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A review on eye movement analysis in map reading process: the status of the last decade

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Abstract: Eye tracking constitutes a valuable tool for the examination of human visual behavior since it provides objective measurements related to the performed visual strategies during the observation of any type of visual stimuli. Over the last decade, eye movement analysis contributed substantially to the better understanding of how visual attention processes work in different types of maps. Considering the clear need for the examination of map user reaction during the observation of realistic cartographic products (i.e. static maps, animated maps, interactive and multimedia maps), a critical amount of experimental studies were performed in order to study different aspects related to map reading process by the cartographic community. The foundation of these studies is based on theories and models that have been developed in similar research domains (i.e. psychology, neuroscience etc.), while the research outcomes that produced over these years can be used directly for the design of more effective and efficient maps. The aim of the present article is to summarize and present the current panorama of the existing eye tracking studies in cartographic research appeared over the last decade. Additionally, methodological contributions (including analysis tools) of cartographic society in the field of eye movement analysis are reported, while existing challenges and future perspectives are also discussed.

Keywords: cartography, eye tracking, eye movement analysis, map reading, map perception

1. Introduction

Map reading process is a complex visual procedure which may be affected by several factors connected to either cognitive or perceptual aspects of human vision. The understanding of how maps work requires the performance of experimental studies that

examine map users' visual behavior and strategies (Vondrakova and Popelka, 2014). Such experimentation is based on theories and models that have been developed in similar research domains (i.e. psychology, neuroscience etc.). Since the transfer of similar research in cartography can be made on the basis of a simple assumption that maps correspond to visual stimuli (Ciołkosz-Styk, 2012), the need to examine map user' reaction during the observation of various cartographic products becomes clear.

Out of the existing experimental techniques, the one of capturing and analyzing eye movements (so called "eye tracking") represents one of the most valuable methods towards the evaluation of different aspects related to map reading process. Although that the first cartographic studies using eye movements analysis were conducted in 1971 (Steinke, 1987; MacEachren, 1995); Williams (1971) investigated the concept of symbols selectivity (using geometric symbols), while Jenks was the first cartographer who implemented eye movement analysis techniques in order to investigate how visual attention of map users is drawn during the observation of a dot map (1973) (reported in Steinke, 1987), the last decade is characterized by an increasing interest of cartographic society to the implementation of eye tracking techniques (Wang et al., 2016). This interest can be proven considering the studies carried out and published over the last few years. At the same time, several workshops and training sessions have been organized from the community during the last years, including the ICA workshop "Eye tracking: why, when, and how?" in 2013 (https://cogvis.icaci.org/icc13_et.html), the series of Eye Tracking for Spatial Research (ET4S) workshops (<http://et4s.ethz.ch/et4s-series/>), and the ICA workshop on 'Designing an conducting user studies' (<https://use.icaci.org/interactive-training-sessions-in-albena/>).

Eye tracking techniques have already been implemented in several domains related to the examination of map reading process, including the study of design principles and functions of cartographic symbolization, the comparison of map users' perception during the observation of 2D and 3D representations, as well as the study of usability of interactive cartographic environments (e.g. Web GIS platforms etc.). Moreover, several studies investigated the spatial abilities of map users while using cartographic products for navigational purposes, and the influence of their expertise on map reading procedures. At the same time, cartographic society has been contributed substantially to eye tracking community by developing and distributing analysis methods and tools that may be also applied widely.

Steinke (1987) provided a first in-depth review about eye movement studies in cartography and several related fields (e.g. psychology etc.). Nowadays, the influence of eye tracking method is noticeable in cartographic research. Recently, Kiefer et al. (2017) have presented a well-documented overview of the contribution of eye tracking technology in spatial research, including spatial cognition, geographic information science and cartography. As indicated by Kiefer et al. (2017), modern eye tracking studies in cartography are based on theoretical concepts developed in research domains that are connected with the study humans' visual behavior while they are tested in "map reading" conditions.

Although the overview provided by Kiefer et al. (2017) constitutes a quite solid groundwork for understanding current trends and challenges in the general field of spatial research, it is also far too important to scrutinize the influence of eye tracking technology and eye movement analysis on different aspects related to map reading process. The aim of this article is to summarize the existing eye tracking cartographic studies that were carried out over the last decade extending the overview presented by Kiefer et al. (2017) (this overview is based on a fundamental classification of maps and geo-visualizations and comprises static, animated and interactive maps). Additionally, methodological contributions (including analysis tools) of cartographic society in the field of eye movement analysis are also reported. The literature review provided in the current article is based on the manual search (through Google Scholar platform as well as through the scientific databases of Scopus and Web of Science) using relative to the topic keywords (such as cartography, map reading, eye tracking, and eye movement analysis) and the extensive study of research works published in the period of the last decade (since 2009). Finally, having demonstrated the updated overview of the field, the prospects for future and challenges are discussed.

The present article consists of two main sections including this of the literature review on research studies using eye movement analysis towards the examination of map reading process and this of concluding remarks and future perspectives where current and future trends in the field are summarized and discussed. Additionally, for the better organization of the status of the last decade, literature review is organized into five different subsections, including studies on cartographic symbolization and design principles, studies that compare 2D and 3D representations, studies which examines issues related to map users' expertise, as well as a separate subsection where cartographic studies related to different topics are investigated and another one where eye tracking analysis tools and methods delivered by the cartographic community over the examined period are presented.

2. Eye movement analysis in map reading process

2.1. Cartographic symbolization and design principles

Cartographic symbolization is a fundamental process in the map production procedure. In particular, cartographers use specific design principles in order to represent qualitative and quantitative differences in geographic data. These principles correspond to the visual variables (Bertin, 1983) in the case of static maps, while their function is accomplished through dynamic variables (DiBiase et al., 1992) for animated maps. Additionally, sound (acoustic) variables (Krygier, 1994) can also be implemented, along with visual and dynamic ones, to support the cartographic design process. Over the last decade, eye tracking studies conducted revealed some first critical evidence about the basic function of design principles. The results of these studies can be used directly for the effective selection of cartographic symbolization.

Garlandini and Fabrikant (2009) examined four basic visual variables of cartographic symbolization (size, color value, and hue, and orientation) in terms of the effectiveness and efficiency of map users in change detection conditions. Effectiveness and efficiency constitute typical measures that correspond to the speed and the accuracy of the detection accordingly. The results of this study indicated that size is the most effective and efficient variable among the tested ones while orientation seemed to be the least effective one. Both effectiveness and efficiency can be also described by the term “selectivity”, which refers to the ability of human vision to spot specific objects of a visual scene while avoiding others. In a series of studies (Krassanakis et al., 2011a; 2011b; Krassanakis, 2013a), the selectivity of a topological feature of having a hole is examined for abstract (geometric) and pictorial symbols. The results of these studies suggest that this feature can lead to more effective searches (faster for the case of abstract symbols). Additionally, these studies revealed some critical indications about the visual patterns during the search of point symbols in cartographic background. Specifically, they revealed that the produced scanpaths were more complicated when target symbols were located on the periphery than in the center (or if they are absent), while the location of a target symbol (which constitutes another fundamental visual variable) seemed to affect the visual search procedure in the next scene in which the same target was searched for. Moreover, their results showed that fixation points mainly corresponded to the parts of the background that consist of point symbols. Similar outcome was also produced in a recent study described by Burch (2017) which highlighted that research participants tend to concentrate on map key symbols when searching in metro maps.

Among typical maps, choropleth maps constitute one of the most popular types for cartographic visualizations. Based on the differentiation of color value, choropleths depict quantitative differences existing in geographic data that refer to areas with specific boundaries. The appropriate selection of the used color schemes may lead to the optimal quality of the cartographic product, as well as to the effective discrimination of different classes by the map user. In a series of eye tracking experimental studies (Brychtová, 2015; Brychtová and Çöltekin, 2016; 2017), the influence of color distance in map legibility is examined. They revealed that the relation between color distance and map ability was positive (Brychtová, 2015) while larger color distances contributed to the better performance of map users (Brychtová and Çöltekin, 2016). Additionally, testing the effect of spatial distance of map symbols in the differentiation of color value and hue, Brychtová and Çöltekin (2017) concluded that larger color distances were required for sequential schemes than for qualitative ones. At the same time, the study presented by Brychtová (2014) showed that map legend position did not seem to have the influence on map reading process for such stimuli, while Brychtová and Çöltekin (2016) concluded that efficient visual search is enforced when medium font labeling sizes (equal to “11 pt”) are used on the map.

The influence of color dimensions (hue, saturation, and value) was also tested, in terms of effectiveness and efficiency, for map users with normal vision and red/green color impairments (Dong et al., 2016). The results of the study presented by Dong et al. (2016) indicated that color hue is the most distinguishable variable for both groups

of map users while the color saturation and value seemed to have equal influence. Map users' performance has been also examined during the process of reading different types of polygons on map background (Kiik et al., 2017). Specifically, Kiik et al. (2017) investigated four types of thematic polygons, including simple and transparent boundaries, hatches and icons. Out of the examined types, hatches appeared to be the most efficient although they also had the most negative effect on map reading process, as well as on preferences of map readers.

The level of abstraction (e.g. in map point symbols), or the level of iconicity of map symbols may have also a direct influence on map reading process, considering it may affect the message delivered through a cartographic product. In a recent research presented by Franke and Schweikart (2017), the concepts of visual encoding and mental representation of maps were tested through the eye tracking study. The examination was based on the use of three different levels of abstraction for landmarks representation, including vignettes, icons, and text symbols and resulted in a better performance (in terms of memory) for text symbols. Moreover, in another empirical study, presented by Brügger et al. (2016), the influence of different types of line symbols was examined. More specifically, considering three different types of symbolization for elevation change visualization on bicycle routes (including color hue, color-coded arrows and elevation profiles), the visual behavior of map users was tested during two different tasks (relative height detection, and slope identification). The results showed that color-coded arrows lead to more accurate performance in terms of height detection while no effects based on the selected visualization were observed for slope identification (Brügger et al., 2016). Additionally, eye tracking methods have been also used in order to examine how visual variables are perceived during the observation of special cartographic visualizations. Recently, Dong et al. (2018) presented an experimental study in order to examine the influence of flow maps properties in map reading process. Their results indicate that the use of curved flows and color gradients seem to be more effective than straight lines and different line thickness correspondingly.

Apart from the typical visual variables, originally proposed by Bertin (1967/1983) for traditional static maps, animated maps and dynamic variables have also been examined through the implementation of eye tracking experiments. In an empirical study in which the perception of multi-component animated maps was examined, it was highlighted that the used dynamic variables served as salient features which affected map users' visual attention (Opach et al., 2014). A similar result was also achieved in the studies presented by Krassanakis (2013a), and Krassanakis et al. (2013a). In more details, testing dynamic variables of duration and rate of change, these studies showed that there was an optimal range within which map users may detect differences that occur on animated maps (Krassanakis, 2013a; Krassanakis et al. 2013a). Furthermore, Krassanakis (2014) and Krassanakis et al. (2016) calculated the minimum duration threshold required for the detection of simple moving point symbols by human central vision. More specifically, they examined the process of point symbol detection on map backgrounds with different level of abstraction and they concluded that detection threshold corresponded to a duration value around 400 ms (Krassanakis, 2014; Krassanakis et al.,

2016). Additionally, in another study demonstrated by Krassanakis et al. (2013b) the post-reaction of map users (after moving point detection) was examined. The results of this study showed that after detected a moving symbol several other cartographic symbols might attract map users' perception (Krassanakis et al., 2013b). Another interesting outcome of this study was that it highlighted that existing saliency models (i.e. models that aim to predict human fixations during the observation of natural scenes) did not allow to predict the allocation of human visual behavior on a complex topographic map quite accurately.

2.2. Comparing 2D and 3D representations

Nowadays, the distribution of map products using digital monitors, either in personal computers or mobile devices, gives the opportunity to represent 3D geographic data in virtual software environment (e.g. geo-browsers etc.). Although the use of digital representations may constitute an impressive way to deliver geospatial information to map users, a critical question of this process refers to the effectiveness and the efficiency of their performance during the execution of map tasks. At the same time, the use of virtual environment in cartographic visualizations boosts the number of available solutions for map symbolization (e.g. 3D point symbols). In the last decade, several eye tracking studies in cartographic research compared the performance of map users during the manipulation of cartographic data and the execution of map tasks in both 2D and 3D environment.

The perception of terrain representation constitutes one of the most challenging issues that emerged regarding the use of 3D virtual environment. In the experimental eye tracking study related to this issue, Popelka et al. (2013) reported that the use of 3D perspective views, compared to typical orthogonal maps, seemed to be more appropriate for the retrieval of corresponding information during typical visibility analysis tasks. In another study, Popelka and Brychtová (2013), using the technique of eye tracking combined with a questionnaire, compared the performance and the preferences of map users during the observation of typical 2D contour map and 3D perspective views for the visualization of terrain elevation. Although no significant difference was found in terms of map users' preferences, the analysis of eye movements showed that there were differences in map users' visual strategies which were revealed based on the implementation of a scanpath comparison process (Popelka and Brychtová, 2013).

The process of visual search for point map symbols was also tested on 3D map visualizations. Specifically, Popelka and Doležalová (2015) examined the influence of non-photorealistic 3D city maps on the detection of point symbols. The 3D effect was produced by the existence of 3D buildings. Their analysis, based on both eye tracking data and questionnaires, indicated that the 3D effect did not produce any differences in map reading process (Popelka and Doležalová, 2015). Furthermore, the 3D effect was also tested by Popelka and Doležalová (2016) as a property of cartographic symbolization. In particular, they examined the influence of 3D point symbols during a map task that required the identification of points' size on both 2D and 3D (using a virtual globe)

maps. Their outcomes highlighted that the use of the virtual globe led to less accurate performance (Popelka and Doležalová, 2016). The influence of 3D map symbols was also tested in an eye tracking experimental study presented by Liu et al. (2017). They examined the effect of the basic visual variables in terms of their “visual guidance” (Liu et al., 2017). They found out that the variables of color hue and shape seemed to serve as dominant variables that guided the visual attention during map reading processes demonstrated on 3D visualizations (Liu et al., 2017).

Eye tracking was also used as a tool for the comparison typical 2D representations with 3D ones during the performance of navigational tasks. More specifically, Dong and Liao (2016) examined map users’ lab-based navigation behavior with the use of typical 2D maps and photorealistic 3D representations. The results of their experimental study indicated that 3D representations seemed to be less effective and efficient in terms of map users’ cognitive load (Dong and Liao, 2016). Their outcomes showed that self-localization and orientation processes were better performed through 3D representations (Dong and Liao, 2016). In a similar study, presented by Liao et al. (2017), map users’ navigational skills were compared by means of 2D maps and 3D geo-browsers. Three discriminated map skills were investigated, including self-localization, spatial knowledge acquisition, and decision-making, on the map backgrounds (both 2D and 3D) provided by Google. The outcomes of this study highlighted that map users’ response time was much faster for 3D geo-browsers (Liao et al., 2017). At the same time, this study confirmed that 3D representation was more helpful when the more complex decision had to be taken. A significant difference, based on the examination of the typical eye tracking metrics of fixation duration and saccades amplitude, between 2D and 3D electronic maps was also discovered by another study presented by Lei et al. (2016). The analysis showed that 2D maps allowed faster browsing procedures than 3D ones in which, “more focused browsing occurs” (Lei et al., 2016). Additionally, it demonstrated that a mixed view consisted of the combination of 2D and 3D representations could be more effective and needed to be considered in the electronic map design (Lei et al., 2016).

2.3. Map users’ expertise

Any model that aims to describe how cartographic communication is achieved needs to consist of three main components: the cartographer (map producer), the map product, and the map user. Of course, there are also some other factors which may have the influence on such communication (e.g. reading conditions, map product nature etc.). Undoubtedly, the huge variety of the existing map production tools, including those online, contributed to the extensive distribution of several maps and related services (e.g. geo-location services etc.) for generic use. However, the aim of the map product or service could be quite specific if particular users and skills were a target (e.g. route maps for pilots, geological maps for geologists and engineers etc.). Hence, a quite interesting aspect that might contribute to the better understanding of map reading behavior is the component of cartographic communication models connected with end map users. Both the classification of map users into well-defined categories (e.g. based on demographic

information etc.) as well as the influence of their characteristics on their map reading performance can be investigated.

Map users' expertise constitutes one of the basic characteristics that can be used to classify map users. The influence of this factor was examined through several eye tracking experimental studies during the observation of different types of cartographic products, while at the same time eye tracking technology was combined with other methods, such as thinking aloud method, questionnaire analysis etc., in order to examine optimal map design practices (Ooms, 2012). Ooms et al. (2012a) presented an experimental study where both expert and novice map users were examined during visual search tasks on dynamic and interactive maps. The study combined eye tracking with time response recording measures and aimed to reveal critical information about users' performed strategies and the cognitive load processes. The results showed that experts turned out to be more efficient in the performed map tasks related to the identification of specific names while novices needed more time for map image interpretation (Ooms et al., 2012a). However, Ooms et al. (2014) concluded that both experts and novices map users had difficulties with the execution of map tasks that required the interpretation and memorization of mirrored maps objects.

The influence of map users' expertise was also tested in specific types of visualizations. More specifically, Stofer and Che (2014) examined the visual reaction of both experts and novices during the observation of scaffolded (ocean) data visualizations. This study revealed that the "meaning-making" strategies adopted by experts were different from those adopted by novices. According to Zittoun and Brinkmann (2012) the term of "meaning-making" is referred to "the process by which people interpret situations, events, objects, or discourses, in the light of their previous knowledge and experience". Stofer and Che supported the results, comparing them with those of a previous "interview-based" study (Stofer and Che, 2014). In another study, presented by Çöltekin et al. (2016), map users with different levels of prior knowledge about soils were tested in order to examine how their effectiveness and efficiency were influenced by different legend presentation types during the execution of typical soil-landscape tasks. The results revealed difficulties of all participants with successful completion of the majority of tasks, proving the complexity of such map products (Çöltekin et al., 2016).

The factor of map users' expertise was also tested through a mixed-method experiment (using digital sketch maps and eye movement analysis) in a recent study presented by Keskin et al. (2018). In particular, this study examined the performance of both expert and novice users during a memory task where participants asked to remember and recall (through delivering sketch maps) the main map elements that were presented on the used stimuli. Their analysis showed that no significant differences existed between experts and novices, as well as between females and males.

2.4. Other applications related to map reading

In the paragraphs above, eye tracking applications are classified into basic subcategories related to cartographic research. Nevertheless, the methods of capturing and analyzing

eye movements also have a great influence on several other aspects of map reading process. At the same time, eye tracking has also been used as an objective evaluation tool for the quality of specific cartographic products (see e.g. the recent study presented by Burian et al. (2018) on the evaluation of urban plans) and the usability of specific tools (see e.g. the study presented by Gołębiowska et al. (2017) where the configuration of a visualization tools consisting of multiple components is examined).

One of the factors that might affect the total effectiveness of the cartographic product is related to map annotation. On the basis of the collection of eye tracking data, Ooms et al. (2012b) showed that both effectiveness and efficiency of label placement methods can be improved without affecting the information delivered to map users through interactive and dynamic maps. Another eye tracking experimental study revealed that the performance of map tasks may be influenced by different types of annotations (Netzel et al., 2017). Additionally, the influence of labels density on maps' complexity and legibility has also been recently studied by Liao et al. (2018) in a two-step experimental process in which questionnaire-based and eye tracking methods were used. The interesting point of their study was that, although they observed the existence of a correlation between label density and perceived complexity through the collection of response times, the used eye tracking analysis did not end with the same result.

Since map complexity is directly affected by the nature (e.g. geometry) of map symbols displayed, the examination of how visual perception works during the observation of symbols in different shapes seems very challenging. The observation of both theoretical (testing) and real cartographic lines (with different shapes and geometries) was tested through an experimental study presented by Bargiota et al. (2013) conducted to examine whether critical points (which are necessary for the implementation of line generalization algorithms) were observed or not. Their results indicated that locations of fixations were connected with regions of the lines that involved critical points. Additionally, except for the basic components (i.e. cartographic symbols and annotation) that shape the main image of the map, secondary elements might also influence the process of map reading. In the memory task-based eye tracking experimental study presented by Edler et al. (2018), it was revealed that the position of the map legend influenced the performance of map users. In more detail, the results highlighted that right-sided legends were decoded faster than left-sided ones.

Presently, taking into consideration that the majority of maps are distributed as digital products with animated and interactive material, the major challenge of cartographic research is connected with the evaluation of the usability of such products. In the experimental study presented by Incoul et al. (2015), the comparison of map users' visual behavior during the observation of both paper and digital cartographic maps revealed that although visual attention allocation was similar in both products, more fixations per second were performed when digital maps were observed. Furthermore, several studies examine the effectiveness and efficiency of interactive (Çöltekin et al. 2009; 2010) and animated maps (Opach and Nossun, 2011; Dong et al., 2014a; 2014b), including cartographic products distributed in GIS environment (Brychtová et al., 2012b; 2013) or through the Internet (web maps) (Alaçam and Dalci, 2009; Manson et al. 2012; Keil et

al. 2018), as well as that of special visualization techniques, such as cartograms (Ulla et al., 2016). The results of these studies revealed that significant differences might exist among different products (e.g. among different web map services), especially considering the map reading process involved the use of different tools and buttons of their graphical user interface (GUI) while at the same time the function of typical visual variables might differ on dynamic cartographic visualizations. For example, Dong et al. (2014b) found that the function of variables of color hue and size was directly related to the size of display. That result is quite critical considering today a map can be demonstrated on several devices with a digital monitor. What is also interesting is the fact that, considering some of methodological attitudes that are followed by aforementioned studies as well as by other studies mentioned in the present work, the examination of usability issues can be also based on the combination of eye tracking methodology with other experimental techniques, such as thinking aloud processes, video recording and questionnaires analysis. Simultaneously, these studies highlight the crucial need to scrutinize how map readers interact with map interface during the “modern” process of map reading.

2.5. Eye tracking analysis tools and methods delivered by cartographic community

In the last decade several tools and analysis methods were also proposed and distributed towards the investigation of map reading procedure with the use of eye tracking techniques. This fact proves that the crucial need for optimizing such methods with cartographic products (Brychtová et al., 2012a) remains active. At the same time, many of the developed software tools can be used for general purposes in similar fields (e.g. in landscape perception research etc.). Hence, the past and the current activity of cartographic community is not limited just to transferring and using existing methods and tools for the investigation of map reading patterns and behaviors but it substantially contributes to the further extension of eye tracking methodological approaches.

The adaptation of commonly used eye tracking techniques in cartographic research requires the selection of appropriate analysis parameters. Such parameters might be connected with selections made either in a “higher” or a “lower” level. The higher-level analysis may require the delineation of areas of interests (AOIs) according to specific map elements while the selection of the appropriate fixation detection parameters constitutes one of the components essential to the lower-level analysis. For example, Popelka (2014) investigated the optimal spatiotemporal parameters for the implementation of a dispersion-based algorithm (I-DT) for cartographic purposes. Moreover, considering performed visual search strategies may differ according to several factors, appropriate methodological approaches could be adapted in order to describe the corresponding visual behavior of map users. For example, Kiefer and Giannopoulos (2012) presented the development of a “gaze map matching” approach which aims to deliver an automatic content-based gaze analysis based on the implementation of a probabilistic Hidden Markov Model (HMM). Recently, Göbel et al. (2017) presented FeaturEyeTrack framework which is based on this approach that works with interactive online maps.

The problem of visual strategies' comparison remains one of the most challenging issues in the eye movement analysis research. ScanGraph (<http://eyetracking.upol.cz/scangraph/>) is one of the tools that can be implemented in order to identify existing similarities among map users' strategies (Dolezalova, and Popelka, 2016a; 2016b). In this tool, scanpath comparison process is based on the use of a modified version of Levenshtein distance and Needleman-Wunsch algorithms (Dolezalova, and Popelka, 2016a; 2016b). Undoubtedly, the categorization of visual strategies might reveal critical indications about the related factors that have the influence on map reading process. Although such approach can be used for quantification of existing differences, it is also far too important to employ sophisticated methods to represent those differences. Additionally, it is also quite vital to establish effective ways to visualize the behavior of the examined sample of participants during the observation of specific stimuli. Heatmap visualizations are probably the most famous method of representing the "overall" visual behavior. Karagiorgou et al. (2014) presented an alternative approach that aims to deliver a visualization tool of the "average" scanning behavior. They produced an inferred polyline based on the implementation of DBSCAN clustering algorithm that represented the average strategy of map users.

Eye tracking data were also used as the basic input for enhancing the interaction between the map user and the map interface. GazeGIS platform (Tateosian et al., 2017) is an identical example of how this approach can be implemented. In particular, GazeGIS serves as the gaze-based geographic information system (GIS) which allows the augmentation of text with geographic information. Hence, this platform, although a prototype, may constitute a different way of navigation and distribution of available geographic information.

Besides the aforementioned analysis tools and applications, some more generic tools suitable for eye movement analysis have been delivered by cartographic society. For example, EyeMMV toolbox (<https://github.com/krasvas/EyeMMV>) (Krassanakis 2013b; Krassanakis et al. 2014) is MATLAB analysis toolbox which fully supports the analysis of eye tracking data in typical eye tracking metrics (fixations, saccades, and scanpath based) as well as the development of popular eye tracking visualization methods. Additionally, the function of this toolbox has been recently extended (LandRate toolbox (<https://github.com/krasvas/LandRate>)) in order to deliver the automatic eye tracking analysis report in simple steps (Krassanakis et al., 2018). At the same time, LandRate toolbox gives the opportunity to calculate the integrated index (LRI) that combines typical eye tracking metrics with weights that can be produced on a basis of expert judgment procedures. Moreover, the 3DgazeR (<http://www.eyetracking.upol.cz/3d/>) is another tool that supports the visualization of eye tracking data on 3D geovisualizations (e.g. digital elevation models) (Herman et al., 2017). Such implementation extends the functionality of typical 2D eye tracking visualization methods in 3D space and may support gaze data visualization during the observation of corresponding types of visual stimuli.

Lately, the cartographic community has also shown an increasing interest in the use of low-cost eye tracking solutions for the implementation of experimental research stud-

ies. Bérces and Török (2013) presented a Do-It-Yourself (DIY) eye tracker that can be used for the performance of cartographic experiments while Ooms et al. (2015) evaluated the suitability of a specific low-cost device (EyeTribe) for scientific experimentation. Moreover, Popelka et al. (2016) suggested how the same device can be integrated with the Hypothesis platform (an updated description of this platform is presented by Šašinka et al. (2017)). Additionally, recently Ooms and Krassanakis (2018) presented a methodological framework that can be used for the measurement of spatial noise of low-cost (and other) eye tracking devices as well as the use of the produced values as an input in the process of fixation detection. Finally, Demšar and Çöltekin (2017) presented recently an integrated methodological approach towards the quantification of interactions between trajectories generated by implementing both eye and mouse tracking procedures. Their analysis showed that, for task performed under unconscious control, mouse tracking data might be correlated with the corresponding eye tracking data. Hence, this study indicated that mouse tracking data, which can be easily collected without the need of any specific hardware, could be used as an indicator of attention processes that take place during the observation of a visual scene.

3. Concluding remarks and future perspectives

Totally, 76 research articles (including those mentioned in the present paragraph) published in the last decade are examined and presented within the present study. In Table 1, the number of the examined studies (both in absolute and percentage values) as well as the corresponded covered periods are reported. Additionally, the percentage of the examined published works per each category is also depicted in Figure 1. As it is observed from both Table 1 and Figure 1, the majority of the examined research studies are related to the study of cartographic symbolization and the relative design principles.

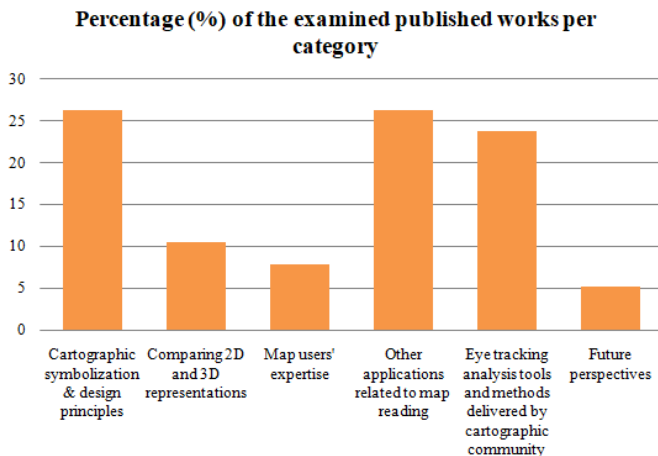


Fig. 1. Categories of the examined research works presented in the present study

Moreover, cartography society contributed substantially to the development of new tools and methods towards the performance of eye movement analysis.

Table 1. The number of the examined studies (both in absolute and percentage values) as well as the corresponded covered periods

Category	Number of studies	Percentage (%)	Period
Cartographic symbolization and design principles	20	26.3	2009–2018
Comparing 2D and 3D representations	8	10.5	2013–2017
Map users' expertise	6	7.9	2012–2018
Other applications related to map reading	20	26.3	2009–2018
Eye tracking analysis tools and methods delivered by cartographic community	18	23.7	2012–2018
Future perspectives	4	5.3	2016–2018
Total	76	100	

In Table 2, the number of the examined studies (both in absolute and percentage values) is also presented per each examined year of the last decade. Furthermore, Figure 2 depicts the corresponded percentage of the examined studies per each year. As it is obvious from both Table 2 and Figure 2, cartographic society was really quite active in the field.

Table 2. The number of the examined studies (both in absolute and percentage values) is also presented per each examined year of the last decade

Year	Number of studies	Percentage (%)
2009	3	3.9
2010	1	1.3
2011	3	3.9
2012	7	9.2
2013	10	13.2
2014	11	14.5
2015	4	5.3
2016	13	17.1
2017	14	18.4
2018	10	13.2
Total	76	100

The amount of research studies reported in the present article proves that eye tracking technology represents a valuable tool for the examination of different aspects of the map reading process. The eye movement analysis constitutes the enhanced method that

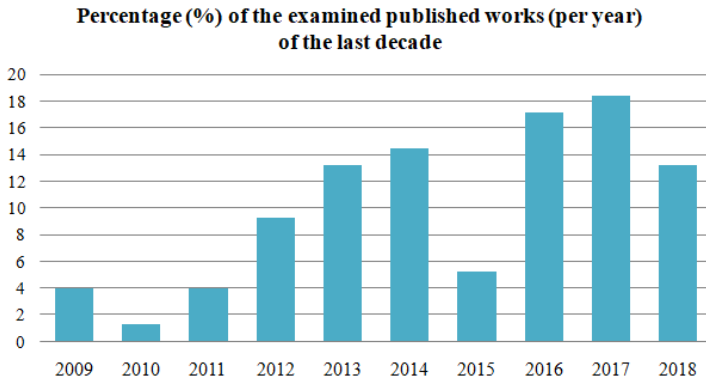


Fig. 2. The examined research works per year of the last decade

serves as subjective approach towards the analysis of visual attention for different types of cartographic products (i.e. printed, static, dynamic, and interactive maps distributed either as standalone media or through the internet). However, as it is also highlighted by the reported studies, eye tracking can be combined either with traditional methods (e.g. questionnaires, response time capturing, thinking aloud protocols etc.) or more sophisticated ones, such as Electroencephalography (EEG). Keskin and Ooms (2018) discusses some of the most challenging issues that emerge during integration of eye tracking with EEG technique towards to support cartographic usability research. At the same time, recent research studies highlight how other eye tracking metrics (see e.g. the study presented by Kiefer et al. (2016) where pupil diameter measurements were used and cognitive load indicators during the performance of map tasks) or specific indicators (see e.g. the ambient/focal coefficient K presented by Krejtz et al., 2017) can be used for the study of map reading strategies.

The knowledge obtained over the last decade is another step toward the deeper understanding of how visual attention works during the observation of maps. The reported findings can be used directly for designing more efficient and more effective cartographic products. Eye tracking data can also be used for modeling the behavior of the user during the execution of specific map tasks (see e.g. the modeling approach followed by Dong et al. (2018)). Additionally, the development and the distribution of commonly available ground truth map-based eye tracking datasets can substantially contribute the implementation of artificial intelligence (e.g. machine and deep learning). Consequently, future maps and map services may be more “smart” and customized to meet users’ needs in different viewing conditions.

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