clicking the corresponding button of the GUI for each geolocation, search and route task. The used metrics of the eye movements were fixations, the number of fixations on a button during each task (based on AOIs), the ratio of the previous two metrics that provided the time a user spent on a specific button during a task and the amplitude of saccades. Based on the analysis of the data collected, Cybulski & Horbiński (2020), noted that the grouping of buttons with similar functionalities in screen corners offered a more efficient GUI, because the users tended to firstly analyze the corner and then search for the desired button. Additionally, the authors noted that the frequency of use of a graphical user interface (GUI) did not generally improve its performance and that users performed better when working with the preferred GUI.

Coordinated and multiple views (CMV) often enhance maps, providing valuable insights. However, they can pose challenges for novices, especially in the absence of guiding tutorials. Golebiowska *et al.,* (2020), employed eye-tracking and participant feedback to investigate into how beginners interact with CMVs (Figure 36). Without providing participants specific instructions or tasks, the study observed their interaction with the CMV tool. The focus was on participants' visual attention, their interaction sequence, and how their attention shifted over time. The study found that while participants were keen on exploring features like dynamic brushing, they frequently relied on explanatory aspects such as labels. The insights from this research study provide valuable guidelines for developing CMV tool tutorials.

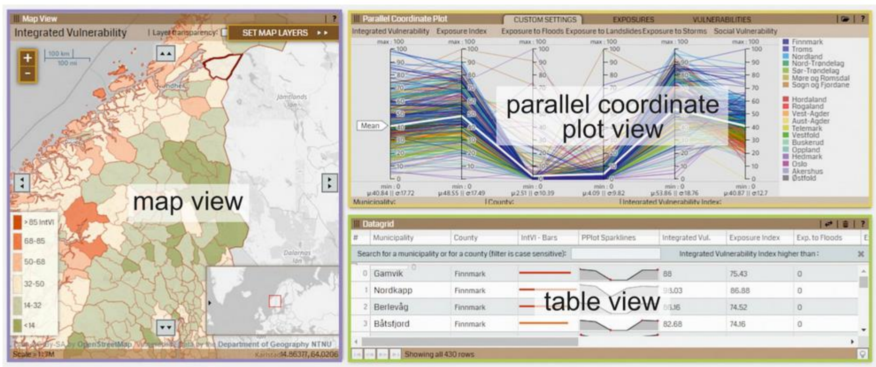


Figure 36: The CMV Tool and the Highlighted Specific Areas of Interest (Source: Golebiowska et al., 2020)

Navigation oriented experiment was used in the study of Xu *et al.,* (2022). They studied the performance of map users by comparing various methods of navigation on an outdoor experiment. The used methods of navigation were firstly digital mobile maps that offered voice instructions, secondly digital mobile maps without voice instructions and lastly analog paper maps. The experiment included eye-tracking, sk*etc*h maps, reviews and questionnaires. In the experiment, participants were required to locate landmarks and either navigate or follow routes of varying lengths to a destination point. The study tried to understand the impact of voice assisted tools in navigation scenarios by determining the wayfinding and visual behaviors of the users and the spatial knowledge they acquired by these navigation methods and means in order to complete the assigned tasks. During the tasks, the participants' eye movements were recorded. As far as the wayfinding factor is concerned, the analysis of the data revealed that the efficiency and cognitive load during the tasks were quite similar, independently to the used navigation method. However, differences were noticed in the time consuming factor. When participants used digital mobile maps that offered voice instructions the time for completion of the task was reduced compared to the other methods. Moreover, it was observed that the voice instructions forced the map users to focus more on moving objects, thus making it more difficult to interpret the maps and the environment. On the spatial knowledge aspect, similarities for all the methods were observed in the estimation of distance and time, as well as the acquisition of landmark knowledge. Nevertheless, the differences reveal that the analog maps were better used for route memorability purposes, while voice assisted maps might have been less effective on that aspect.

4.3 Characteristics of Map Users Related Studies

The demographic characteristics, the level of a map user's expertise and the background knowledge are an important research subject in map cognition and map reading. Researchers aim to understand the variables that influence the map reading strategies of individuals. Many demographic characteristics have been used to classify and interpret map reading strategies such as gender, country of residences and educational level. One of those variables that is well documented and studied is the level of knowledge and expertise of participants in regard to the examined cartographic product.

Ooms *et al.,* (2014), studied the attentive behavior of map users with different levels of expertise using eye-tracking analysis. Two groups of individuals participated in the study, each group represented the novices and the experts. The task required to draw by memory maps presented to the participants, while their eye movements were recorded. The presented maps were three topographical maps and two of them got mirrored in order for the authors to examine the results in the attentive behavior of the map users on map deviations. The analysis of the eye-tracking data depended on metrics such as fixation counts and durations along with gridded visualizations of the eye movement data and scanpaths. The authors concluded that the fixation duration of the expert group was much shorter compared to novices. The shorter duration of fixation came as a result of the faster interpretation of map features, because of the familiarity and background knowledge of the experts. Deviating colors influenced the attentive behavior of map users. Both groups displayed similar eye movement patterns. However, both novices and, to a lesser extent, experts faced challenges recalling, storing, and reproducing map features present in the mirror deviations of the examined maps.

Keskin *et al.,* (2018), investigated the spatial cognition of participants on digital 2D maps based on their gender (male, female) and level of expertise (expert and novice) by implementing sk*etc*h maps and eye-tracking technology. The sk*etc*h map (Figure 37) offered insights to the map features such as visual variables (presence, location, size, shape and color) to which the participants paid attention by analyzing the order of the redrawn symbols of the map. The time to complete a task, the average fixation duration and the count of fixations are quantitative metrics the eye-tracking method offered to the authors for assessing the cognitive load and the map reading process of the map users. The comparison of the eye-tracking data and sk*etc*h maps can reveal different map reading and attention strategies of the participants. The results of the drawing order showed that the experts and the males converged on their choice to draw roads first. On the other hand, both novices and females had a similar inclination to sk*etc*h hydrographic elements from the digital map. The evaluation of the drawn features indicated that no difference could be revealed between neither the level of expertise nor the gender of the map users. The reading and drawing process represented by all eye-tracking data and trial durations revealed no significant differences no matter the level of expertise or gender.

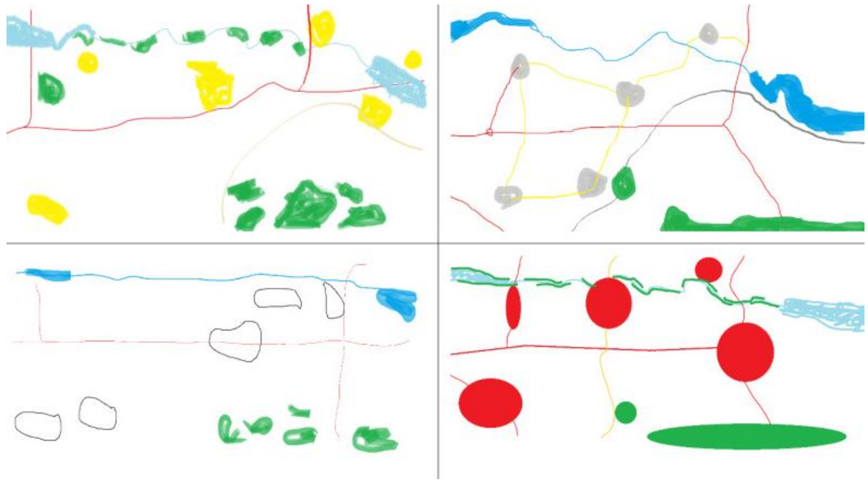


Figure 37: Paradigms of Sketch Maps of Participants in the Study (Source: Keskin et al., 2018)

The combination of eye-tracking and EEG in map reading process was performed in an experimental study by Keskin *et al.,* (2019). Their study researched the map reading strategies between map experts and novices by performing spatial memory oriented tasks. In the initial task, participants were prompted to examine a map display showcasing various elements. Afterward, they had to draw the map features from memory, effectively creating a sk*etc*h map. The second task included more stimuli in order to investigate the impact of task complexity, but the analysis of this task was presented in the following research and only preliminary results were taken under consideration. Both tasks were carried out while EEG and eye-tracking recordings took place. The analysis of the data obtained by the eye movements and EEG methods indicated that no significant differences were noted between experts and novices, although EEG metrics pointed out higher cognitive load on novices. The study suggested that although combining EEG and ET is difficult due to various methodological and technical challenges, it is an extremely useful method for examining the individual differences and similarities among map users through cognitive and perceptual processes. The research of Keskin *et al.,* (2020), extended and supplemented the results of Keskin *et al.,* (2019), study as it fully investigated the data of eye-tracking and EEG from the second experiment about task difficulty. The analysis consisted of reaction time and accuracy of responses per task completion, fixation, saccade and EEG metrics. While no differences were observed between novices and experts, when the participants were categorized as good learners or relatively poor learners, there was an important difference in their overall performance. The categorization of good or relatively poor learners was based on the criteria of correctness of answers in task difficulty experiments. Therefore, as good learners those participants who answered better than the average were classified and as relatively poor ones those who answered lower than the average.

Lapon *et al.,* (2020), performed a research study in order to examine which personal characteristics of humans influenced their ability to interpret spatial information in problem solving map oriented tasks (Figure 38). The novelty of the study lies not only in the subject itself but also in the amount of the participants (almost 100,000) and the countries (more than 150) they were from. This study showed a methodology that employed informal organizations and media to gather an exceptionally enormous and geographically assorted pool of research subjects. This study sought to comprehend the factors influencing an individual's global-scale cognitive map by determining the accuracy with which the true sizes of countries and continents are perceived. A global-scale cognitive map is understood as one's mental representation of the world. Participants were tasked online to compare the actual sizes of ten pairs of countries or continents. Following this, they completed a questionnaire detailing demographic information. The data of the accuracy and the quality of the answers along with the demographic characteristics were subjected to statistical analysis. Was noted that the estimation of the real size of countries or continents is a very difficult task to perform and that generally, each group of participants estimated approximately equally inaccurately. The results showed that even though the factor of country of residence did not affect the participants' understanding about spatial information, other variables such as gender, migration background, level of expertise and experience with maps had an immense impact on the global-scale cognitive map an individual formed.

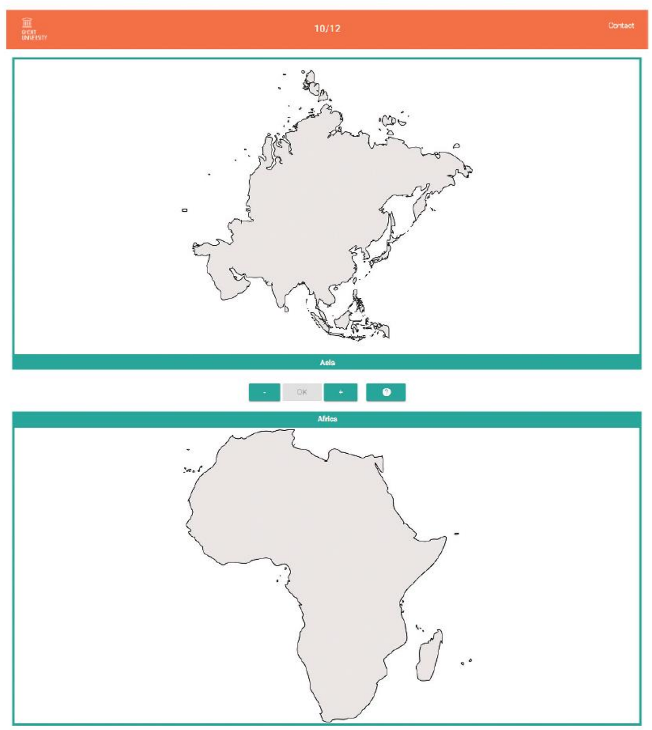


Figure 38: Setup of Online Test For Participants to Estimate Real Size of Both Countries (Source: Lapon 2020)

Keskin *et al.,* (2023), performed a study to explore the memorability, the task difficulty and the differences on level of experience, through eye-tracking recordings on 2D web maps. Memorability is captured by identifying which map symbols the map users could easily recall. The task difficulty can be explained by analyzing the eye movements and by assessing if the recognition performance was impacted by the difficulty of the task. Exploring the possibility of different map reading strategies and cognitive processes between experts and novices they addressed how the level of experience could affect the recognition performance. A framework was presented to streamline AOI analysis, encompassing a wealth of gaze tracking data like fixation and fixation duration, which was employed during the evaluation of the gathered information. The conclusions of the study were that as far as the factor of memorability goes, the most dominant graphical symbols in the recall process of the participants were polygonal map features such as hydrographic areas and road junctions. Additionally, Keskin *et al.,* (2023), observed that the task level of difficulty and map symbolizations were more important than the level of expertise of the participants in attention and recognition procedures, even though the experts in comparison to the novices had more robust allocation of selective attention.

Another subject in research studies is how specifically geography education could affect spatial ability and visual research. Dong *et al.,* (2019), studied the impact geography courses can have on map based spatial abilities by implementing eye-tracking analysis during tasks. The authors designed a digital interactive and static map that included a topographic map of Lushan Mountain (China) and a corresponding photo of the area by Google Earth, along with specified buttons to select, confirm, submit answers and proceed to the next task. It was required by 55 participants, all of them undergraduate students majoring in geography from Beijing Norma University, to complete ten tasks before and after participating in geography courses. The first phase of the study was performed before the students participated in any geography course and they had low geography experience. After six months of geography courses, the second phase took place and the students completed the same tasks again. During these tasks, qualitative and quantitative metrics were measured. The response time and the accuracy of the responses of the participants were measured during tasks. Additionally, the eye movement analysis provided fixation, fixation duration, saccades, the total number of fixations within a specific AOIs and switch time and fixations between a topographic map and a Google Earth image. After the two phases were completed, the researchers performed a qualitative and quantitative comparison of the obtained data to reveal the impact of geography courses on map-based spatial and cognitive ability of the students. The results proved that the spatial and cognitive ability of the students in solving map-based tasks were improved after participating in geography courses. The students' accuracy was improved (22.3%), while the response time was lower (14.7%). The eye movement analysis concluded that the fixation duration decreased (18.4%), while the fixations of the participants represented a more cohesive and robust behavior between fixations and switches. Dong *et al.,* (2019), concluded that the geography courses could indeed impact and improve the cognitive and spatial ability on map understanding. Moreover, the authors noted the need to perform further investigation to other factors that may be associated with improving spatial ability and study tasks. A similar outcome was mentioned in the study of Dong *et al.,* (2023), as they explored the influence of geography education in spatial ability using behavioral and fMRI experiments. The implementation of fMRI assisted in a way that could help the authors determine how the geography education compared to non-geography education shaped the students' brain activity to comprehend spatial ability. The participants were divided into groups and each group represented a different geography education level, from major geography freshman to non- geography major seniors. Their results of the task were compared and used for conclusion about the study’s subject. The participants participated in two experiments, the first experiment required to complete orientation tasks and to answer geography related questions, followed by the statistical analysis of the collected data. During the second experiment, the groups of participants completed the same geography related tasks with different stimuli, while fMRI technology was implemented for data acquisition. The analysis of the data showed that compared to non-geography students, students with higher geography education had better mental rotation, spatial visualization, and spatial relation reasoning skills. Moreover, geography education enhanced students' spatial reference, spatial memory, visual attention, and spatial decision-making abilities.

Simultaneously, methods of analysis of the obtained data can be proposed for comparing participants’ characteristics on map reading oriented tasks. McArdle *et al.,* (2015), studied a cluster technique of mouse trajectories on online web maps in order to identify the level of expertise of the map users. The aim of the study was to present a geovisual environment and to acquire spatiotemporal data referred to mouse movements, in order to analyze and categorize them in groups with similar behavioral properties regarding the level of experience of participants on web maps. Through ten spatial-oriented tasks, 27 participants were required to search, identify, decipher and interpret symbols on web maps while their cursor movements were recorded. The results revealed that the use of an incremental clustering strategy could be applied to identify differences between experts and novice users on web mapping environments.

Havelková & Gołębiowska (2020), studied the strategies of incorrect answers in thematic maps using eye-tracking. Unlike the majority of studies performed in cartography that focus on the analysis of the correct answers of the participants, Havelková & Gołębiowska (2020), examined the strategies which the participants who could not solve correctly the tasks at hand followed. Both qualitative (questionnaire) and quantitative (eye-tracking) metrics (Figure 39) were applied to back up their conclusions. Twelve tasks were to be completed by 39 participants representing both expert and intermediate level of expertise. In the study, participants were given tasks to solve. Each task presented three possible answers, with only one being correct. Four fictional thematic maps with similar arrangement, layout and features were representing four different types of thematic maps (three tasks per type). These types included area shading, line symbols, choropleth and diagram. After the task during which the eye movements of the users were recorded, the participants filled out a questionnaire that included questions related to the eye-tracking testing, the difficulties they had completing the task and the usage of map elements. The outcome of the reading strategies for the participants that failed to answer correctly indicated improper use of map legend, while the map users failed to understand and use basic elements of the map’s layout. Furthermore, the strategies of the participants who answered incorrectly were described by fast and less cautious approaches. Finally, based on these observations, the authors suggested possible solutions to prevent failed performances.

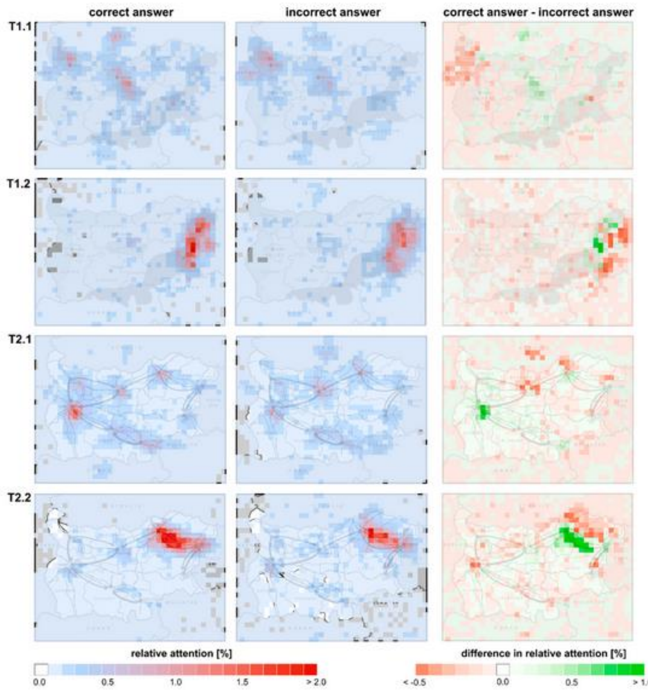


Figure 39: Attention Maps: Correct Responses (Left), Incorrect Responses (Middle), and Difference (Right) (Source: Havelková & Gołębiowska 2020)

In the study of Beitlova *et al.,* (2023), eye movement recordings and metrics were employed to propose methods that could assist the verification of cartographic communication models. The map reading strategies represented by the eye-tracking data of the authors, of other cartographers and of geography novices were compared and they revealed differences in map cognition between the three groups. Among all groups, a more comprehensive and effective map reading strategy was observed. A method was developed and introduced to quantify the differences in map reading strategies based on the order of visited Areas of Interest, and it was successfully tested. Based on that method and the analysis of the eye-tracking data, the response time and the accuracy of tasks revealed that author's responses, their trial duration, and their eye-tracking metrics were more effective compared to the other groups of participants.

4.4 Analysis Tools

The cartographic community has developed different methods and tools for analyzing eye and mouse tracking data. These tools offer the ability to perform well established analysis on data.

Krassanakis *et al.,* (2014), developed an eye movement toolbox, titled Eye Movements Metrics and Visualizations (EyeMMV). This toolbox offers a post experimental procedure for examining and studying eye movement metrics. While it supports and analyzes all main eye movement metrics and techniques, the novelty of EyeMMV is that it offers the identification of fixation based on an algorithm that utilizes a two-step spatial dispersion threshold. Based on EyeMMV, Krassanakis *et al.,* (2018), introduced a new software tool called LandRate toolbox that serves as an addition to EyeMMV toolbox. LandRate offers a comprehensive analysis report based on experimental eye-tracking data. Additionally, the Landscape Rating Index (LRI) was introduced, a rating index that is based on the aggregation of measured eye-tracking metrics (ETMs) with weights produced by expert judgment procedures. The novelty of this introduced index is that it uses both the quantitative eye-tracking method and the expert's opinions. The LRI metric was used in the study of Tzelepis *et al.,* (2020). Another eye-tracking tool developed by Göbel *et al.,* (2019), is FeaturEyeTrack. It functions as a framework that assists the eye-tracking analysis on interactive digital and web maps. This tool automatically corresponds and logs the gaze movements with the vector graphical elements of the interactive map. FeaturEyeTrack logs gaze movements in geo and screen coordinates while considering the fixated visited graphical elements of the interactive map. Simultaneously, besides the gaze movements, FeaturEyeTrack records the mouse activity of the participant on the digital interactive map. This framework enables real-time logging of content-dependent gaze data on interactive map, while determining which maps features an observer is utilizing to complete a task. This capability arises from the direct mapping of eye track data to the visible features on a cartographic map, coupled with the ability to gather gaze data in geo-coordinates. A new python module, PeyeMMV, has been introduced by Krassanakis, (2023). This module incorporates the two-step spatial dispersion fixation detection algorithm previously found in the EyeMMV (Krassanakis, *et al.*, 2014) and LandRate (Krassanakis, *et al.*, 2018) MATLAB toolboxes.

Various toolboxes for analyzing mouse tracking data have been designed either by cartographers or programmers, and by researchers of different scientific fields (*e.g.,* psychology, neurosciences). The designed toolboxes offer a plethora of analysis and visualizations of quantifying data and they can be used either as a standalone version or as a plugin in existing tools. Arroyo *et al.,* (2006), designed MouseTrack , a web logging system that records mouse movements on websites while offering a basic visualization of the cursor movements. Later in 2008, Voßkühler *et al.,* (2008), introduced Open Gaze and Mouse Analyzer (OGAMA) a software that records, stores and analyzes both eye-tracking and mouse tracking information of slide-show based stimulus for experiments and usability research studies. Freeman & Ambady (2010), introduced in 2010 a software package titled MouseTracker (Figure 40), that focuses on the recording and analysis of mouse movements in examining the real time perceptual process. In a graphics-based user-interactive environment, MouseTracker enables researchers to design, carry out, visualize and analyze mouse trajectories using pictures, letter strings, and sounds.

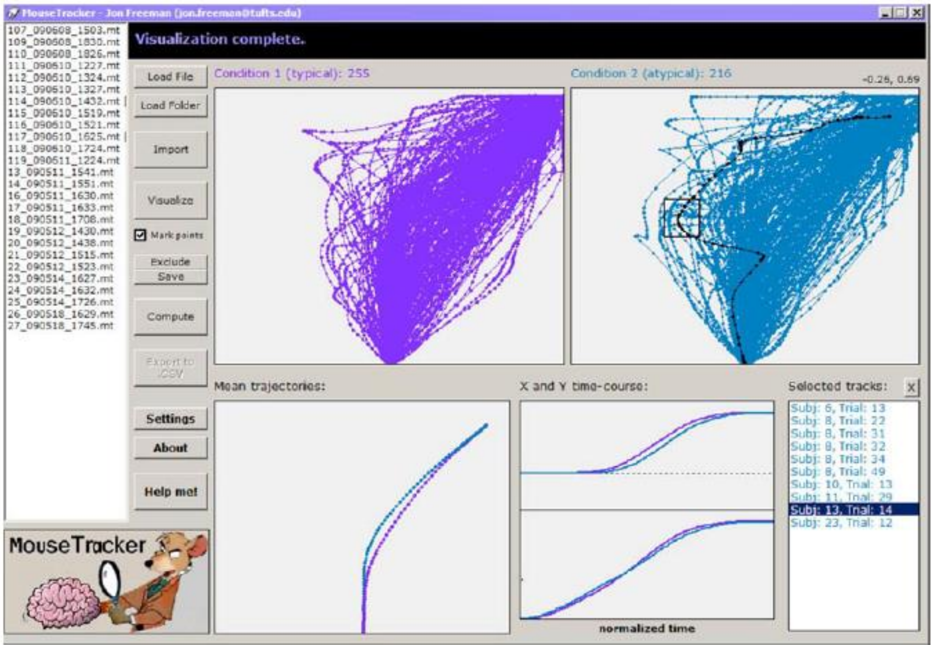


Figure 40: Mouse Tracker's Typical User Interface (Source: Freeman & Ambady 2010)

Dolezalova & Popelka (2016), introduced ScanGraph (Figure 41), a tool for eye-movement data analysis. Recognizing the varied approaches to scanpath comparisons, this tool has been optimized to handle sequences of differing lengths. Results are presented as straightforward graphs, where similar sequence groups are showcased as cliques within the graph. Popelka *et al.,* (2018), enhanced the ScanGraph tool with new algorithms for similarity calculation and improved clique detection methods. Moreover, updates have expanded its compatibility, and its ability to simultaneously assess similarities across multiple participants and various stimuli.

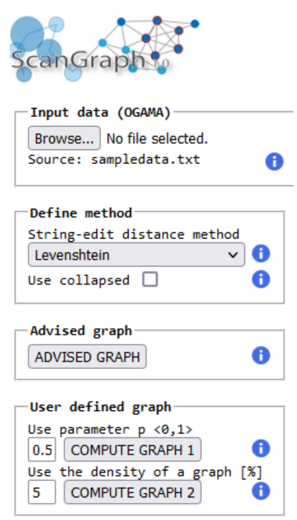


Figure 41: ScanGraph User Interface (Source:http://eyetracking.upol.cz/scangraph/)

Kieslich & Henninger (2017), presented another mouse tracking software, called Mousetrap. Mousetrap works as a plugin for OpenSesame, in order to add mouse tracking analysis. Through integrating with the already-existing experimental software, Mousetrap makes it possible to conduct mouse tracking research through a graphical user interface while not demanding programming skills by the users. Herman *et al.,* (2017), introduced 3DgazeR, a tool designed for analyzing eye-tracking data within interactive 3D models. Instead of the traditional and time-intensive method of analyzing screen recordings frame by frame, 3DgazeR streamlines the process by computing 3D coordinates for specific gaze points. This is achieved by leveraging the position and orientation of a virtual camera alongside the 2D gaze coordinates on the screen. The tool's capabilities are showcased through a case study featuring Digital Elevation Models as stimuli. Furthermore, Mathur & Reichling (2019), introduced an open-source software for performing online experiments using mouse tracking analysis through Qualtrics platform. The authors noted in their article where the software is introduced, that the aforementioned tool can offer an insight about the physical manifestations of each category's cognitive competition by analyzing the mouse trajectories of the users in categorization oriented tasks. One of the most recent mouse movement tracking software for analysis was introduced by Krassanakis & Kesidis (2020), called MatMouse. This toolbox, developed by cartographers, is designed primarily for visual search experiments on cartographic materials but is not exclusive to them. MatMouse provides specialized functions tailored for mouse tracking procedures and their subsequent analysis. It is adept at analyzing data through diverse metrics and producing related visualizations. Additionally, it supports the creation of statistical grayscale heatmaps, serving as a definitive objective point of reference or ground truth. Sultan (2021), developed a utility tool to analyze eye-tracking data from interactive web maps, simplifying the process of analyzing frame-by-frame screen recordings in existing eye-tracking systems. The primary feature of this tool translates the screen coordinates of a user's gaze into real-world coordinates and supports exports in standard spatial data formats. As presented, various tools have been produced to assist the mouse tracking analysis in cognitive and perceptual processes over the last at least fifteen years. The designed tools, even if they differ in analysis and visualizations of used data, in accuracies, in the developed programming language, in the way of implementation and in ease of use, they all presented a wide range of applications that enhance and extend the opportunities the eye-tracking method has to offer.

4.5 Artificial Intelligence (AI) in Cartography

Within the cartography community, there's a growing trend towards a proposed procedure that provides insights into map perception and cognition. Research has delved into trends focusing on the development of automated approaches for analyzing experimental methods. One notable outcome is the integration of artificial intelligence and machine learning as tools to evaluate visual perception on maps. Keskin & Kettunen (2021), suggested the development of an artificial intelligence-assisted (AI) system that can adapt to the eye movement patterns of its users, allowing the control of geovisualization through them, thus assisting in the information extraction process from areas where the eyes focus on. The adaptation of that framework which is described by Keskin *et al.,* (2022), explored the possibilities and designing factors of creating adaptive map interfaces which learn through deep learning the user's behavior on 2D static vector maps which are represented by eye-tracking measurements and data. As Gaze – Aware Interactive Map System (GAIMS), the authors described a system that could utilize and learn according to the user's eye movement behavior, in order to redesign and revisualize the examined map. A more extensive analysis of the methodology described the challenges and the relevant literature explained in Keskin & Kettunen (2023), research study.

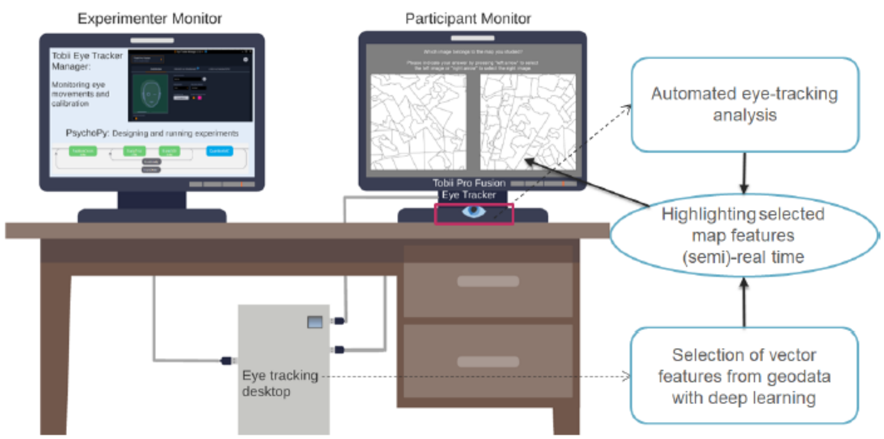


Figure 42: Concept Desing of GAIMS (Source: Keskin et al., 2022)

In addition to the AI assistance in cartography, Wahyono *et al.,* (2020), developed and introduced a smart travel map using AI. By implementing K-Nearest Neighbor (K-NN), the authors developed an algorithm that can recommend a thematic map with the three most suitable tourist attractions, based on a user's location and on seven criteria of the user's interests. The criteria are relative to the tourist attraction categories, the supporting facilities, the distance of the user's location and the cost.

A different approach of the machine learning application in cartography is presented by Li & Xiao (2023). The authors, in their research explored and proposed a methodology that used machine learning for cartographic purposes. Li & Xiao (2023), utilized four different machine learning methods to create, train and evaluate the models. The four developed models were designed with the purpose of identifying if an image is a map, recognizing the area that corresponds to the map and finally identifying the projection used for the creation of the map. The outcome of the study revealed that even though the designed machine learning models could make correct identifications, the models themselves were very dependent on the information and data used to train them. If spatial patterns and specific information were not included in the training test, the models would fail to identify the region, the map projection and in some cases even the type of the image (map or no map). Additionally, the authors noted that the machine learning models exhibited differences in recognition processes compared to humans.

4.6 Other Applications

Other applications of research studies could involve the implementation of experimental methods in evaluating and improving bureaucratic processes. Hepburn *et al.,* (2021), attempted to understand the cognitive sequence in decision making and map reading of users on Environmental Impact Assessments (EIAs) geovisualizations, using eye-tracking technology. EIA are part of a mandatory Environmental Statement that needs to be submitted in the United Kingdom when designing and running large engineering processes. Hence, understanding the cognitive process of EIA submissions could assist to better and more accurate representations. The eye-tracking data recorded by this research study, consisted of fixation, saccades, fixation duration and counts. The participants were 35 employees of an engineering consultancy with experience in EIA submissions. Interestingly enough, the experiment took place in their working environment and not as we have seen from the majority of studies in controlled conditions (labs). The authors chose that option because they wanted to mimic the working conditions and environment so that the everyday working distractions could be taken under consideration. Participants were tasked with ranking four potential routes for laying cable in an environmentally sensitive area. Firstly, they had to select their preferred basemap between Open Street Map (OSM) and satellite imagery. Then, they were asked to rank the routes having basic data and information presented in layers. Finally, they had to rerank the routes while being provided with additional data found in EIAs databases in the form of layers. After analyzing the gathered data, no relationships between participants and base map selection could be discovered and indicating the flexibility of the participants to select freely this variable did not affect their decision making. Most of the participants (80%) interacted with the additional layers provided for the reranking of the routes, while only a few of them (28%) interacted with the existing layers (were turned on by default). As Hepburn *et al.,* (2021), noted that behavior indicates that the volume of existing layers could in fact impact their decision making. Therefore, the map users had different interaction methods that can influence their decision making and their reading of EIAs representations.

The study of Augmented Reality (AR) is a subject the cartographic community has investigated and has foreseen its possible and future applications. Map users encounter an enhanced experience in which virtual elements are displayed in real world environments. Real world environments offer spatial information to which the AR-user has direct access, thus, cartographic applications could take advantage of these conditions. The implementation of AR can offer new aspects to 3D visualizations, which are translated to a new field in cartography where spatial cognition and visual search can be studied. Yonov & Petkov (2020), expanded the utilization aspect of AR. They proposed a framework for the design of an application that would implement augmented reality for the navigation of mountain areas. The authors go through all possible steps for the design of such applications, investigating the procedures for data acquisition, the modeling and the visualization of the spatial information. Dickmann *et al.,* (2021), studied the influence of augmented reality in cartography and presented the implementations and elements of this method. At the same time they described the requirements for creating AR elements and how their graphical visualization can be achieved on mobile devices, glasses and small displays. The authors pointed out the potential of utilizing AR in the field of cartography while raising possible limitations and challenges of the method.

In an effort to propose a study procedure applicable to the limitation and restrictions caused by the COVID–19 pandemic, Knura & Schiewe (2021), proposed a framework (Figure 43) that substitutes eye-tracking based studies. In their proposal, thinking aloud protocols and mouse tracking were implemented to collect data via online based map task-solving experiments. The authors indicated that the constant verbalization of the participants' thoughts along with the cursor movements during tasks could be enough for usage, for map evaluation and understanding of a user's behavior. As limitations, the authors described the manual encoding, since it is more time consuming, the accuracy of the encoding and the accurate alignment of the verbal statements of the participants with their cursor movements.

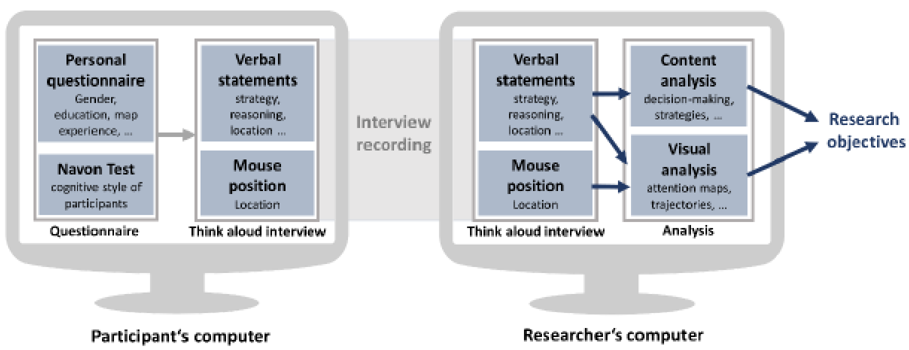


Figure 43: Study Design (Source: Knura & Schiewe 2021)

Other studies about creating datasets have been also developed by the community. Similar to the datasets that have been proposed by the aforementioned research studies of Keskin *et al.,* (2023) and Tzelepis, *et al.,* (2020), He *et al.,* (2023) proposed an eye movement dataset that contains geospatial images, titled GeoEye. This dataset includes 550 images from remote sensing, street view, and thematic maps that were freely viewed by 110 college students. The aim of this article was to encourage the application of eye-tracking methodology as a research tool in visual attention and map cognition oriented studies by offering a dataset that the future studies can experiment on new theories and hypotheses. In addition to the development of such resources, other research studies aim to refine the methodological parameters. For instance, Bergmann Martins *et al.,* (2023), research study aimed to identify the optimal participant count for map-oriented experiments, recognizing that variables such as map details and participant demographics can influence this number. By analyzing 200 cartographic articles, the research aimed to deduce standard participant counts for distinct experimental methods. Out of these, 85 were specifically relevant. The outcomes suggested that qualitative studies centered on verbal feedback typically involve 20-30 participants, while those focusing on participant actions tend to have 30-40 participants. However, quantitative studies required larger groups, ideally around 100 participants, though a minimum of 50 can also be effective.

5. Discussion and Open Questions for Future Research

In this chapter, an analysis of the examined studies is performed. Simultaneously, diagrams and statistics both in percentages and absolute values, derived from the presented research studies are used to disclose trends in regard to subject, quantitative methods and design of the experiments. Subsequently, future research subjects are proposed and observations are mentioned as resulted by the examinations of the studies.

5.1 About the Subjects of Studies

In total, 98 studies are reviewed and presented in Sections 4 and 5. These studies concern the period between 2006-2023, they cover a wide range of subjects and implement experimental methods performed mainly by the cartographic community. General but also specific trends can be revealed by the analysis and review of the published articles. The studies were classified according to the subject they were researching. Based on that principle, the conclusion to eight thematic categories was made. The number of studies per subject in absolute values is reported in Figure 44.

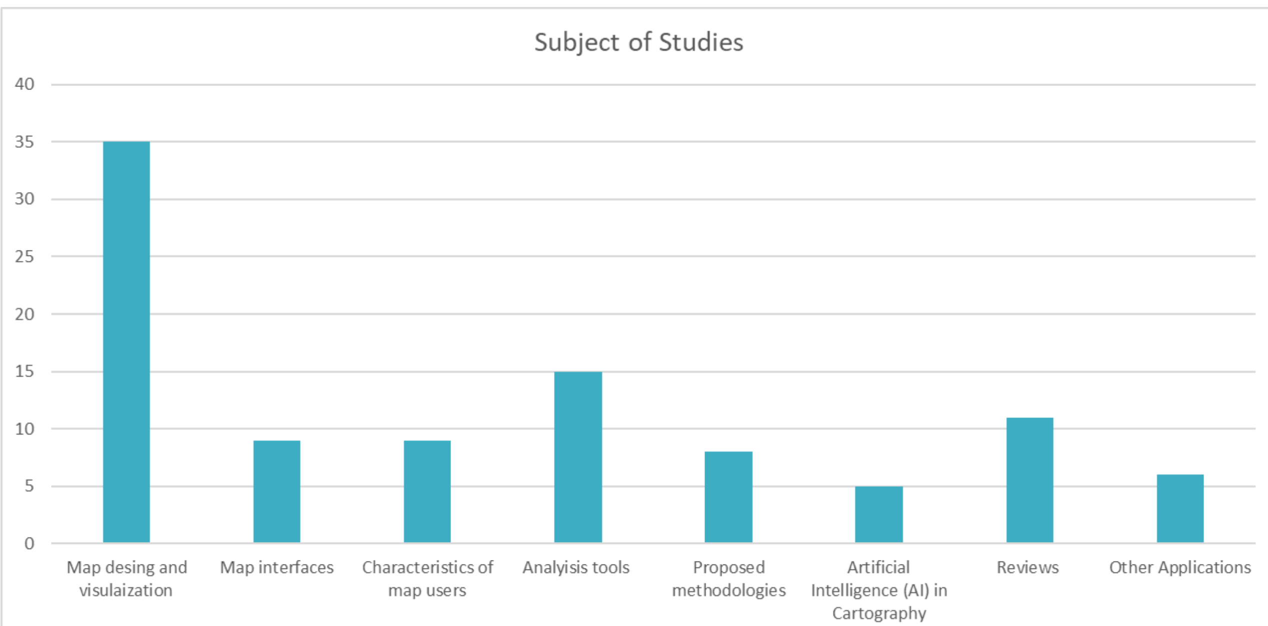


Figure 44: Number of Studies per Subject

In Table 1 the absolute values and percentage along with the total value of papers presented in this thesis are reported.

Table 1: Absolute values and percentage per subject

Subject	Absolute Value	Percentage (%)
Map Design and Visualization	35	36%
Map Interfaces	9	9%
Characteristics of Map users	9	9%
Analysis Tools	15	15%
Proposed Methodologies	8	8%
Artificial Intelligence (AI) in Cartography	5	5%
Reviews	11	11%
Other Applications	6	6%
Total	**98**	**100%**

From both Table 1 and Figure 44 the following conclusions can be derived about the subjects the cartographers study. The most dominant subject utilizing experimental methods is map design and visualizations. The 36% of the examined studies investigated the designing principles on maps. The final product of a cartographic procedure is typically a map that aims to communicate information to the map users, therefore, it is expected by the cartographers to perform research studies for determining the most efficient and effective methods in geovisualizations. Simultaneously, researchers can examine the results of proposed methodologies and graphical visualizations by observing and interpreting the behavior, the cognitive process and the strategies of map users during task oriented empirical experiments. A more in depth examination of the published papers included in this category of subjects, discloses that the effectiveness and efficiency of visual (Garlandini & Fabrikant, (2009); Dong, *et al.,* (2014)) and dynamic (Łucjan & Wojtanowicz, 2018) variables on various types of maps is studied (static, animated, interactive) with the purpose to offer insight about the overall hierarchy of the visual variables and the most effective manifestation of each visual variable.

On the one hand, the visual variables are a well-studied subject, as they were defined first by Bertin (1967), and their efficient application on map creation and map design is essential. Similarly, dynamic variables research has resulted in increased and widespread implementation on digital, animated and interactive maps, manifested mainly through web maps. The study of Krassanakis *et al.,* (2016), measured the threshold of scene duration, a variable that is related to the calculation of rate of change. On the other hand, little to no amount of sound variables oriented studies have been produced, at least not to the amount of research studies compared to visual and dynamic variables. Although the implementation of sound variables can be found in a smaller range of applications, that should not negate the influence that their effective application can have on interactive, digital and dynamic maps. The study of Xu *et al.,* (2022) although it did not examine sound variables, is related to the effectiveness of sound and voice in navigation tasks. The researchers examined the impact of voice assisted digital maps in wayfinding and navigation tasks. The results disclosed that although voice instructions may have a negative effect on route memorability, the navigation tasks were completed faster when voice instructions were present. Future studies could examine the impact of the sound variables on the navigation tasks of Xu *et al.,* (2022)'s study. The research of sound variables can be challenging, as it may be difficult to design an experiment using eye or mouse tracking metrics because the examined variables are based not on visual but on hearing sense. However, EEG and fMRI methods can assist by taking advantage of the high temporal and spatial resolution these methods can offer accordingly.

Identical studies were performed about map features, such as symbols (Stachoň *et al.,* (2020); Kapaj *et al.,* (2023)), legend (Brychtová (2015); Çöltekin *et al.,* (2017)), labels (Liao, *et al.*, 2019); (Cybulski & Krassanakis, 2022) and fonts (Korycka-Skorupa & Gołębiowska, 2020). Specifically, the cartographer's objective is to discover both the elements that attract the map user's attention and the factors that influence their map reading process. Map symbols are the most common tool of a cartographer to communicate spatial information and phenomena to the map reader. Additionally, it is not unusual for researchers to perform studies that examine, compare and reveal the most efficient representations. Studies comparable to the study of Stachoň *et al.,* (2020) and Kapaj, *et al.,* (2023) are performed where the effectiveness of various symbolizations is measured and compared. Identical methodology can be applied to examine the effectiveness of various cartographic symbols on different map types (Dong, *et al.*, 2018), data types (Gröbe & Burghardt, 2020) or map backgrounds (Pappa & Krassanakis, 2022). The symbolization obviously is not limited only to point symbols, but it also extends to lines such as road networks (Liu, *et al.*, 2019), polygons and beyond, vector and raster data.

The findings of Cybulski & Krassanakis, (2022) revealed that the placement of cartographic symbols holds considerable importance in visual search studies, and that the map users perform different visual search strategies depending on if the language of the label is known to them. Similar results were also noted by the study of Stachoň, *et al.,* (2020). The study of Korycka-Skorupa & Gołębiowska, (2020) proved that the usability of numbers as a means to represent quantitative data can be achieved when creating simple visualizations. Future studies can explore the impact of that hypothesis on more complex maps. Moreover, an extension to the work that has already be done by both studies of Korycka-Skorupa & Gołębiowska, (2020) and Cybulski & Krassanakis, (2022) could be the exploration of the influence of different visual, dynamic and sound variables when used in conjunction with numbers for representation of qualitative data or labels with different languages, accordingly by means of eye, mouse tracking or a combination of the two.

In addition, the study of map legends can provide insights about the effectiveness of a map. Map users and especially students tend to first read the map legend (Beitlova, *et al.*, 2020) and then attempt to solve a task or view the map. The map design can create conditions that affect the map reading process even before the user reads the map, therefore, the operational application of the legend is a subject of great importance. Legend position as proved in the study of Brychtová (2015) does not affect the overall readability of the map, although the study is limited to choropleth maps. Furthermore, the design and organization, especially in complex and difficult to understand map types and phenomena (*e.g.,* socio economic indexes), may affect the readability of the map as proved by Beitlova *et al.,* (2020). The study of Çöltekin *et al.,* (2017), revealed that the different types of legend designs of soil-landscape maps could have different impact on different map users. However, the study is limited to a specific type of map and as the authors admitted, the high level of the difficulty of the tasks had many participants fail successful completion, even though we can derive correlation about complex concepts and map legend.

Another aspect of cartographic visualization that is explored is the 3D visualizations of spatial information. The most well-established methodology for determining the efficiency of 3D visualizations is to compare them to their 2D counterparts. Using that methodology, Dong & Liao (2016) disclosed that 3D representation is less efficient compared to 2D visualizations in navigation with digital mobile maps. A possible extension of that study could explore the behavior by implementing eye tracking methods, in an experiment that would take place in a real world environment where the real life distractions could be taken under consideration, while designing a digital environment that addresses the findings of this current study. Liao *et al.,* (2017) in their research, extended the findings of the Dong & Liao, (2016) study as they observed the differences in decision making on 2D maps and 3D geo-browsers. The study of Popelka & Doležalová (2015) revealed that no differences in symbol's search were noticed, whether 2D or 3D visualizations were implemented or not. The conclusion of this study comes in line with the conclusion of the study of Kapaj *et al.,* (2023). Interestingly, the two studies used similar thematic city maps as stimuli, while the aim of the studies, the medium of transmission of the cartographic product and the level of expertise of the participants differed.

As proved by the literature review, choropleth map, is an intriguing and well documented subject of the cartographic community. Examination of choropleth maps, on the applicability of different cartographic methods (Popelka, 2018), on the visual perception of spatial patterns (Schiewe, 2019), temporal trends on choropleth (Cybulski, 2022) and on the use as a benchmark to assess the effectiveness of new visualization methods (Jia, *et al.*, 2023) are some of the researched topics. Similar to choropleth maps, hill-shading methods are studied both for their suitability and for the effectiveness of their application. Farmakis-Serebryakova & Hurni (2020), examined which hill-shading methods are best suited for a set of landforms, whereas Tzelepis *et al.,* (2020), investigated the influence of multidirectional hill-shading. Both studies concluded that the hill-shading methods that implement multidirectional illumination can have effective use.

Experimental methods have been implemented as a tool to review and examine existing cartographic products. A typical subject of that type of studies is maps that serve educational and practical purposes. The examination of the efficiency and the effectiveness of educational cartographic material can provide essential information about the possible improvements. The improvement of educational cartographic products results in improvements of the spatial learning, spatial search, map cognition and reading of students (Beitlova, *et al.*, 2020) thus, forming communities described by cartographic sensitivity. The study of Beitlova *et al.,* (2020) concluded that improvements in the atlases used in geography courses in the Czech Republic are needed. Same conclusions were reached by the study of Bugdayci & Bildirici (2016), about the overall performance of atlases used in geography and social studies in Turkey, and by the study of Paresadko & Baltabaeva (2017), who examined the school atlases used in Turkmenistan. This behavior of cartographic products is not limited only to educational material. Burian *et al.,* (2018). evaluated the quality of urban plans in Czech Republic and observed that the ambiguous symbolization of the plans caused difficulties in map reading and understanding of the urban plans. These studies prove that the update of educational cartographic products is a needed requirement in order for countries to provide the most effective educational materials. Future research studies could study more educational products from various countries and various educational levels to determine their effectiveness. Another subject of research could propose methodologies about either examination or procedures for updating obsolete cartographic educational materials, thus finding patterns or trends in common cartographic inadequacies. Another aspect is presented by Hepburn, *et al.,* (2021) as the study aims to improve the cartographic products prepared for submissions of government documents related to the Environmental Statement in the United Kingdom.

The observation of the visual strategies performed on cartographic products that serve practical purposes is another topic. Defining the attended elements of map users on maps, results in overall designing improvements and focus on map features that should be given more importance. The studies of Netzel, *et al.,* (2017) and Burch, (2018) highlighted similar conclusions about the use of visual variable of color on geovisualizations of metro maps. Both studies determined that the visual search, strategies and attention on metro maps are independent to the implementation of color or grayscale. Based on that deduction, future studies could examine the impact of visual (size of symbols, labels position, *etc*.), dynamic and sound variables on analog, digital and mobile metro maps, with different experimental methods besides eye tracking, like fMRI or EEG.

The review of the published literature includes studies about the impact of the map interfaces in the cognitive process of the map users. More specifically, that type of studies recorded 9 out of 98 papers (9%) as showed in Table 1 and Figure 44. In the same way, map graphical symbolizations and visualization methods are studied, research studies about the evaluation and organization of map interfaces have emerged. The wider use of digital and web-based maps over the years has created the need for the cartographers to examine the features that are related to the interactivity of maps. The study of Cybulski & Horbiński (2020) revealed that the grouping of buttons that share similar functionalities in screen corners offered a more efficient GUI. Manson *et al.,* (2013) identified among various expressions of zoom functionality on maps (pan zoom, double clicking, zoom by rectangle and wheel zoom), that the map interface utilizing zoom by rectangle was the most efficient, although participants expressed the desire of the inclusion of all tools in one interface. However, the study of Popelka *et al.,* (2019) disclosed that the map users were using the web maps in its simplest form, without searching for any further functionality or tools provided by the web weather maps. The study of Xu *et al.,* (2022) proved that map interfaces which utilize voice instructions can be more effective in navigation and wayfinding tasks, compared to analog and non-voice assisted digital maps. Chen, *et al.,* (2017), in their study revealed that hybrid interfaces based on widgets and gestures perform better on multi touch tabletops. Wilson *et al.,* (2010), addressed the subject of the overload of spatial information on maps. According to their study, better performance was observed when the participants personalized their maps in regard to the spatial information presented to them, thus revealing that overloaded maps are not ideal and that the preference of the map user has a significant impact on the visual search and understanding of the map. In general, the studies of Wilson *et al.,* (2010), Popelka *et al.,* (2019), Manson *et al.,* (2013) and Cybulski & Horbiński (2020) observed identical conclusions concerning the impact of the preference of the map user on map interfaces. The element of preference and how it influences the users when interacting with a map should concern the researchers for further investigation.

The usability and scope of map interfaces is going to keep growing and improving. The conclusions of the studies provided significant findings about the preference and visual attention of the map users. The studies showcased either utilized existing map interfaces or crafted designs based on them, possibly operating under the assumption that one might possess an optimal structure. The development and examination of the effectiveness of a map interface that utilizes the findings of the presented studies could be a subject of future research. Comparisons between the developed map interface and other well established and well used map interfaces could be derived. Furthermore, the presented studies are mainly designed for map interfaces for bigger displays. Exploring their effectiveness on smaller displays, such as smartphones and mobile applications could be a subject of future research. Questions about whether the visual search and spatial learning of map users remain the same between map interfaces on computer screens and mobile screens, could also be investigated. The same concerns can be raised about which types of tools and applications work best on touch screens and mobile phones. The impact of visual, dynamic and sound variables on smartphones and touch screens could be explored further by the cartographic community. In regard to sound variables, questions about how effective map interfaces are or can be about communicating spatial information to people with vision impairment or low vision could be the subject of future research.

Another area garnering attention is the study of how different characteristics of map users impact visual search and map perception. As indicated in Table 1 and Figure 44, the 9% of the reviewed studies delved into this topic. The human vision is a multifactorial result of various characteristics. The exploration of the impact of these characteristics on map perception and visual learning is a subject of great importance for the cartographic community. The level of expertise of the participants is a common classification which one may encounter in an empirical research. It refers to the prior knowledge of the participant on the examined subject, that is usually revealed by the years of experience or level of education. Simultaneously, other demographic characteristics can be used for the classification of the participants, age, gender, country of residence, *etc*.

The studies of Ooms *et al.,* (2014), and Keskin *et al.,* (2018), concluded that independent of the level of experience of the participants no differences were observed in drawing maps by memory, even though experts had faster reactions than novices. An extension of the previous studies was explored by Keskin *et al.,* (2019) that included besides eye tracking data, EEG measurements. Although the conclusions remained the same as those on Ooms *et al.,* (2014), and Keskin *et al.,* (2018), the analysis of the EEG metrics revealed that the novices had higher cognitive load during the tasks compared to the experts. This finding suggests that even if no differences were observed, novices might have needed more time and potentially exerted greater mental effort to complete the tasks. Differences were observed when instead of dividing the participants based on their level of expertise, they were divided based on their performance on the tasks. Thus, the study of Keskin *et al.,* (2023), indicated that other factors such as task level of difficulty and map symbolizations were more important than the level of expertise of the participants in attention and recognition procedures. Similarly, Lapon *et al.,* (2020), in their study concluded that one of the factors influencing the ability to interpret spatial visualizations is the level of expertise. In contrast, in the study of Beitlova *et al.,* (2023), differences were observed between the authors' metrics and strategies, compared to the metrics and strategies of other groups of participants. That conclusion discloses that another factor that influences the map users performance is the familiarity with the cartographic product, the examined phenomenon and the visualization techniques.

While this series of studies (Ooms *et al*., (2014); Keskin *et al.,* (2018); Keskin *et al.,* (2019); Keskin *et al.,* (2023)) didn't yield definitive results regarding the impact of expertise levels on visual perception and cognition of maps, they did provide valuable insights. As far as memorability oriented map tasks are concerned, no differences can be observed, although there are indications based on eye tracking and EEG analysis that the novices compared to experts had to "work harder" for the completion of the tasks. The findings support that prior knowledge (Lapon, *et al.*, 2020) and familiarity (Beitlova, *et al.*, 2023) can impact the performance of the map users. In addition, important conclusions are not limited to experts - novice comparisons but other characteristics or conditions may be more impactful, such as the level of difficulty or map symbolization (Keskin, *et al.*, 2023). Future studies that combine eye tracking, EEG and fMRI could strongly offer insights about the aforementioned conclusions.

The influence of prior knowledge and geography education was proven also by the studies of Dong *et al.,* (2019), and Dong *et al.,* (2023). Both studies confirmed the hypothesis that the geographic education has an immense impact on both the spatial and cognitive ability of map users in solving map-based tasks, while skills of mental rotation, spatial visualization, spatial relation, reasoning, spatial memory, visual attention, and spatial decision-making are enhanced. McArdle *et al.,* (2015) successfully proposed a method that could determine and identify differences between experts and novice users on web mapping environments. Furthermore, Havelková & Gołębiowska (2020) explored the characteristics that lead to poor performance in map solving tasks, in an effort to identify the behaviors and patterns of map users that lead to these results.

Another topic of interest not yet fully researched in regard to the prospect of applications is the field of artificial intelligence (AI). As recorded in Table 1 and Figure 44, only 5 out of 98 (5%) studies have explored or implemented a combination of AI and cartographic geovisualizations. AI assisted and machine learning methods can contribute to the field of cartography. While the literature review of studies proved thin compared to other subjects, suggestions and frameworks have been produced. The cartographic community's articles are mainly focused on suggestions of a proposed framework, rather than the applications implementing AI from a cartographic perspective. In a series of published articles, Keskin & Kettunen (2021), Keskin *et al.,* (2022), and Keskin & Kettunen (2023) describe and propose a system that could utilize and learn according to user eye movement behavior in order to redesign and revisualize the map. In a simpler form of the idea of Keskin & Kettunen (2023), Wahyono *et al.,* (2020), designed a system that is able to suggest tourist attractions based on map users' interests. Furthermore, Li & Xiao (2023) successfully developed various machine learning models that were able to identify if an image is a map, recognizing the area that corresponds to the map and finally identifying the projection used for the representation of the map. Although the study proved successful, the authors highlighted some limitations. The machine learning models were heavily dependent on the trained material. Future studies could address that limitation by proposing solutions.

Another field slightly researched but with a growing interest by the cartographic community is the implementation of Augmented Reality (AR) on maps. The studies in cartography about AR are mainly focused on implementations of the method on mobile phones ((Yonov & Petkov, 2020) ; (Dickmann, *et al.*, 2021)). AR can provide an enhanced experience on navigation (Yonov & Petkov, 2020) but there are some limitations the community needs to address. Dickmann *et al.,* (2021) expressed limitations relative to omission of spatial information and tracking range of the AR equipment. As they explain, spatial information of the real world could be missed if users do not systematically scan their surroundings due to differences in the field of view of humans and AR equipment. The tracking range of objects of the real world can be limited by AR equipment thus, failing in capturing the environments in large scale projects. Therefore, AR could be used mainly for projects where conditions of small scale and indoor environments are met (Dickmann, *et al.*, 2021). Additionally, challenges noted by Yonov & Petkov (2020) are found in data acquisition procedures, modeling and visualizing AR and map related products. AR implementation on maps can be a complex and time consuming process but the advantages of the method are significant as they can introduce a new field of research for cartographers to study. AR can offer an enhancement of basic graphical cartographic visualizations for navigation and orientation purposes. In that regard, future studies can explore the impact of visual, dynamic and sound variables on cartographic products that utilize AR. Expanding the role of AR in map products, studies investigating the impact of the method on improvements about the spatial ability and spatial learning of the users could take place.

Over the years, the cartographic community has not only advanced research studies on map reading and graphical visualizations but also developed various tools. These tools, reflecting the state of the art, trends, and emerging needs, aim to support both current and future studies, enhancing their ability to derive conclusions. The development of analysis tools for the most established experimental methods has been a large part of the performed research. The 15% (15 out of 98) of studies (Table 1 and Figure 44) examine various analysis tools. Various tools have been developed over the years that offer eye tracking analysis and visualizations, mouse tracking analysis and visualizations, mouse and eye tracking analysis and visualizations. Table 2 contains all the analysis tools that were examined and presented along with a brief description, the published paper and the year of the introduction.

Table 2: Examples of Analysis Tools Developed

Analysis Tool	Article	Description	Year
MouseTrack	(Arroyo, *et al.*, 2006)	Mouse tracking on websites	2006
OGAMA	(Voßkühler, *et al.*, 2008)	Eye/mouse tracking metrics	2008
MouseTrap	(Freeman & Ambady, 2010)	Mouse tracking analysis	2010
EyeMMV	(Krassanakis, *et al.*, 2014)	Eye tracking metrics	2014
ScanGraph	(Dolezalova & Popelka, 2016)	Eye movement data analysis	2016
Mousetrap	(Kieslich & Henninger, 2017)	Mouse tracking analysis	2017
LandRate	(Krassanakis, *et al.*, 2018)	Eye tracking / experts judgement	2018
FeaturEyeTrack	(Göbel, *et al.*, 2019)	Eye tracking analysis	2019
Qualtrics	(Mathur & Reichling, 2019)	Mouse tracking analysis	2019

MatMouse	(Krassanakis & Kesidis, 2020)	Mouse tracking analysis and visualizations	2020

A conclusion that could be easily drawn by reviewing the Table 2 is that the development of the analysis tools is well supported by the community. Based on their publication dates, analysis tools have been developed and introduced since the inception of these methods and continue to evolve today. Whenever a new method gains traction within the community, tools to assist with its implementation are swiftly developed. Eye tracking and mouse tracking prevail as the methods that provide the most analysis tools. The next step of the analysis tools could target the methods of EEG and fMRI. Tools that can provide metrics based on either EEG and fMRI can be challenging but they would significantly assist the process of data analysis. As Keskin & Ooms (2018), mention in their research, specifically for the combination of eye tracking and EEG in map perception, the synchronization of both EEG and eye tracking data poses difficulties. Therefore, a tool that could automate the process of compatibility for eye or mouse tracking data with data produced by neuroscience based methods, such as EEG and fMRI, could be useful. In addition, automated procedures of analysis on methods such eye and mouse tracking could concern future research studies. He *et al.,* (2023), developed an eye movement dataset that can be used in future studies to propose methodologies, test theories and perform experiments. Similar datasets could also be developed for mouse tracking with more participants, given the ease of use of the method. Considering the challenges and difficulties of the EEG and fMRI methods in data acquisition, the development of a dataset for future studies on map cognition could be very useful.

The implementation and the application of experimental methods is a well-documented subject. Researchers have performed literature reviews of the techniques of eye tracking, mouse tracking, fMRI and EEG as a means to advocate for the examined method. They present advantages and encourage researchers to implement those methods in future studies. Of the examined research studies ,11% (Table 1 and Figure 44) of the published articles performed a literature review. Lai *et al.,* (2013) conducted an educational research review about eye tracking methodology used in studies from 2000 to 2012. In a twelve year period, the authors reviewed and presented a plethora of studies conducted by implementing eye tracking technology. The research included various studies using eye tracking in scientific fields mainly in social sciences. The study presented the basic metrics and measurements used in the reviewed studies as the authors attempted to discover patterns and strategies. A classification based on the related learning topic and eye movements measures used of the reviewed studies was performed. The authors aim to unravel the tendencies of the researched subject when implementing eye tracking along the various metrics and eye movement measurements used. Years later, Mahanama *et al.,* (2022), performed a study that reviewed all the existing measures and metrics in eye tracking and pupillometry. An extensive review of all metrics and potential analysis of data gathered from eye movements was conducted.

Insights into the area of application for each metric were provided, along with explanations of each metric's use. Moreover, to enhance understanding, the findings from a select group of studies that utilized each type of measure were documented. The purpose of this study was to present the implications of each metric and its results as they can be easily neglected, due to the wide range of fields where eye tracking is used as a researching tool. It is believed that this review can assist future researchers in choosing the most appropriate eye movement metrics.

A similar study to Lai *et al.,* (2013), but focused on research studies specifically about spatial search and the use of eye tracking was conducted by Kiefer *et al.,* (2017). The researchers gave a comprehensive overview of how eye-tracking is applied in the research domains of spatial cognition, GIS, and cartography, emphasizing the prevailing trends and challenges in these areas. Krassanakis & Cybulski (2019), performed a literature review of the implementation of eye tracking technology in studies related to cartography. The study was performed during the decade between 2009 and 2018, expanding the research findings of Kiefer, *et al.,* (2017). They also reviewed research studies that aimed to understand the map reading and cognitive process of map users by acquiring and analyzing eye tracking data. The reviewed studies were classified based on the research subject within the field of cartography, thereby highlighting the contribution of the eye-tracking methodology. The classification consisted of cartographic symbolization principles, comparing 2D to 3D representations, map user’s level of expertise, various other applications of eye movements, analysis about map perception and analysis tools of eye tracking developed by the cartographic community. Existing difficulties and future points of view are additionally talked about. Subsequently, Krassanakis & Cybulski (2021), presented a review of eye tracking technology, in order to observe, reveal existing trends and offer future perspectives about the contribution of eye tracking analysis in the cartographic research field. Similarly, Fairbairn & Hepburn (2023), conducted a literature review about the state of art and contribution of eye tracking techniques in the field of cartography. It was observed that there was limited evidence regarding the impact of the eye-tracking method on cartography or how cartographic research contributed to advancements in the broader human-computer interaction community. To address this gap, potential subjects and objectives for future research studies were proposed.

As far as mouse tracking methods in cartography and map cognition are concerned, many reviews have been produced over the years. Kieslich *et al.,* (2020), examined the influence of three different design factors of mouse tracking, in exploring the cognitive process. The designed tasks required by the participants to classify typical and atypical paradigms. The study tried to understand which factors can impact and assist a research designed to interpret mouse tracking movements for analyzing the cognitive process. Krassanakis & Misthos (2023), analyzed in their study the method of mouse tracking, when used to examine the perception in the scientific field of cartography and specifically on digital maps. The study described a typical methodology for implementing mouse tracking experiments on digital maps, the analysis of the metrics acquired by the method, along with the visualizations and diagrams that can be derived, in order to assist the designing process of future applications. Finally, the research presented the advantages and disadvantages of the mouse tracking, while discussing the future potentials of the method. The use of mouse tracking in the future is also explained by the study of Krassanakis *et al.,* (2021), who proposed an experimental framework that described the advantages of performing cartographic visual studies online, utilizing mouse tracking data by implementing a toolbox (MatMouse) that offers functions and analysis of cursor movements.

Kessler & Battersby, (2023), examined literature centered on deciphering the cognitive and perceptual facets of map projections. They concluded that map projection is a complex and highly technical subject that requires specialized knowledge to be fully understood. The authors provided six approaches that the future studies need to take under consideration in order to eliminate map user's difficulties with projections and in general map understanding. Similarly, Mocnik (2023), investigated the factors in maps that can affect usability, readability and interpretability. The author explained the challenges in map creation and why it is a complicated process, while highlighting spatial data quality, applicability and coherence as important elements to the map functionality.

5.2 About the Trends Over the Years

Regarding the studies examined, a factor that merits further exploration is the chronological progression and discernible trends over the years. It's crucial to note that while these observations are based on the selected research, many more studies have been published on the subject. Figure 45 presents the percentage of the studies published over the period of 2006-2023.

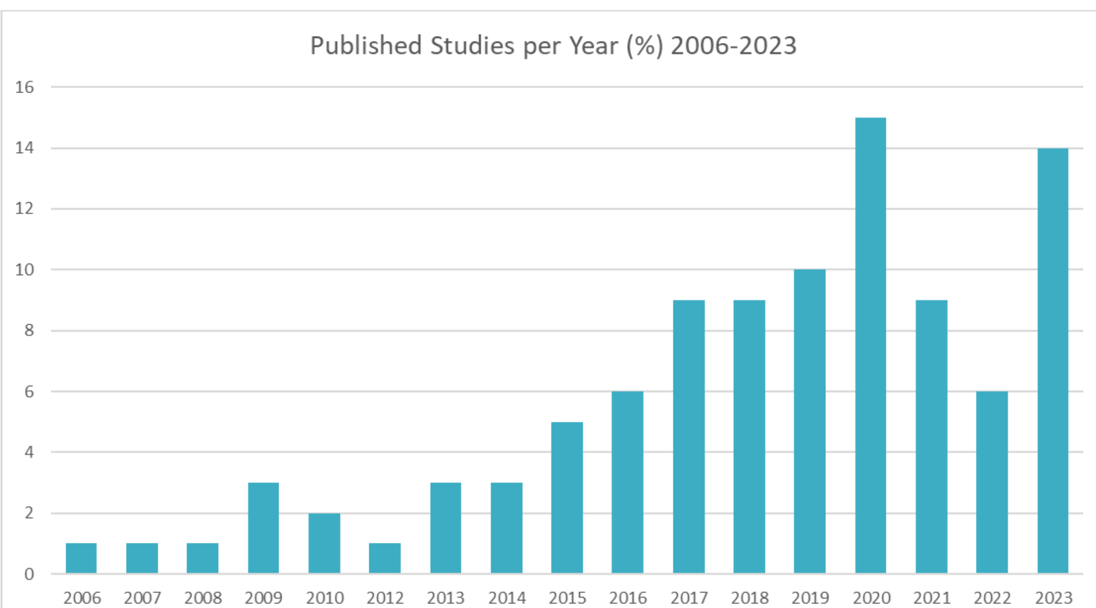


Figure 45: Absolute Values of Published Research Studies per Year, 2006-2023

Table 3 presents both the absolute values and the percentage of the published articles between 2006 and 2023.

Table 3: Published Research Studies per Year in Absolute Values and Percentage (%)

Year	Absolute Value	Percentage (%)
2006	1	1%
2007	1	1%
2008	1	1%
2009	3	3%
2010	2	2%
2012	1	1%
2013	3	3%
2014	3	3%
2015	5	5%
2016	6	6%
2017	9	9%
2018	9	9%
2019	10	10%
2020	15	15%
2021	9	9%
2022	6	6%
2023	14	14%
Total	**98**	**100%**

Figure 45 and Table 3, reveal the growth of the studies implementing experimental methods in cartographic research from 2006 until 2023. The published articles are continuously increasing, since 2009 until 2020. The published articles seemed to be fewer in s 2020 and 2021 but this may be the result of the COVID – 19 pandemic, when lab based experiments were not able to be completed because of the quarantine restrictions. The investigation of the impact of these restrictions in cartographic research, the examination of the procedures and methodologies used by published papers, as well as the possible mentioned limitations and challenges during the pandemic could be an interesting subject of a future study.

Based on the analysis of the articles reviewed in this thesis, the cartographic community has been utilizing eye tracking since at least 2009 (Çöltekin, *et al.*, 2009), and its use continues to the present day (He, *et al.*, 2023). It's important to note that these observations are specific to the studies discussed in this context. They don't encompass a complete perspective of all cartographic research, especially considering that eye-tracking in cartography predates 2009. This discloses the longevity of the method and the robustness of its results. Mouse tracking was firstly presented as an experimental method in cartography in 2013 (Manson, *et al.*, 2013) and has been implemented until today (Pappa & Krassanakis, 2022). fMRI was first introduced as a method through which map based experiments could be performed in 2007 (Lobben, *et al.*, 2007), and EEG was mentioned as a possible method in 2016 (Keskin, *et al.*, 2016), while the first experimental research implementing EEG was recorded in 2020 (Keskin, 2020). This analysis highlights the evolution of methodologies within the cartographic community over the years. Traditional methods, such as questionnaires and reaction time and accuracy measurements, have transitioned to a supplementary role. The rise of eye tracking has solidified its place as the predominant method in current map perception studies, with mouse tracking following closely behind. Additionally, the incorporation of advanced neuroscience techniques, like EEG and fMRI, underscores the community's expansion into more intricate methods.

5.3 About the Experimental Methods in Cartography

Prior to more sophisticated methods, such as eye and mouse tracking, fMRI and EEG, cartographers, when studying map cognition, employed metrics like reaction times, trial durations and auxiliary information collected by questionnaires. As observed by the studies, no research was concluded while strictly only one individual experimental method was implemented by the researchers. Most studies were conducted by implementing to some extent, a combination of methods. For instance, when a study is using eye tracking it does not mean that other metrics are not calculated. The most common practice would include for instance eye tracking method with a type of questionnaire (*e.g.,* Dong *et al.,* (2018)), or reaction time and accuracy of responses (*e.g.,* Liao *et al.,* (2019)). Questionnaires could serve as a method to collect both qualitative and quantitative data. This reveals that the research studies are not reliant on one method to collect information about the examined subjects, but various combinations are employed in order to secure an amplitude of data. The most common approach would include the combination of eye tracking, and reaction time and accuracy of responses (*e.g.,* Çöltekin *et al.,* (2009); Liao *et al.,* (2019); (Beitlova *et al.,* (2020); Beitlova *et al.,* (2023)). Basically, all the task oriented experiments would use reaction time and accuracy as they can be easily measured. Figure 46 presents the percentages of the use of methods in the examined articles.

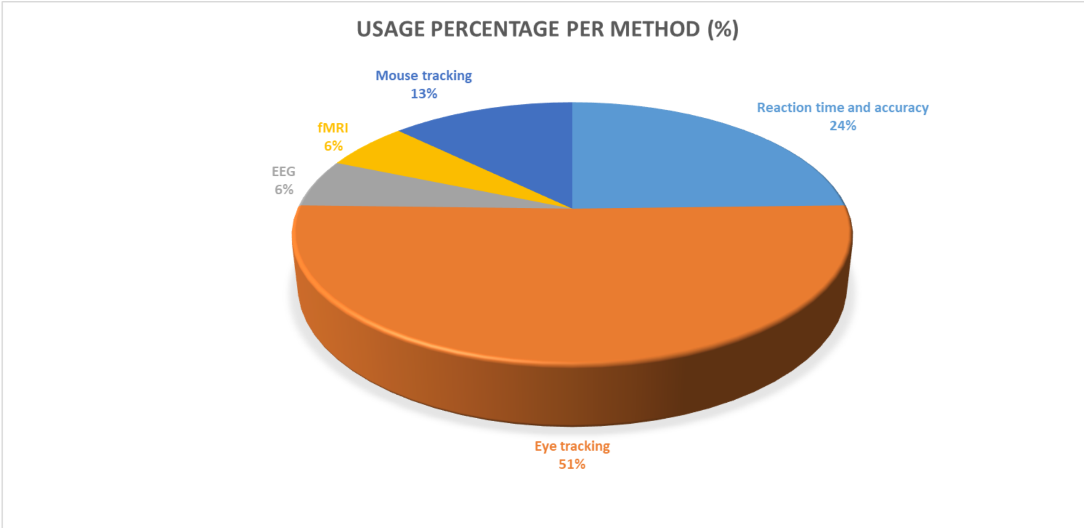


Figure 46: Chart Pie with the Usage Percentage (%) of Each Method

The 51% of the studies implemented eye tracking methods in order to acquire data. This reveals that eye tracking can be considered as the most dominant amongst the other examined methods. Eye tracking has been used by a plethora of studies for a variety of subjects. The method has been used as a tool to evaluate and support hypothesis about map designing principles (*e.g.,* Kapaj *et al.,* (2023)), map interfaces (*e.g.,* Çöltekin *et al.,* (2009)) and level of expertise of maps users (*e.g.,* Havelková & Gołębiowska (2020)). Many analysis tools have been developed for this method (*e.g.,* Voßkühler *et al.,* (2008); Krassanakis *et al.,* (2018)), as well as reviews about the influence and applicability on the cartographic field (*e.g.,* Kiefer *et al.,* (2017); Krassanakis & Cybulski (2019)). The application of eye tracking by a plethora of studies in cartography discloses that the method offers trustworthy results. Additionally, the community seems to continuously examine the impact of the method, while constantly researching ways to improve its application. The method itself is also improving compared to previous years, when it required larger equipment and more complex procedures.

At the same time, eye tracking is proven to be a flexible method that can easily be combined with other methods to acquire both qualitative and quantitative data. The most common method to be combined with eye tracking is reaction time and accuracy (*e.g.,* Netzel *et al.,* (2017)), but it is not limited to it. Other combinations include questionnaires that describe both qualitative and quantitative data (*e.g.,* Dong *et al.,* (2018)), think aloud protocols (*e.g.,* Popelka *et al.,* (2019)) and sketch maps (*e.g.,* Keskin *et al.,* (2018)). To a lesser extent eye tracking has been implemented with mouse tracking (*e.g.,* , Demšar & Çöltekin (2017)) and EEG (*e.g.,* Keskin *et al.,* (2020)), not particularly because the combination of these methods is not sufficient or effective enough, but because either a method is not fully explored yet by a cartographic perspective (*e.g.,* EEG) or in the case of mouse tracking is considered more of a substitute of eye tracking.

The study of Bergmann Martins *et al.,* (2023), indicated that ideally, quantitative map-related research should involve around 100 participants, though a minimum of 50 can be sufficient. Gathering data from more participants becomes time-intensive, especially with methods like eye tracking that necessitate one-on-one sessions. Ensuring consistent visual attention during tasks is essential for eye tracking, but not all participants maintain focus. If they lose interest, their data may need to be excluded from the analysis. This issue was especially notable in tasks involving student participants (*e.g.,* Beitlova *et al*., (2020)).

Future research might delve into the effects of unsupervised experiments using the method. Additionally, some studies could concentrate on devising methodologies for conducting eye-tracking experiments remotely over the internet. Another intriguing avenue would be to explore potential solutions for recording multiple participants simultaneously. Besides ways to improve the implementation of the method, researchers could investigate the combination of the method with augmented and virtual reality artificial intelligence (*e.g.,* Keskin & Kettunen (2021)).

The 24% of the studies (Figure 46) included reaction time and accuracy measurements, the second highest of the methods used in total. The method is very simple to use and does not require additional equipment. The metrics measured by this method were used for further statistical analysis (*e.g.,* ANOVA) and were combined with qualitative information obtained by questionnaires to assist researchers to extract results and conclusions (*e.g.,* Lapon *et al.,* (2020)). Reaction time and accuracy was mainly combined with questionnaires (*e.g.,* Lapon *et al.,* (2020)), eye tracking (*e.g.,* Çöltekin *et al.,* (2009); Havelková & Gołębiowska (2020)), mouse tracking (*e.g.,* Pappa & Krassanakis (2022)) or a combination of various methods (*e.g.,* reaction time and accuracy, questionnaires and eye tracking, (*e.g.,* Havelková & Gołębiowska (2020)). The ease of use and the simplicity of the method in combination with the robustness of the measurements disclose the importance of the method. These features suggest that they can potentially be employed in both supervised and unsupervised conditions, offering the prospect of remote map-task-solving experiments. The ease of this method allows simultaneous testing by a larger number of participants. While questionnaires, reaction time, and accuracy metrics have traditionally been reliable methods for data collection, the advancement of modern techniques like eye tracking has shifted these traditional methods to an auxiliary role.

Mouse tracking method was used in the 13% (Figure 46) of the examined studies. The implementation of the method is less used compared to eye tracking or reaction times and accuracy, but the method itself can provide sufficient results. The subjects where the cartographic community employed mouse tracking are similar to the subjects of the studies which implemented eye tracking. The method is especially efficient for evaluating the map user’s behavior when exploring the usability of map interfaces (*e.g.,* Manson *et al.,* (2013)). There are many similarities between mouse and eye tracking due to the nature of the measured metrics. Mouse movements are considered the extension of the visual search when referring to digital maps, hence many cartographers have examined the potential of mouse tracking to substitute eye tracking methodologies. Indeed, many of them used the mouse tracking technique (*e.g.,* Knura & Schiewe, (2021)). On the one hand, that could be considered as a possible application of this method. On the other hand, many researchers advocated for the use of mouse tracking not as a substitute but as an additional tool in examining map attention and cognition. The study of Çöltekin *et al*., (2009), highlighted the addition of mouse tracking in the design of the experiment as a future possibility. Simultaneously, both the developed analysis tools (*e.g.,* Krassanakis & Misthos (2023)) and the review methods pointed towards the same objective. The flexibility of the mouse tracking is similar to this of eye tracking. In the examined published research works, mouse tracking was combined with reaction time and accuracy metrics (*e.g.,* Pappa & Krassanakis (2022)), thinking aloud protocols (*e.g.,* Knura & Schiewe, (2021)) and eye tracking (*e.g.,* Demšar & Çöltekin (2017)). Mouse tracking procedures bear resemblance to eye tracking. However, instead of capturing participants' eye movements, it focuses on calibrating the movement of the cursor.

The advantages of the method are the ease of use, the simplicity, the accessibility, while no particular familiarity of the participant is needed. The method requires the movement of a computer mouse with no additional equipment, it can be performed in both supervised and unsupervised environments and independently to where it is conducted, either in lab-based tasks or remotely (*e.g.,* Knura & Schiewe, (2021)). This method is ideal for experiments aiming to acquire a large amount of data. It's not limited by the number of participants or their country of residence, as it can be used remotely in unsupervised environments. While the combination of the method with other experimental methods is highlighted, no studies were found implementing a combination of either EEG or fMRI with mouse tracking. Hence, future studies could study the combination of mouse tracking with these more sophisticated methods.

The 6% (Figure 46) of the studies implemented EEG as a tool to interpret human behavior on map related cognitive processes. From a cartographic perspective, this method is considered new for implementation, as was proven by the literature research. The first report on the application of the method was recorded in 2016 (Keskin, *et al.*, 2016), while the first empirical research implementing it, in combination with eye tracking was observed in 2019 (Keskin, *et al.*, 2019). Not many studies have used this method, hence the search was limited. EEG typically used in neuroscience, provided the cartographers with insights about the participant's brain activity reaction to a visual stimuli (map) and spatial memory tasks (Keskin *et al.,* (2019); Keskin *et al.,* (2020)). Consequently, the research studies that employed EEG focused on exploring participants' behavior and map reading strategies. EEG has limitations, in the sense that it offers measurements of high temporal resolution, therefore, it is best to be combined with other experimental methods for additional information, such as eye tracking (Keskin *et al.,* (2019); Keskin *et al.,* (2020)).

EEG is considered as a complicated method to be implemented. The raw data collected by EEG have to be preprocessed in order for the noise and other redundant information to be removed. One the one hand, the method requires specific electrical devices, familiarity with the set-up procedures and the interpretation of the data (Keskin *et al.,* (2019)). Hence, it demands supervised and laboratory-based procedures. On the other hand, EEG can be performed simultaneously with eye tracking procedures as it was described in the study of Keskin *et al.,* (2019). Another challenge that arises when combining the data of EEG with the data acquired by a different experimental method is the synchronization of the data. Hence, EEG "besides the preprocessing steps when combined with other methods" requires a synchronization of the data. Automating the preprocessing stage and data management might be feasible, as suggested by Keskin *et al.*, (2019). However, certain interpretation procedures need manual attention. This involves inspecting the data for each participant individually, which can be both overwhelming and time-consuming. The data analysis process is the most challenging and requires the most attention by the researchers. During the experimental phase, EEG procedures require low to no movement by the participants, since a sudden move could result in artificial and false data (Keskin, *et al.,* 2019). Additionally, the methodology and the data analysis of the method suggest that it would be more efficient in smaller sample sizes of participants (*e.g.,* 20 participants in Keskin, *et al.,* (2019)), as it is a time consuming procedure in both experiments and data processing. While the EEG data provide invaluable insights into individuals' behavioral strategies during map-related tasks, its integration with other experimental methods offers a more holistic understanding. The EEG captures real-time neural responses, highlighting cognitive processes that are often inaccessible through other methods. This depth of information can help decipher intricate patterns of thought, decision-making mechanisms, and even emotional reactions, while interacting with maps. However, the use of EEG is not without its challenges Keskin *et al.*, (2019). Implementing EEG in research requires specialized equipment, trained personnel, and controlled environments to ensure the reliability of the collected data. The complexity of the brain's electrical activity means that data analysis can be intricate, demanding sophisticated tools and expertise to interpret the results accurately. Additionally, synchronizing EEG data with other experimental methods can pose technical challenges, especially when trying to align neural responses with specific actions or events. Moreover, compatibility issues might arise when integrating EEG data with information from different sources or platforms. While EEG provides a deep insight into neural activities during map-related tasks, researchers must remain aware of its complexities and potential challenges when applying and analyzing the data(Keskin *et al.*, (2019)). The experimental studies of Keskin *et al.,* (2019) and Keskin *et al.,* (2020) were focused on the subject of spatial memory on maps. Further studies could explore with this method other subjects, such as cognitive load on more complicated maps or reading strategies on map interfaces with different dynamic variables at study in free view oriented experiments. Furthermore, the combination of the method with mouse tracking could be examined. Moreover, eye tracking can be used in conjunction with brain imaging methods such as EEG and Functional Resonance Imaging (fMRI). Keskin (2020), explains that although eye tracking has many applications in cartography, no extensive research on *"how human supports spatial tasks"* has been made yet.

Similar to EEG, fMRI is also a method from neuroscience that can offer insights about map reading strategies of individuals. The 6% (Figure 46) of the examined studies implemented it. Even though there were studies advocating (Lobben, *et al.*, 2007) for the use of this method in cartography since 2007, the research about fMRI implementation proved relatively limited in published cartographic studies. Research studies conducted in 2019 and 2023 utilized functional magnetic resonance imaging (fMRI) to assess the map users' cognitive and spatial abilities. The subject of these studies examined spatial pattern cognition (Liu, *et al.*, 2019) and the improvement of spatial abilities (Dong, *et al.*, 2023). In contrast with EEG, fMRI was implemented in combination with a less complicated experimental method, which was the statistical analysis of accuracy of responses and trial duration. fMRI like EEG is a quite complex, sensitive and overwhelming method both in the department of implementation and data analysis. fMRI is a sophisticated method that can be performed under supervised and controlled environment conditions since it requires specific procedures and equipment (magnetic resonance scanner) for data collection. The method is sensitive to sudden head movements, because it could lead to false results. In the study of Dong *et al.,* (2023), ten participants had to be excluded because of excessive head movements. The fMRI method results in functional imaging data corresponding to information of high spatial resolution that need to be preprocessed and filtered out of redundant information. Possible combination with other methods, such as eye and mouse tracking or EEG would probably require an identical approach to EEG, where a complex procedure of synchronizing and converting data to compatible formats would be necessary.

While the literature research at the moment of conducting this thesis, shows that no studies were found using both EEG and fMRI extensively in the field of cartography, I believe it can provide significant findings by combining the high temporal and spatial information these two methods can offer respectively, in regard to exploring the cognitive process of map users. In addition, the combination of eye or mouse tracking should be explored. Future studies should examine the use of the method in other cartographic subjects, such as expert/novice map reading comparisons on complex cartographic backgrounds.

5.4 Future Prospects by the Community

The ever-evolving community of cartographers continually researches methodologies, both in experimental procedures and analysis, seeking ways to enhance and achieve more robust results. The combination of eye and mouse tracking has been a subject of studies and it has been used by many empirical experiments (Manson *et al.*, (2013); Çöltekin *et al.*, (2017). Furthermore, the integration of neuroimaging techniques, like EEG and fMRI has been explored, though not specifically in map-related research. Studies by Huster, *et al.,* (2012), Iannotti *et al.,* (2015) exemplify this approach, promoting the combined use of these methods. They provide methodologies for integration and discuss the potential advantages that can emerge. Similar investigations could be undertaken within the field of cartography."

The aspect of performing experiments without being supervised by the researchers could be explored. The majority of the presented studies was performed on controlled environments, while the experiment procedure was fully supervised by the researchers. Online and web cam based experiments (Farmakis-Serebryakova & Hurni (2020); Lapon *et al.,* (2020); Pappa & Krassanakis (2022)) have been performed by the cartographic community. Mainly, the experimental methods used for such implementation are limited to questionnaires and mouse tracking as multiple tools have been developed (Mathur & Reichling (2019); Krassanakis *et al.,* (2021)) to assist that procedure. Challenges about online studies have been known. Dandurand *et al.,* (2008), supported that online based problem-solving experiments can be less accurate when compared to laboratory-based environments. The study of Pappa & Krassanakis (2022), that was performed online, did mention problems and limitations during the experiment, that were mainly focused on unstable internet connections. During the years of the pandemic and the restrictions under COVID -19, research studies of indoor and lab-based experiments were unable to be performed. Execution of studies using eye tracking were very difficult to be accomplished under these conditions. Knura & Schiewe (2021), proposed a framework that substitutes eye tracking based studies. Limitations about the accuracy and the procedure of the encoding have been raised. Besides, the limitations and the challenges, performing quantitative methods in cartography remotely, is a subject the community is studying and can be explored not only as a substitute procedure to lab-based experiments but also to analyze the prospects as an alternative method. Future studies could explore how an identical procedure could be produced for eye tracking. Although, it is understandable for the eye tracking technique to be performed on laboratory-based experiments and controlled environment at least this aspect should be explored and compared with the traditional lab - based method. The possibility has been mentioned also by Krassanakis & Cybulski (2021).

6. Conclusions

The current thesis explored the state of the art of different experimental methods used in cartography and map cognition related-studies, while not limiting itself to one specific method. The contemporary aspect was offered by the period of the examined studies, covering the years between 2006 and 2023. Thus, insights regarding the evolution of research methods and procedures used in cartographic studies could be drawn. This thesis attempted to capture the dominant trends of the cartographic community in map - cognition and map - perception related studies. The examined studies detailed the benefits and drawbacks, practical applicability, ease of use, and implementation difficulties for each technique. Simultaneously, insights about the subjects and the area of application for each experimental method could be discovered. The literature review revealed that the experimental methods used for obtaining qualitative data were consisted of Reaction-Time and Accuracy metrics, Eye Tracking, Mouse Tracking, Electroencephalography (EEG) and Functional Resonance Imaging (fMRI).

A thorough review was conducted on 98 cartographic research studies focused on map cognition and perception from 2006 to 2023. The research methodology primarily utilized online academic databases like Google Scholar, using relevant keywords. Further depth was achieved by exploring the bibliographies of these articles, with a special emphasis on studies from the last two to five years. In addition to providing insights into the implemented experimental methods, the study of the published research studies provided information regarding the cartographic questions, hypotheses, and subjects investigated, using these methods. Hence, a categorization and an analysis of the subjects of the studies was selected in order to reveal the topics that the cartographic community is interested in answering.

The map is the final product of the cartographic procedures that is responsible to communicate to the map user effectively and efficiently spatial and non-spatial information. It is imperative for the cartographers to explore the possibilities of evolving, improving and creating more efficient visualizations. The most studied subjects were associated to map-design and map-visualization principles (36% and 35 out of 98 studies). These principles concern map-features and map-graphic elements in regard to their representation, location, and expression, in order for the spatial information to be represented as accurately as possible, and efficiently communicated for the map user. The cartographic community is concerned with the examination of the efficiency of visual and dynamic variables in different map types (static, animated, interactive) and spatial data. Studies have been performed about determining the most accurate map-symbols and map-symbolizations to represent spatial data of various scales. Map-legend design and its location on the map gathered similar interest, as it is a map feature that the majority of the map users consulted in their map reading processes. At the same time, studies regarding the evaluation of existing cartographic products like, static and paper-maps were conducted. The wider use of digital maps significantly affected the map-visualizations techniques thus, instigating the need of cartographers to design and support 3D visualizations. Consequently, research topics have arisen about both the effective representation of 3D map-visualizations and the comparisons of 3D and 2D, in regard to map reading-strategies.

Over the last decade, another thoroughly explored topic that has garnered comparable attention involves the study of how different traits of map users impact visual exploration, map perception, and map reading (9 out of 98 papers, 9%). The most prevalent method of categorizing map users is by their level of expertise, distinguishing between novices and experts. The more extensive utilization of interactive and web-maps shaped the necessity for the investigation of the effectiveness and organization of map user-interfaces and interactivity of maps (9 out of 98 papers (9%)). Although, not covered in publications as extensively as the aforementioned subjects, the map cognition research can be combined with more contemporary techniques such as artificial intelligence (AI), deep-learning (5 out of 98 papers, 5%), augmented and virtual reality, in both designing map-products and in assisting the analysis of the data collected by the experimental methods.

The engagement of the cartographic community is not limited, only to conducting research studies that investigate the map perception and map cognition of map users. As the literature review revealed, many studies are related to reviews on the state of art (11 out of 98, 11%), to the development of analysis tools for simplifying the implementation of experimental methods (15 out of 98, 15%) and to proposing new experimental methodologies and procedures (8 out of 98, 8%). The published literature reviews, the developed analysis tools and the proposed methodologies suggest that the community is committed to evolve and update the procedures of the experimental methods, while offering further advances in map cognition research.

A steady increase of the published research studies is observed from 2006 until today (2023). Eye tracking is being used as early as 2008 and it is being implemented until today. Similar conclusion can be derived, also for mouse tracking as it is presented as an experimental method in map cognition related-studies in 2013 (Manson, *et al.*, 2013) and it is being implemented until today (Pappa & Krassanakis, 2022). fMRI was first introduced as a method through which map based experiments could be performed in 2007 (Lobben, *et al.*, 2007), and EEG was mentioned as a possible method in 2016 (Keskin, *et al.*, 2016). the first experimental research implementing fMRI was recorded in 2019, (Liu, *et al.*, 2019) and EEG was recorded in 2020 (Keskin, 2020).

The review highlighted that most experimental studies employ a combination of methods rather than just one. This mixed-method approach provides researchers with a rich dataset, promoting deeper insights and more accurate conclusions. The most frequent combination observed was eye tracking paired with reaction time and accuracy metrics, given their easy accessibility in task-based studies. Other noted combinations included eye tracking with mouse tracking, mouse tracking with reaction time and accuracy, and EEG with eye tracking.

Eye tracking is reviewed as the most used and implemented method in map cognition studies for acquiring quantitative data. The use of the map requires from the map user to visually search the spatial information. Thus, examining the eye movements of map users is considered a highly trustworthy methodology for evaluating maps and geo-visualizations. Over the years, eye tracking has emerged as the preferred method for map-related experimental studies, as evidenced by these reviews and the analysis of developed tools. The small size of the required equipment, the set up and the ease of data post-processing, have made the method not only ideal, but also suitable for its combination with other methods. Eye tracking was certainly the most used method for combining it with other experimental methods such as questionnaires, reaction time and accuracy, think-aloud protocols, sk*etc*h-maps, mouse tracking and EEG. However, eye tracking has some limitations because it requires specific equipment, controlled environments and supervision for one participant at a time.

Reaction time and accuracy of responses is considered as one of the oldest methods in task-oriented cartographic-studies. These metrics can be easily obtained naturally, as the experiment progresses. They offer an abundance of metrics and post-analysis for further investigation. They are very easy and simple to use without necessarily needing specific equipment, in supervised and unsupervised experimental conditions. Today, as the other methods progressed, developed and became easier to apply, reaction time and accuracy metrics are used mainly, as a supplementary method for providing additional quantitative data.

Mouse tracking, while less prevalent than eye tracking and reaction time accuracy methods, has cemented its place since the advent of eye tracking. Initially seen as an alternative to eye tracking due to similarities in measured metrics, it's now recognized not as a replacement but as a complementary tool for studying map attention and cognition. Today, mouse tracking is highly valued for its flexibility, particularly in unsupervised and remote experiments, and it pairs well with many of the same methods as eye tracking. Among its strengths are its straightforwardness, accessibility, and user-friendly nature, without demanding prior expertise from the participant. Exclusively for digital maps, the only required equipment is a computer mouse.

EEG and fMRI, though complex, offer unique insights in cartographic research, especially when compared to the more commonly used eye and mouse tracking methods. Their use has been largely focused on examining the spatial memory and behavior of map users. EEG, a newer addition to cartographic studies, boasts high temporal resolution and has been used alongside eye tracking. On the other hand, fMRI, derived from neuroscience, excels in spatial resolution, and has been linked to metrics like trial duration and response accuracy. Both these methods necessitate specialized equipment, controlled settings, and trained staff. The data they produce also require careful and thorough pre-processing. Yet, their advantage lies in offering a direct view into human brain activity, an insight other methods can't provide.

When considering experimental methods, integrating mouse tracking with fMRI and EEG holds promise, much like the successful combination of EEG and eye tracking seen in past studies. Combining fMRI and EEG can deliver high-resolution insights into brain activity during map interactions. Given the complexity of both fMRI and EEG methods, especially in data pre-processing, there's potential for developing automated tools to streamline the process and ensure easier synchronization with data from eye and mouse tracking. As fMRI and EEG are relatively novel in map cognition studies, future work should focus on standardizing implementation, refining experimentation procedures, and simplifying data analysis. The next evolution in experimental methods could pivot towards remote eye tracking. Although current trends favor mouse tracking for remote studies due to its ease of implementation, there's scope to further probe the viability and benefits of remote eye tracking, especially when compared to controlled environments and its potential in unsupervised experiments.

The transition from traditional paper maps to dynamic, web-based, and interactive formats has brought varied means of information dissemination, from computer displays to smaller screens like smartphones, smartwatches, and portable navigators. This shift underscores the importance of understanding differences in map reading strategies and visual searches across these platforms. Concurrently, it's pivotal to evaluate the efficacy of various map interfaces and their functionalities, depending on the communication medium. Research tools like eye tracking, mouse tracking, EEG, and fMRI, either individually or in combinations, can play a pivotal role in these investigations.

The integration of artificial intelligence (AI) and machine learning (ML) in the field of map cognition could lead to a multitude of new research directions. Although there are proposed methodologies, limited practical application of AI and ML has been recorded in published papers. Similar to the study of Keskin (2022), data gathered by the discussed experimental methods, could be used and applied to AI and ML algorithms to predict navigation decisions based on past behavior. These models could help improve the design of maps and navigation aids. AI could be used to create personalized maps that adapt to an individual's specific needs and preferences, improving the user experience. The needs could be determined by behavioral data obtained by the experimental methods. Difficult cartographic concepts for map users to understand, such as map-projections (as proved in their study, Kessler & Battersby (2023)) could use AI to assist in the visualization of complex spatial data, making it easier for humans to comprehend and interpret. Additionally, AI algorithms could be used to interpret behavioral data of map users to detect patterns, anomalies, or specific features in spatial data, providing insights that may be missed by human-analysts.

The rise of Augmented Reality (AR) and Virtual Reality (VR) offers intriguing prospects for map cognition research. AR and VR present a controlled, immersive platform for studying navigation. Researchers could delve into contrasts between real-world navigation and its virtual counterpart or assess how VR/AR spatial representations influence navigational skills, using eye-tracking experiments. Building on the spatial memory studies that leveraged EEG and eye-tracking with digital maps, there's potential to examine how AR and VR impact spatial memory and how immersive 3D map interactions boost spatial understanding. Finally, comparative studies between traditional maps and AR/VR maps, as well as the efficacy of AR/VR-specific map interfaces, present promising research avenues.

Bibliography

Arroyo, E., Selker, T. & Wei, W., 2006. *Usability tool for analysis of web designs using mouse tracks.* Montréal, In Proceedings of the CHI '06 Extended Abstracts on Human Factors in Computing Systems, pp. 484-489.

Beitlova, M., Popelka, S., Konopka, M. & Macku, K., 2023. Verification of Cartographic Communication Models Using Detection of Map Reading Strategies Based on Eye Movement Recording. *The Cartographic Journal,* pp. 1-20.

Beitlova, M., Popelka, S. & Vozenilek, V., 2020. Differences in Thematic Map Reading by Students and Their Geography Teacher. *ISPRS International Journal of Geo-Information,* 9(9), p. 492.

Bergmann Martins, V., Rosa Amorim, F., Augusto Reolon Schmidt, M. & Stamato Delazari, L., 2023. Study about the appropriate number of participants in map user studies. *International Journal of Cartography,* 9(2), pp. 196-206.

Bertin , J., 1967. *Sémiologie graphique : les diagrammes, les réseaux, les cartes.* Paris: Gauthier-Villars.

Bertin , J., 1987. *Semiology of Graphics, Diagrams, Networks, Maps.* WI: University of Wisconsin Press.

Brychtová, A., 2015. Exploring the Influence of Colour Distance and Legend Position on Choropleth Maps Readability. *Modern Trends in Cartography: Selected Papers of CARTOCON 2014,* pp. 303-314.

Brychtova, A. & Coltekin, A., 2016. An Empirical User Study for Measuring the Influence of Colour Distance and Font Size in Map Reading Using Eye Tracking. *The Cartographic Journal,* 53(3), pp. 202-212.

Bugdayci, I. & Bildirici, I. O., 2016. Evaluation of Educational Atlas Maps in Terms ofCartographic Design. *IOP Conference Series: Earth and Environmental Science.*

Burch, M., 2018. Which Symbols, Features, and Regions Are Visually Attended in Metro Maps?. *Intelligent Decision Technologies 2017,* pp. 237-246.

Burian, J., Popelka, S. & Beitlova, M., 2018. Evaluation of the Cartographical Quality of Urban Plans by Eye-Tracking. *ISPRS International Journal of Geo-Information,* 7(5), p. 192.

Chen, L., Wang, L., Huang, W. & Chen, G., 2017. A Comparative Study of Map Exploration Interfaces for Multi-Touch Tabletops. *International Journal of Human–Computer Interaction,* 33(8), pp. 677-691.

Clive, M. A., Lindsay, J. & Leonard, G., 2017. More Than Meets the Eye: Volcanic Hazard Map Design and Visual Communication. *Advances in Volcanology.*

Çöltekin, A. *et al.*, 2017. Perceptual complexity of soil-landscape maps: a user evaluation of color organization in legend designs using eye tracking. *International Journal of Digital Earth,* 10(6), pp. 560-581.

Çöltekin, A., Heil, B., Garlandini, S. & Fabrikant, S. I., 2009. Evaluating the Effectiveness of Interactive Map Interface Designs: A Case Study Integrating Usability Metrics with Eye-Movement Analysis. *Cartography and Geographic Information Science,* 36(1), pp. 5-17.

Cybulski, P., 2022. An Empirical Study on the Effects of Temporal Trends in Spatial Patterns on Animated Choropleth Maps. *ISPRS International Journal of Geo-Information,* 11(5), p. 273.

Cybulski, P. & Horbiński, T., 2020. User Experience in Using Graphical User Interfaces of Web Maps. *ISPRS International Journal of Geo-Information,* 9(7), p. 412.

Cybulski, P. & Krassanakis, V., 2022. The effect of map label language on the visual search of cartographic point symbols. *Cartography and Geographic Information Science,* 49(3), pp. 189-204.

Dandurand, F., Shultz, T. R. & Onishi, K. H., 2008. Comparing online and lab methods in a problem-solving experiment. *Behavior Research Methods,* 40(2), pp. 428-434.

Demšar, U. & Çöltekin, A., 2017. Quantifying gaze and mouse interactions on spatial visual interfaces with a new movement analytics methodology. *PLOS ONE,* 12(8).

Dent, B. D., Torguson, J. S. & Holder, T. W., 2009. *Cartography Thematic Map Design.* Sixith Edition ed. New York: McGraw-Hill.

DiBiase, D., MacEachren, A. M., Krygier, J. B. & Reeves, C., 1992. Animation and the Role of Map Design in Scientific Visualization. *Cartography and Geographic Information Systems,* 19(4), pp. 201-214.

Dickmann, F., Keil, J., Dickmann, P. L. & Edler, D., 2021. The Impact of Augmented Reality Techniques on Cartographic Visualization. *KN - Journal of Cartography and Geographic Information,* 71(4), pp. 285-295.

Dolezalova, J. & Popelka, S., 2016. ScanGraph: A Novel Scanpath Comparison Method Using Visualisation of Graph Cliques. *Journal of Eye Movement Research,* 9(4).

Donders, F., 1868. *On the speed of mental processes,* WG: Acta Psychologica 30.

Dong, W. & Liao, H., 2016. Eye tracking to explore the impacts of photorealistic 3D representations in pedestrian navigation performance. *Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci.,* pp. 641-645.

Dong, W. *et al.*, 2014. Using eye tracking to evaluate the usability of animated maps. *Science China Earth Sciences,* 57(3), pp. 512-522.

Dong, W., Wang, S., Chen, Y. & Meng, L., 2018. Using Eye Tracking to Evaluate the Usability of Flow Maps. *ISPRS International Journal of Geo-Information,* 7(7), p. 281.

Dong, W. *et al.*, 2023. Geography education improves spatial ability: evidence from fMRI and behavioral experiments. *Cartography and Geographic Information Science,* 50(3), pp. 289-305.

Dong, W. *et al.*, 2019. Using Eye Tracking to Explore the Impacts of Geography Courses on Map-based Spatial Ability. *Sustainability,* 11(1), p. 76.

Fairbairn, D. & Hepburn, J., 2023. Eye-tracking in map use, map user and map usability research: what are we looking for?. *International Journal of Cartography,* pp. 1-24.

Farmakis-Serebryakova, M. & Hurni, L., 2020. Comparison of Relief Shading Techniques Applied to Landforms. *ISPRS International Journal of Geo-Information,* 9(4), p. 253.

Fitts, P. M., Jones, R. E. & Milton, J. L., 1950. Eye movements of aircraft pilots during instrument-landing approaches. *Aeronautical Engineering Review,* 9(2).

Freeman, J. B. & Ambady, N., 2010. MouseTracker: Software for studying real-time mental processing using a computer mouse-tracking method. *Behavior Research Methods,* 42(1), pp. 226-241.

Garlandini, S. & Fabrikant, S., 2009. *Evaluating the Effectiveness and Efficiency of Visual Variables for Geographic Information Visualization.* Berlin, Springer Berlin Heidelberg, pp. 195-211.

Göbel, F., Kiefer, P. & Raubal, M., 2019. FeaturEyeTrack: automatic matching of eye tracking data with map features on interactive maps. *GeoInformatica,* 23(4), pp. 663-687.

Gołębiowska, I., 2015. Legend Layouts for Thematic Maps: A Case Study Integrating Usability Metrics with the Thinking Aloud Method. *The Cartographic Journal,* 52(1), pp. 28-40.

Golebiowska, I., Opach, T. & Rød, J. K., 2020. Breaking the Eyes: How Do Users Get Started with a Coordinated and Multiple View Geovisualization Tool?. *The Cartographic Journal,* 57(3), pp. 235-248.

Gröbe, M. & Burghardt, D., 2020. Micro diagrams: visualization of categorical point data from location-based social media. *Cartography and Geographic Information Science,* 47(4), pp. 305-320.

Havelková, L. & Gołębiowska, I. M., 2020. What Went Wrong for Bad Solvers during Thematic Map Analysis? Lessons Learned from an Eye-Tracking Study. *ISPRS International Journal of Geo-Information,* 9(1), p. 9.

He, B. *et al.*, 2023. A geospatial image based eye movement dataset for cartography and GIS. *Cartography and Geographic Information Science,* 50(1), pp. 96-111.

Hehman, E., Stolier, R. M. & Freeman, J. B., 2015. Advanced mouse-tracking analytic techniques for enhancing psychological science. *Group Processes & Intergroup Relations,* 18(3), pp. 384-401.

Hepburn, J., Fairbairn, D., James, P. & Ford, A., 2021. How do decision makers interact with geospatial data? An eye tracking study. *Abstr. Int. Cartogr. Assoc.,* Volume 3, p. 109.

Herman, L., Popelka, S. & Hejlova, V., 2017. Eye-tracking Analysis of Interactive 3D Geovisualization. *Journal of eye movement research,* 10(3).

Huster, R. J., Dedener, S., Eichele, T. & Herrmann, C. S., 2012. Methods for Simultaneous EEG-fMRI: An Introductory. *The Journal of Neuroscience,* 32(18), pp. 6053-6060.

Iannotti, G. R. *et al.*, 2015. Pulse Artifact Detection in Simultaneous EEG–fMRI Recording Based on EEG Map Topography. *Brain Topography,* 28(1), pp. 21-32.

Jia, F. *et al.*, 2023. Effectiveness of Rectangular Cartogram for Conveying Quantitative Information: An Eye Tracking-Based Evaluation. *ISPRS International Journal of Geo-Information,* 12(2), p. 39.

Kapaj, A. *et al.*, 2023. How does the design of landmarks on a mobile map influence wayfinding experts' spatial learning during a real-world navigation task?. *Cartography and Geographic Information Science,* 50(2), pp. 197-213.

Karsznia, I., Gołębiowska, I. M., Korycka-Skorupa, J. & Nowacki, T., 2021. Searching for an Optimal Hexagonal Shaped Enumeration Unit Size for Effective Spatial Pattern Recognition in Choropleth Maps. *ISPRS International Journal of Geo-Information,* 10(9), p. 576.

Keskin, M., 2020. *Exploring the Cognitive Processes of Map Users Employing Eye Tracking and EEG,* Ghent University: Department of Geography, Faculty of Sciences.

Keskin, M. *et al.*, 2016. *Contribution of Neuroscience Related Technologies to Cartography.* Albena, Proceedings, 6th International Conference on Cartography and GIS.

Keskin, M. & Kettunen, P., 2021. Designing AI-assisted interactive map displays to explore spatial information. *Abstr. Int. Cartogr. Assoc.,* Volume 3, p. 148.

Keskin, M. & Kettunen, P., 2023. Potential of eye-tracking for interactive geovisual exploration aided by machine learning. *International Journal of Cartography,* pp. 1-23.

Keskin, M., Krassanakis, V. & Çöltekin, A., 2023. Visual Attention and Recognition Differences Based on Expertise in a Map Reading and Memorability Study. *ISPRS International Journal of Geo-Information,* 12(1), p. 21.

Keskin, M. & Ooms, K., 2018. *Possibilities of eye tracking and EEG integration for visual search on 2D maps.* Zurich, ETH Zurich.

Keskin, M., Ooms, K., Dogru, A. & De Mayer, P., 2018. Digital sk*etc*h maps and eye tracking statistics as instruments to obtain insights. *Journal of Eye Movement Research into spatial cognition,* 10(3), p. 4.

Keskin, M., Ooms, K., Dogru, A. O. & De Maeyer, P., 2019. EEG & Eye Tracking User Experiments for Spatial Memory Task on Maps. *ISPRS International Journal of Geo-Information,* 8(12), p. 546.

Keskin, M., Ooms, K., Dogru, A. O. & De Maeyer, P., 2020. Exploring the Cognitive Load of Expert and Novice Map Users Using EEG and Eye Tracking. *ISPRS Int. J. Geo-Inf.,* 9(7).

Keskin, M., Rönneberg, M. & Kettunen, P., 2022. Cartographic adaptation through eye tracking and deep learning: Gaze-Aware Interactive Map System (GAIMS). *Abstr. Int. Cartogr. Assoc.,* Volume 5, p. 107.

Kessler, F. C. & Battersby, S. E., 2023. Cognition and perception of map projections: a literature review. *Cartography and Geographic Information Science,* pp. 1-16.

Kiefer, P., Giannopoulos, I., Raubal, M. & Duchowski, A., 2017. Eye tracking for spatial research: Cognition, computation, challenges. *Spatial Cognition & Computation,* 17(1-2), pp. 1-19.

Kieslich, P. J. & Henninger, F., 2017. Mousetrap: An integrated, open-source mouse-tracking package. *Behav Res Methods,* 49(5), pp. 1652-1667.

Kieslich, P. J. *et al.*, 2020. Design factors in mouse-tracking: What makes a difference?. *Behavior Research Methods,* 52(1), pp. 317-341.

Klippel, A., Hirtle, S. & Davies, C., 2010. You-Are-Here Maps: Creating Spatial Awareness through Map-like Representations. *Spatial Cognition & Computation,* 10(2-3), pp. 83-93.

Knura, M. & Schiewe, J., 2021. Map Evaluation under COVID-19 restrictions: A new visual approach based on think aloud interviews. *Proc. Int. Cartogr. Assoc.,* Volume 4, p. 60.

Korycka-Skorupa, J. & Gołębiowska, I. M., 2020. Numbers on Thematic Maps: Helpful Simplicity or Too Raw to Be Useful for Map Reading?. *ISPRS International Journal of Geo-Information,* 9(7), p. 415.

Kosinski, R. J., 2013. *A Literature Review on Reaction Time,* Lab/110/reaction. htm: [online] Available http://biae. clemson. edu/bpc/b.

Kraak, M. -. J. & Ormeling, F., 2010. *Cartography: Visualization of Geospatial Data.* 3rd ed. Essex: Pearson Education Limited.

Krassanakis, V., 2023. PeyeMMV: Python implementation of EyeMMV's fixation detection algorithm,. *Software Impacts,,* Volume 15.

Krassanakis, V. & Cybulski, . P., 2019. A review on eye movement analysis in map reading process: the status of the last decade. *GEODESY AND CARTOGRAPHY,* 68(1), pp. 191-209.

Krassanakis, V. & Cybulski, P., 2021. Eye Tracking Research in Cartography: Looking into the Future. *ISPRS International Journal of Geo-Information,* 10(6), p. 411.

Krassanakis, V. & Filippakopoulou, V., 2023. *Spatial representations: Creation techniques, theoretical principles, evaluation methods [Undergraduate textbook].* Kallipos: Open Academic Editions.

Krassanakis, V., Filippakopoulou, V. & Nakos, B., 2014. EyeMMV toolbox: An eye movement post-analysis tool based on a two-step spatial dispersion threshold for fixation identification. *Journal of Eye Movement Research,* 7(1).

Krassanakis, V., Filippakopoulou, V. & Nakos, B., 2016. Detection of moving point symbols on cartographic backgrounds. *Journal of Eye Movement Research,* 9(2).

Krassanakis, V. & Kesidis, A. L., 2020. MatMouse: A Mouse Movements Tracking and Analysis Toolbox for Visual Search Experiments. *Multimodal Technologies and Interaction,* 4(4), p. 83.

Krassanakis, V., Kesidis, A. L., Pappa, A. & Misthos, L. -. M., 2021. *Performing cartographic visual search experiments online: opportunities and challenges.* Virtual Workshop, In Proceedings of the Workshop on Adaptable Research Methods for Empirical Research with Map Users.

Krassanakis, V. & Misthos, L.-M., 2023. Mouse Tracking as a Method for Examining the Perception and Cognition of Digital Maps. *Digital,* 3(2), pp. 127-136.

Krassanakis, V. & Misthos, L.-M., 2023. Mouse Tracking as a Method for Examining the Perception and Cognition of Digital Maps. *Digital,* 3(2), pp. 127-136.

Krassanakis, V., Misthos, L.-M. & Menegaki, M., 2018. *LandRate toolbox: An adaptable tool for eye movement analysis and landscape rating.* ETH Zurich: Proceedings of the 3rd International Workshop.

Krassanakis, V. & Vassilopoulou, V., 2018. Introducing a data-driven approach towards the identification of grid cell size threshold (CST) for spatial data visualization: An application on marine spatial planning (MSP). *Journal of Urban and Environmental Engineering,* Volume 12.

Krygier, J., 1994. Chapter 8 - Sound and Geographic Visualization,. *Modern Cartography Series, Academic Press,* Volume 2, pp. 149-166.

Lai, M.-L.*et al.*, 2013. A review of using eye-tracking technology in exploring learning from 2000 to 2012. *Educational Research Review,* Volume 10, pp. 90-115.

Lapon, L. *et al.*, 2020. People's global-scale cognitive map versus their personal characteristics: a worldwide study. *Cartography and Geographic Information Science,* 47(6), pp. 550-564.

Liao, H., Dong, W., Peng, C. & Liu, H., 2017. Exploring differences of visual attention in pedestrian navigation when using 2D maps and 3D geo-browsers. *Cartography and Geographic Information Science,* 44(6), pp. 474-490.

Liao, H., Wang, X., Dong, W. & Meng, L., 2019. Measuring the influence of map label density on perceived complexity: a user study using eye tracking. *Cartography and Geographic Information Science,* 46(3), pp. 210-227.

Li, J. & Xiao, N., 2023. Computational Cartographic Recognition: Identifying Maps, Geographic Regions, and Projections from Images Using Machine Learning. *Annals of the American Association of Geographers,* 113(5), pp. 1243-1267.

Liu, B. *et al.*, 2019. Using fMRI to Explore the Influence of Road Network Patterns on Geospatial Cognition. *Proc. Int. Cartogr. Assoc.,* Volume 2, p. 75.

Lobben, A. K., Olson, J. M. & Huang, J., 2007. *Using fMRI in Cartographic Research.* In, Conference Proceedings, p. 10.

Lobben, A., Lawrence, M. & Olson, J. M., 2009. fMRI and Human Subjects Research in Cartography. *Cartographica,* 44(3), pp. 159-169.

Logothetis, N. K., 2008. What we can do and what we cannot do with fMRI. *Nature,* Volume 453, pp. 869-878.

Longley, P. A., Goodchild, M. F., Maguire, D. J. & Rhind, D. W., 2005. *Geographical Information Systems and Science.* West Essex: John Wiley & Sons Ltd..

Luce, R., 1986. *Response Times: Their Role in Inferring Elementary Mental Organization,* New York: Oxford University Press.

Łucjan, K. & Wojtanowicz, P., 2018. Continuous or discontinuous? Empirical study on animated maps. *Polish Cartographical Review,* 50(3), pp. 127-140.

Lynch, K., 1960. The Image of the City. *MIT Press.*

MacEachren, A., 1995. *How maps work: Representation, Visualization & Design.* New York: Guilford Press.

MacEachren, A. M., 1992. Visualizing Uncertain Information. *Cartographic Perspective,* Volume 13, pp. 10-19.

Mahanama, B. *et al.*, 2022. Eye Movement and Pupil Measures: A Review. *Frontiers in Computer Science,* Volume 3.

Maldonado, M., Dunbar, E. & Chemla, E., 2019. Mouse tracking as a window into decision making. *Behavior Research Methods,* 51(3), pp. 1085-1101.

Manson, S. *et al.*, 2013. Using Eye-tracking and Mouse Metrics to Test Usability of Web Mapping Navigation. *Cartography and Geographic Information Science,* Volume 39, pp. 48-60.

Mathur, M. B. & Reichling, D. B., 2019. Open-source software for mouse-tracking in Qualtrics to measure category competition. *Behavior Research Methods,* 51(5), pp. 1987-1997.

McArdle, G., Tahir, A. & Bertolotto, M., 2015. Interpreting map usage patterns using geovisual analytics and spatio-temporal clustering. *International Journal of Digital Earth,* 8(8), pp. 599-622.

Mocnik, F.-B., 2023. Why we can read maps. *Cartography and Geographic Information Science,* 50(1), pp. 1-19.

Montello, D., 2002. Cognitive Map-Design Research in the Twentieth Century: Theoretical and Empirical Approaches. *Cartography and Geographic Information Science - CARTOGR GEOGR INF SCI,* Volume 29.

Netzel, R. *et al.*, 2017. User performance and reading strategies for metro maps: An eye tracking study. *Spatial Cognition & Computation,* 17(1-2), pp. 39-64.

Ooms, K., De Maeyer, P. & Fack, V., 2014. Study of the attentive behavior of novice and expert map users using eye tracking. *Cartography and Geographic Information Science,* 41(1), pp. 37-54.

Pappa, A. & Krassanakis, V., 2022. Examining the preattentive effect on cartographic backgrounds utilizing remote mouse tracking. *European Cartographic Conference – EuroCarto,* Volume 5, p. 111.

Paresadko, V. & Baltabaeva, Z., 2017. Local lore school Atlas of Turkmenistan as the result of foreign students' scientific research. *Problemi Bezperervnoï Geografičnoï Osvìti ì Kartografiï,* pp. 55-61.

Peterson, M. P., 1994. Cognitive Issues in Cartographic Visualization. *Modern Cartography Series,* Volume 2, pp. 27-43.

Popelka, S., 2018. *Eye-tracking evaluation of 3D thematic maps.* Warsaw, Proceedings of the 3rd Workshop on Eye Tracking and Visualization, Association for Computing Machinery.

Popelka, S. & Brychtova, A., 2013. Eye-tracking Study on Different Perception of 2D and 3D Terrain Visualisation. *The Cartographic Journal,* 50(3), pp. 240-246.

Popelka, S. & Doležalová, J., 2015. Non-photorealistic 3D Visualization in City Maps: An Eye-Tracking Study. *Modern Trends in Cartography: Selected Papers of CARTOCON 2014,* pp. 3557-367.

Popelka, S., Dolezalova, J. & Beitlova, M., 2018. *New features of scangraph: a tool for revealing participants' strategy from eye-movement data.* Warsaw, Poland, Association for Computing Machinery.

Popelka, S., Vondrakova, A. & Hujnakova, P., 2019. Eye-tracking Evaluation of Weather Web Maps. *ISPRS International Journal of Geo-Information,* 8(6), p. 256.

Robinson, A. H. *et al.*, 2002. *Elements of Cartography.* Αθήνα: Πανεπιστημιακές Εκδόσεις Ε.Μ.Π..

Robinson, A. H. & Petchenik, B. B., 1976. *The Nature of Maps. Essays towards Understanding Maps and Mapping..* Chicago: University of Chicago Press.

Roth, R. E., 2017. Visual Variables. *The International Encyclopedia of Geography,* pp. 1-11.

Schiewe, J., 2019. Empirical Studies on the Visual Perception of Spatial Patterns in Choropleth Maps. *Journal of Cartography and Geographic Information,* 69(3), pp. 217-228.

Słomska-Przech, K. & Gołębiowska, I. M., 2021. Do Different Map Types Support Map Reading Equally? Comparing Choropleth, Graduated Symbols, and Isoline Maps for Map Use Tasks. *ISPRS International Journal of Geo-Information,* 10(2), p. 69.

Spivey, M. J., Grosjean, M. & Knoblich, G., 2005. Continuous attraction toward phonological competitors. *PNAS,* 102(29), pp. 10393-10398.

Stachoň, Z. *et al.*, 2020. An eye-tracking analysis of visual search task on cartographic stimuli. *8th International Conference on Cartography & GIS: Proceedings VOL.1.*

Steinke, T., 1987. Eye Movement Studies In Cartography And Related Fields. *Cartog.Int.J.Geogr.Inf.Geo,* 24(2), p. 40+73.

Sultan, M. N., 2021. Development of a georeferenced eye-movement data creation tool for interactive web maps. *Palacký University Olomouc.*

Tzelepis, N. *et al.*, 2020. Evaluating the perceived visual complexity of multidirectional hill-shading. *Geodesy and Cartography,* 69(2), pp. 161-172.

Voßkühler, A., Nordmeier, V., Kuchinke, L. & Jacobs, A. M., 2008. OGAMA (Open Gaze and Mouse Analyzer): Open-source software designed to analyze eye and mouse movements in slideshow study designs. *Behavior Research Methods,* 40(4), pp. 1150-1162.

Wahyono, I. D. *et al.*, 2020. New Smart Map for Tourism using Artificial Intelligence. *2020 10th Electrical Power, Electronics, Communications, Controls and Informatics Seminar (EECCIS),* pp. 213-216.

Welford, A., 1980. *Choice reaction time: Basic Concepts,* New York: Academic Press.

Whelan , R., 2008. Effective Analysis of Reaction Time Data. *The Psychological Record,* 58(3), pp. 475-482.

Wilson, D., Bertolotto, M. & Weakliam, J., 2010. Personalizing map content to improve task completion efficiency. *International Journal of Geographical Information Science,* 24(5), pp. 741-760.

Xu, Y. *et al.*, 2022. How do voice-assisted digital maps influence human wayfinding in pedestrian navigation?. *Cartography and Geographic Information Science,* 49(3), pp. 271-287.

Yonov, N. & Petkov, D., 2020. Augmented Reality Navigation Map of Mountain Area. *8th International Conference on Cartography and GIS, Proceedings Vol. 1 .*

Żyszkowska, W., 2017. Levels and properties of map perception. *Polish Cartographical Review,* 49(1), pp. 17-26.