


Article

# Eye-tracking Evaluation of Weather Web Maps

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**Abstract:** Weather is one of the things that interest almost everyone. Weather maps are therefore widely used and many users use them in everyday life. To identify the potential usability problems of weather web maps, the presented research was conducted. Five weather maps were selected for an eye-tracking experiment based on the results of an online questionnaire: DarkSky, In-Počasí, Windy, YR.no, and Wundermap. The experiment was conducted with 34 respondents and consisted of introductory, dynamic, and static sections. A qualitative and quantitative analysis of recorded data was performed together with a think-aloud protocol. The main part of the paper describes the results of the eye-tracking experiment and the implemented research, which identify the strengths and weaknesses of the evaluated weather web maps and point out the differences between strategies in using maps by the respondents. The results include findings such as the following: users worked with web maps in the simplest form and they did not look for hidden functions in the menu or attempt to find any advanced functionality; if expandable control panels were available, the respondents only looked at them after they had examined other elements; map interactivity was not an obstacle unless it contained too much information or options to choose from; searching was quicker in static menus that respondents did not have to switch on or off; the graphic design significantly influenced respondents and their work with the web maps. The results of the work may be useful for further scientific research on weather web maps and related user issues.

**Keywords:** web maps; cartography; user issues; eye-tracking technology; weather; meteorology

## 1. Introduction

Maps have been popular for centuries, moreover, crafted for several millennia. With the development of technologies in the twentieth century, digital forms have become popular. At the beginning of the twenty-first century, a variety of web applications have gradually become modern trends and a regular part of everyday life. Web maps as another form of cartographic work have become popular [1,2].

Many people see the Internet as a revolution for cartography because of new approaches and new technologies. While previously published maps were tied to a paper medium and expensive large-format colour print technology and had limited distribution and use, the Internet has made it possible not only to distribute maps to a much larger audience but also to incorporate interaction and animation [3–5]. These maps are becoming progressively more suitable, as some traffic and weather maps are updated every few minutes [3].

Numerous web map studies have been performed. Research topics have varied from theoretical foundations to purely applied studies: how web maps provide users with information [6], how the use of web-based maps could be made easier for users [7], what problems are associated with web map design [8], what the usability problems are, and others [9–15]. In the conclusions of those studies, problems related to the map field are often mentioned. One of the most significant conclusions that

can be made is that a large number of web maps have a small map field and unnecessarily large web map controls or legends.

Many modern studies use the eye-tracking technology. Eye-tracking is used for usability tests, evaluation of interactive map interfaces [16], evaluation of animated maps of traffic flows [17], analyses of maps and plans [18], analyses of 3D geovisualizations [19], analyses of dynamic stimuli [20–24], and in general to evaluate the process of map reading and map use [25]. User studies in cartography provide enormous opportunities for further development of maps [26].

The research presented below focuses on the question of what problems users have with some of the most commonly used thematic maps on the Internet: weather web maps.

### 1.1. Weather Maps

Maps containing meteorological characteristics and meteorological data, generally known as “weather maps”, were selected for the study from a wide range of available web maps, the main reason for this choice being that these maps are considered complex visual displays [23] and are one of the most used thematic web maps.

The term “weather maps” loosely refers to any cartographic depiction of weather or weather-related phenomena, including climatic maps. There are four main types of weather web maps [24]. Maps in the first three categories (weather maps in a narrower sense, satellite image maps, and radar image maps) describe recent or current conditions in the atmosphere. The fourth type consists of maps that predict future conditions. The development of web maps has been enormous, and most weather web maps now combine all of these types.

Web maps may be static or dynamic. Each of these categories is further subdivided into view only and interactive maps [4]. The current trend is to use animation to show the natural development of weather. A method called semi-static animation was introduced by Nossum [27] using an example of temperature forecast for four days. The concept’s core was to make all information visually available to the user at any given time of the animation. The bottlenecks encountered in animated (web) maps are no longer because of hardware, software or data, but in the limited visual and cognitive processing skills of the map reader [28].

Semi-static and dynamic animations have been analysed in numerous studies [27,29]. Analysis of eye-tracking data revealed that the viewing behaviour of respondents for both map types (animation and semi-static animation) are surprisingly similar [30]. Weather maps have also been the subject of studies focusing on other issues, such as map reading and visual salience [23], communication issues concerning climate forecasts [31], and methods of cartographic visualization [32].

### 1.2. Geovisualization Methods

There is great variability in the range of maps produced, not only because of the potential availability of technologies. The differences are in the specifics of the presented phenomena, the chosen methods of cartographic expression, graphic design, and many other aspects.

The suitability of selected methods of spatial data visualization and particular implementations significantly affect a user’s ability to determine the correct information from a map. The quantification and evaluation of different factors affecting how information in a map is perceived by different user groups is the main task in many types of research [33–35]. Addressing modern trends in cognitive cartography and cartographic visualization methods can lead to insights in, and improvement to, cartographic production.

Methods of geovisualization represent a set of rules to express the spatial characteristics in a map. Methods of geovisualization are also described as cartographic visualization methods, methods of representation, means of expression, interpretive methods, graphical representation, mapping expression, and others. In most cases, they are not universally standardized, and the methods of geovisualization used generally depend on the personality and expertise of the author creating the visualization. Although there are a number of textbooks that describe map creation, approaches vary

and, thus, the map designs of individual cartographers also vary [36]. However, the approach is uniform in the evaluation of map symbology through visual variables, which describe the graphic dimensions across which a map or other visualization is varied to encode information [37]. The methods of cartographic visualization on weather web maps are analyzed and described in the selected weather web map sub-descriptions.

The spatial data visualization process (geovisualization) can result in different levels of processing of the final visualized product, from a simple data view (graphical representation of spatial data layers) to a map (cartographic visualization with all the features and compositional elements). While maps are produced for different target groups for different purposes and present many different topics, the approaches to geovisualization are also changing in many aspects [38]. One possible aspect is time. The preferred methods of geovisualization may differ in the various age groups of map-makers as well as age groups of target users. Differences also exist in national approaches and various cartographic schools. Nevertheless, the selection of appropriate geovisualization methods and appropriate parameters of each method is the main task for a person with an education in cartography.

To ensure the correct map communication goals, user testing should be conducted, complex, non-technological aspects, user and usability issues can be addressed and evaluated during the map production analysis.

There are fewer methods of cartographic visualization which express meteorological elements. A basic point method is used to visualize stations, measurement points or other point-located variables. Area symbols are also often used to visualize presented phenomena, because meteorological indicators have the characteristic of being continuous data and are mostly presented as continuous surfaces. The most used methods include isolines, graduated symbols (diagrams), points, line symbols, and areas (area patterns) [39].

The composition of weather web maps varies greatly. Some authors see an advantage in the most uncomplicated map composition with the most basic controls so that the map is not overcrowded with information or options and that users can work and control it as simply as possible, other authors attach more importance to very interactive maps with a complex composition and large number of controls and visualization options [4,5,16,40].

The primary objective of the study presented in this article is to analyse how web-based weather maps are used and perceived. Only design aspects were evaluated, not the accuracy of the predictive model, rate of data update or other aspects. A more detailed analysis of weather web map functionality and interactivity may be considered for future work. The results of the presented research may be useful to ordinary users or for further scientific research on web maps and related user issues.

## 2. Materials and Methods

### 2.1. Materials – Description of Selected Web Maps

Many web portals contain web maps with meteorological content. These include Windy, In-Počasi, DarkSky, Wundermap, YR.no, PovodnovyPlan, Meteoeearth, Ventusky, Meteoblue, Rainviewer, Weather, and many others. Web maps, portals, and weather apps take different forms. For the most part, they have very similar content; namely the visualization of meteorological phenomena. Some maps contain a large number of thematic layers and some contain only basic meteorological indicators, such as temperature, precipitation, wind or frontal systems.

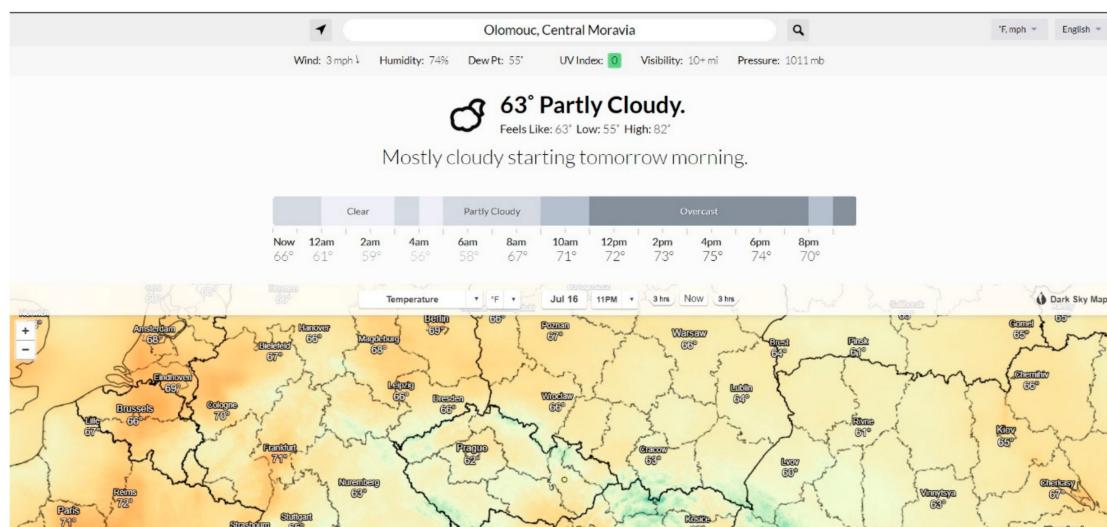
For the eye-tracking experiment, five web weather maps were selected. No study was found with a complete comparison of weather maps, even though weather web maps are widely used by the public almost every day. Their use is not limited by previous knowledge or expertise and they can be used by almost anyone. The evaluated maps were: DarkSky (<https://darksky.net/>), Windy (<https://www.windy.com>), In-Počasi (<https://www.in-pocasi.cz>), YR.no (<https://www.yr.no/kart>), and Wundermap (<https://www.wunderground.com/wundermap>). This number was selected so that

the time required for the entire experiment did not exceed 30 minutes and to minimize the fatigue and disorientation experienced by respondents.

The set of the evaluated web maps was designed so that the selected weather web maps included both foreign and Czech web-based weather maps and maps both known and unknown to the public. Our laboratory conducted an online survey to gauge the familiarity of a Czech audience to a range of web-based weather maps, both of Czech and foreign origin. Of 140 respondents, 34% indicated that they commonly use weather maps. The three most frequently indicated weather web maps were YR.no, In-Počasí, and Windy. Due to their differences in visualization methods, the less commonly used maps, DarkSky and Wundermap, were also selected for testing. These maps are not all representatives of the different types of maps, but as described, they are the three most frequently used maps (according to online survey) and two maps that the respondents know but do not ordinarily use.

### 2.1.1. Dark Sky

DarkSky (Figure 1) is a start-up established in 2011 in England and includes web and mobile weather forecast applications for the world. The map is directly loaded, and the composition is organized into horizontal blocks. A search field and basic information about the location the user is looking for is at the top, with the current meteorological indicator values and a timeline. The next block is a map with additional graphs and temperature forecasts for the coming days. Switching thematic layers is easily accessed in the popup menu. The application contains data about temperature, wind speed and direction, clouds, precipitation, dew point, UV index, ozone, and a layer with emoticons. The application is simple and has no advanced map features compared to the other evaluated sample weather web maps.



**Figure 1.** DarkSky map preview. The map has a simple composition, highlighting the basic information based on the location that is in the top field. The sample map in the preview is presenting temperatures.

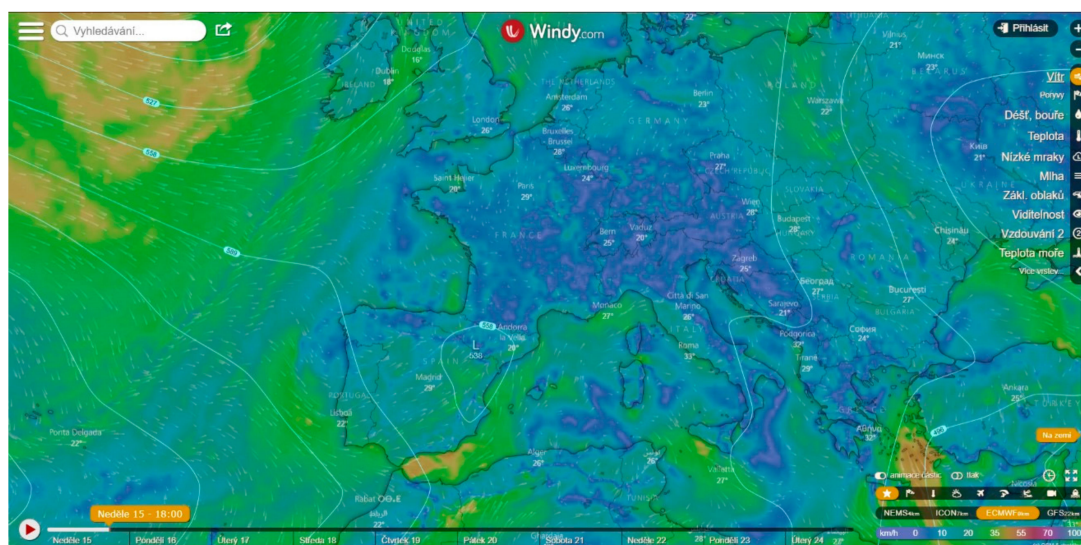
Area patterns combined with the isoline method are implemented in this map. One thematic layer also offers emoticons in the point method. The map does not contain a legend. Methods are used correctly; nevertheless, a legend is missing. The application's design is simple and easy to use.

### 2.1.2. Windy

Windy (Figure 2) is an application developed by the Czech company Seznam.cz and is very detailed. For example, a user can choose his or her particular altitude. The map contains up-to-date weather information and forecasts for nine days. The map is loaded directly and has all controls in the



map field. The composition is divided into four distinct areas: search, timeline, display options menu, and information menu. The layout of controls is logical and intuitive.



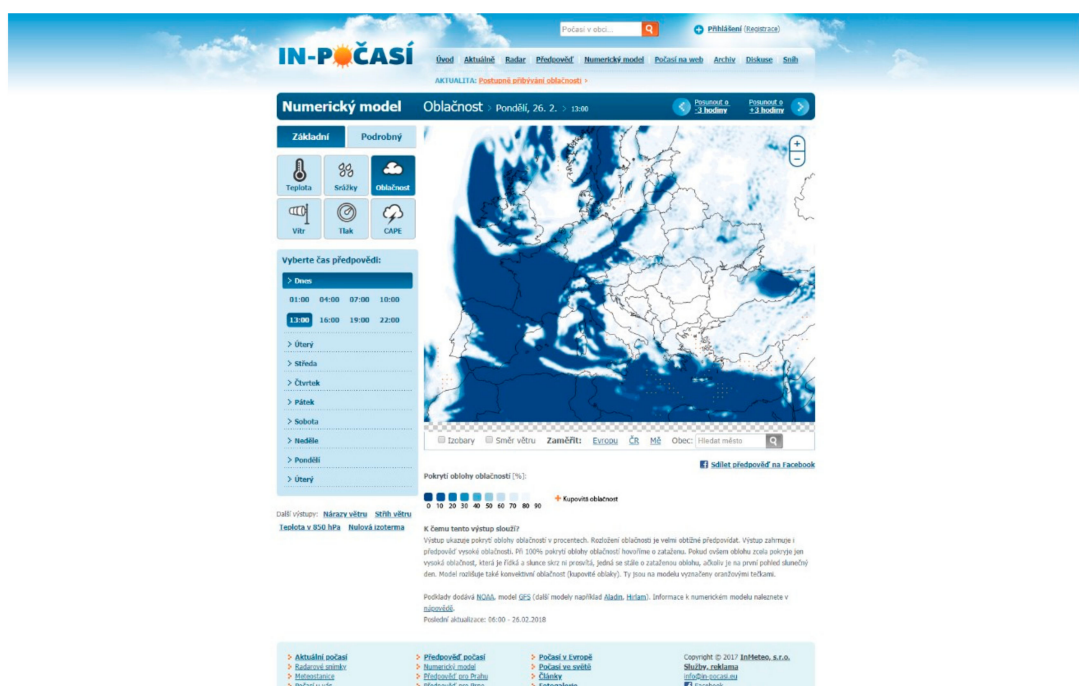
**Figure 2.** Windy map preview. The map has a composition divided into logical elements (search, timeline, display options, information menu). The sample map in the preview is presenting temperatures.

The map offers many options, for example, a wind conditions view for surfing, kiting and paragliding. The user can also choose layers for different activities (not only sports), such as aeroplane cloud elevation, sea currents for boats and snow elevation for skiers. It allows the user to choose the prediction model to calculate the prediction. Isoline and area pattern methods are used. The legend is in the lower-right corner of the map field.

### 2.1.3. In-Počasí

The In-Počasí web portal (Figure 3) is produced by the Czech Hydrometeorological Institute and contains a detailed weather forecast for the Czech Republic and a less detailed forecast for Europe. The portal is extensive and contains abundant weather information, including a map showing six meteorological phenomena in partial thematic layers. The map design is simple and intuitive. The composition of the map is balanced. At the top is a date bar with thematic layer information, while the section at the left allows thematic content and time options to be set. Below the map is a legend and supplementary information. Map controls are located outside the map field. The map does not show any interactive elements.

Only the isolines method is used, and it is used correctly. The only exception is the use of a colour scale, which can sometimes be confusing to users; the presented amount of cloud cover is maximum in white and minimal in dark blue colour, which is not usual. The legend is located below the map field.



**Figure 3.** In-Počasi map preview. The map is part of a web-page layout and has additional controls as web-page composition elements. The sample map presents the amount of cloud cover.

#### 2.1.4. YR.no

YR.no (Figure 4) is a Norwegian web portal and mobile app, including a map showing weather information. The user can choose to see the weather in the form of text, symbols, and diagrams or as a map. The meteorological map is available for Europe and Asia. The map's composition is divided into three areas: a layer switching menu, timeline, and the top bar dedicated to search.



**Figure 4.** YR.no map preview. The map composition elements are clearly graphically separated. The sample map presents the cloud coverage and precipitation.

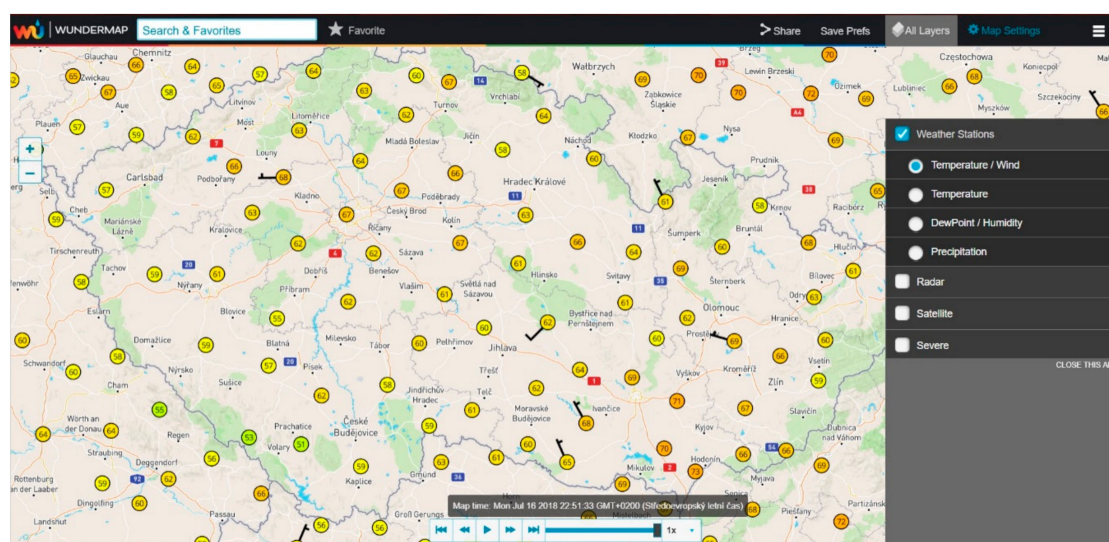
Controls are embedded in the map. Switching thematic layers is different for Nordic countries and the rest of the world. Besides the basic meteorological indicators, other indicators are available,

for example, UV radiation, sea currents or wave heights. Advanced and special features are not provided.

The main method used is the isoline method, which is deployed correctly, and the legend is well placed. The overall simple design permits easy searching. A positive feature of this web map is its interactivity when searching for interest areas—other charts and forecasts with relatively detailed values are displayed in this map. The disadvantage of this map is the difference in detail when displaying data for either Nordic countries or the rest of the world.

### 2.1.5. Wundermap

Wundermap (Figure 5) is produced by German Weather Underground. The map is loaded directly and the data are provided for the whole world. The page is divided into several blocks that are somewhat chaotically deployed: at the top is a search box and a button for sharing or switching on/off the thematic layer menu, in the right corner is a panel to control the thematic layers themselves, at the bottom is the timeline. Controls are standard and located in a menu at the edge of the map.



**Figure 5.** Wundermap map preview. The map has a simple composition with switching between the tabs (all layers, map settings). The sample map presents the temperature and wind.

The map contains both basic and advanced map features, although the thematic content is not interpolated, and the point method is used for “weather stations”, which are irregularly scattered across the displayed territory. The map legend is hidden in the map settings tab and is incomplete.

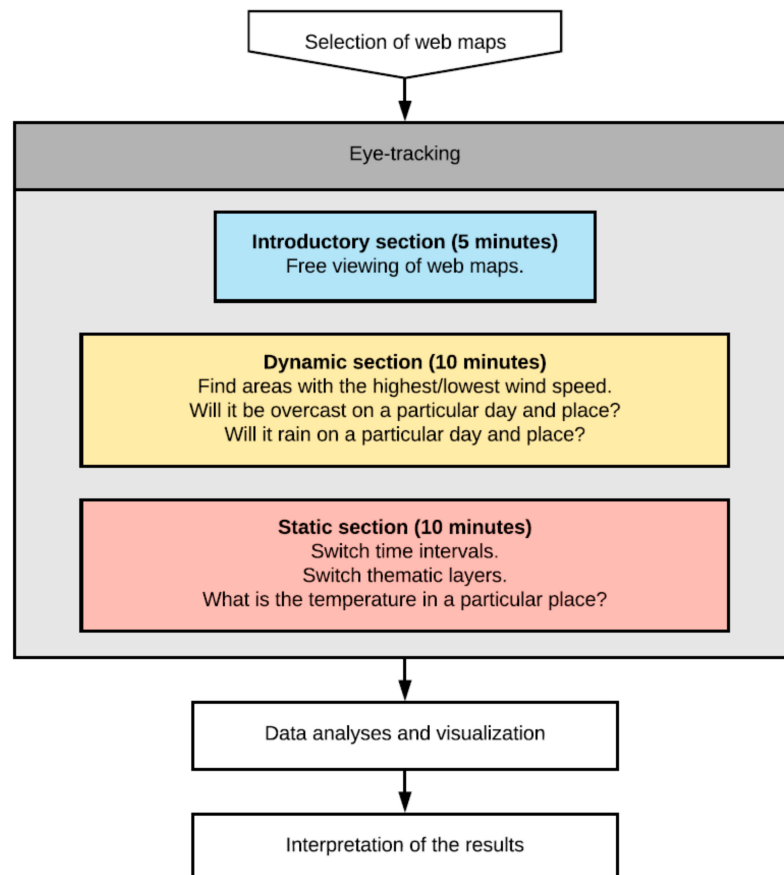
### 2.2. Methods

The five maps described above were tested in an eye-tracking experiment complemented by think-aloud analysis. The eye-tracking experiment was performed at the Department of Geoinformatics, Palacký University Olomouc, Czech Republic, between 19 February 2018 and 23 March 2018. The eye-tracking laboratory is specifically designed for conducting eye-tracking experiments and is equipped with an SMI RED 250 eye-tracker with an operating frequency of 250 Hz. The eye-tracking data recordings were supplemented by audio and video recordings of the respondents. These data were used for further think-aloud analysis. When the eye-tracking experiment was completed, the results were analysed, evaluated and interpreted.



### 2.2.1. Design of the Experiment

The SMI Experiment Center™ software was used to design the experiment. The eye-tracking test was divided into introductory, dynamic and static sections (Figure 6).



**Figure 6.** Map evaluation process.

The introductory section consisted of free viewing of selected web maps, one minute for each map. Users could work with the map and learn about its functionality. This section took five minutes. In the dynamic section, each map always had three questions (three rounds of questions for five evaluated weather maps). This section of the test was designed to take no more than ten minutes. Questions in each round were defined differently for each web map so that the respondent was prevented from memorizing the correct answer and forced to work with the evaluated weather web map. The dynamic section of the test was presented “live” – so each respondent saw different weather pattern because they were looking at different days.

The static section of the test also provided three rounds of questions and was designed to take no more than ten minutes. In static testing, the respondent was prevented from interacting with the elements in the map and could only view the static image (screenshot) of the evaluated weather web map. For the last question (*what is the temperature in a particular place?*), locations were changed so that respondents did not memorize the answer.

The first round of questions in the dynamic section addressed wind speed. The respondent was required to answer two questions concerning which area of the Czech Republic currently had the highest or lowest wind speeds. The second round of questions consisted of five questions concerning cloud cover. Respondents were asked to respond whether clouds were at a specific location and time. Questions in the third round concerned precipitation. The respondents answered whether rain would occur at a particular place and time.

The questions were defined so that users had to switch thematic layers, use the search or scroll map, switch timelines and be able to work with the legend in order to answer them correctly. Responses were recorded using a webcam with audio recording and logging of mouse clicks. The test was not devised to elicit the correct answer but to analyse how users worked with the map and whether they could find the required features to accomplish the task. The correctness of the response was therefore only an accompanying indicator of whether the user had correctly understood the phenomenon displayed.

As mentioned, the static section of the test also had three rounds of questions and took no more than ten minutes. The difference between static and dynamic testing is significant. In static testing, the respondent was not permitted to interact with the elements in the map and could only view the static image (a screenshot clip) of the evaluated weather web map. This type of testing cannot be used to determine whether a user can actively use a web map as a whole. Static testing evaluates whether a user understands the phenomenon and can find the basic web map controls and understand the map layout.

The respondents were asked the same questions about all web maps. Respondents were required to indicate in the static picture where to switch the weather forecast to another day, where to switch thematic layers, or to answer what the temperature was at a given location. For these questions, each map presented was of a different location to prevent the user from memorizing the same answer.

### 2.2.2. Respondents

Web maps showing the weather and phenomena associated with weather are usually up to date and accessible to anyone. The target user group of these maps is therefore extensive and not limited by age, employment, literacy or nationality. Weather information is available to everyone around the world. This suggests that weather web maps should be adapted to a large number of user groups. Therefore, the user interface of a weather web map and level of adaptation to user needs should be tailored to the comprehensive needs of different target user groups.

Testing was therefore targeted at multiple user groups. Thirty-four respondents participated in the eye-tracking experiment (14 males and 20 females, median age 23 years). These respondents were separated into two groups of users: novices (16) and experts (18). Students who had not studied Earth Sciences and other respondents without a more in-depth knowledge of meteorology, geoinformatics or cartography were included in the group of novices. This separation may not always be tangible. Nevertheless, a non-geographic student may understand maps and have more experience than a student in Earth Sciences. For a more reliable separation, respondents were asked whether they had any previous experience with web maps, and if so, were included in the expert group. All respondents were from the Czech Republic or Slovakia and the instructions were in Czech. The respondents participated in the study voluntarily and were not paid for the experiment.

To obtain representative test results, testing a predetermined number of respondents is appropriate. This number depends on the nature of the test data, specifically on the number of problems that may arise when solving tasks. Therefore, ten users were tested in the first stage and six problems were identified during testing, these being difficulties in navigating the web map, inability to find an answer without assistance, a poorly recognizable colour scale, inability to find where to switch thematic layers, misunderstanding of the presented phenomena, and inability to find where to switch time intervals.

The online calculator *MeasuringU* [41] ([https://measuringu.com/problem\\_discovery/](https://measuringu.com/problem_discovery/)), which calculates an estimated sample size from the given occurrence of problems, was used to help estimate the ideal number of respondents. This calculator is based on normalization and the binomial probability equation. Problems recorded from the sample of respondents (in this case, the first ten respondents) were entered into the matrix. The calculator estimates how many respondents would be appropriate for testing to detect at least 99% of the problems encountered (Figure 7). In this case, the result was 26 respondents. As mentioned above, a total of 34 respondents participated in the test, which was more than recommended.



Input	Results
Discover <input type="text" value="99%"/> of all Problems.	Given <b>15</b> total problems and <b>2</b> unique problem(s), the adjusted problem occurrence is <b>0.16</b> . Which is the avg of Normalization: 0.14 and GT: 0.18  For the goal of discovering <b>99%</b> of all problems available for discovery, the recommended sample size is <b>26</b> participants.
Total participants <input type="text" value="10"/>	
Problems Discovered: <input type="text" value="6"/>	
<input type="button" value="Build Matrix"/>	

**Figure 7.** Estimated number of respondents based on the occurrence of problems (MeasuringU).

### 2.2.3. Analytical Methods

Before the recorded data were statistically evaluated and analysed, data pre-processing was performed. This included a data check and quality control and the exclusion of respondents where a recording error appeared during the experiment. DataLoss, or a percentage of incorrectly measured records, was less than 1%, and the rated data, therefore, retained a high reporting value, as only two user records were removed from the experiment. Fixations and saccades were identified using the I-DT algorithm with dispersion = 80 px and duration = 50 ms. Popelka [42] explains this setting in more detail.

The first step of data analysis was to evaluate the accuracy of respondents' answers. This analysis was not straightforward. In the first task of the dynamic section of the experiment, answers were recorded by clicking on the map. The analysis of this kind of data was a lengthy process. Testing was performed over several weeks and with screen recording (dynamic eye-tracking test). The data displayed on the weather map were therefore continually updated, and each respondent saw different values. The accuracy of answers in the dynamic section was done manually based on recorded videos or using notes created during the testing.

The eye-tracking experiment was divided into three parts– the introductory test section, dynamic test section and static test section. The methods of analyses vary due to the different nature of the recorded data in these three parts.

In the Introductory Section of the experiment, the results were gained based on the video recordings of respondents' work with the map overlaid by eye-movements. After viewing all recorded videos, a fundamental insight applying to all the web maps used in the experiment was gained.

Processing the results of the Dynamic Section was very time-consuming, as it was necessary to analyse data using dynamic Areas of Interest. Since each respondent worked with the map individually, dynamic Areas of Interest were created for each web map and each respondent separately. These areas of interest (AOIs) were: map fields, timer switching, switching of thematic layers and other information such as legends and supplementary charts. These layers were not active throughout testing and appeared according to how respondents clicked on them. Creation of dynamic AOIs is highly time-consuming, so only six respondents were chosen for this type of analysis. Data were visualized using Sequence Chart method, which displays each respondent's eye-movement data in time as rows. The colour of these rows corresponds to the visited AOIs.

Analysis of the Static Section was much easier, since all respondents were looking on the same stimuli – screenshots of the web maps. The first method, called Gridded AOI is implemented using the open-source OGAMA. The image was divided into a regular grid, each grid segment displaying how many fixations were recorded there.

Another method utilized in eye-movement data visualization is called FlowMap and is implemented in V-Analytics software. FlowMaps use Thiessen polygons generated based on the fixation distribution. Arrows between these polygons display the number of moves between them.

ScanGraph was another method used to study the above task. This method was developed to identify differences in the stimulus reading strategy of different groups of respondents [43]. Before analysing the data, areas of interest over the stimulus must be created and marked, for example, A, B, C, etc. The Scanpath of each respondent can then be replaced by a string of letters expressing the order of the visited areas of interest. ScanGraph calculates the similarity of these strings by employing three different algorithms: Levenshtein distance, Needleman-Wunsch algorithm and Damerau-Levenshtein distance. Individual respondents are visualized as nodes in the graph, and ScanGraph searches the so-called “cliques” in this graph - a group of respondents who are similar to each other at least to a specified degree. The tool can be used to determine, for example, whether the stimulus was read differently by men and women or experts and novices.

Both the Dynamic and Static Sections were also analysed statistically using the Wilcoxon rank sum test, since the data did not have a normal distribution. Statistically significant differences are marked by an asterisk in the figures below. We chose three eye-tracking metrics to analyse data – Trial Duration, Fixation Count and Scanpath Length. Description of these metrics and their meanings is in Table 1.

**Table 1.** Description of the eye-tracking metrics used and their meanings.

Trial Duration	Longer time needed to solve a task indicates a problem with user interface or higher complexity of the task.
Fixation Count	A higher number of fixations indicates a low level of search efficiency or an inappropriate user interface of the evaluated application [44].
Scanpath Length	A longer scanpath indicates less efficient searching (perhaps due to a sub-optimal layout) [45].

In addition to eye-tracking, the Think-Aloud method was also used to analyse respondents’ behaviour during the experiment. Unfortunately, the majority of respondents had problems with verbalizing their actions. They were therefore given the required silence during testing to fully concentrate. For this reason, the Think-Aloud method was only employed with some of the more experienced respondents.

### 3. Results

#### 3.1. Accuracy of Answers

The first step in evaluating the eye-tracking experiment was to analyse the accuracy of respondents’ answers. All responses recorded during the test are listed in Table 2.


The first task of dynamic testing was to identify areas with the highest or lowest wind intensity by clicking on the map. From the table, it is evident that this task was highly problematic in the case of Wundermap. The information about wind speed is combined with the information about the temperature. Temperature was expressed by colour and number (degrees), but the wind speed was displayed using the symbol shape. This was confusing for the respondents. For the rest of the maps, fewer users responded with incorrect answers.


In the second and third task of the dynamic testing, respondents answered whether it would be cloudy (task 2) or rainy (task 3) in a particular place. It was found that if respondents knew how to find the answers, their responses were correct in most cases. In Table 1, red indicates situations when a respondent chose the wrong answer or gave up (chose to answer the question with “No Answer”). The bold in the table refers to situations when a little assistance from the researcher was needed. The most significant problems in tasks 2 and 3 were encountered with the Wundermap map, in which respondents were not able to orient themselves.


**Table 2.** Responses to questions and tasks given by the respondents in the dynamic and static sections of the test. Green indicates correct answers, red is incorrect answers, and bold plus exclamation mark indicates answers where a small amount of assistance was required.

	Dynamic part															Static Part														
	Task 1					Task 2					Task 3					Task 1					Task 2					Task 3				
Participant	Darksky	Windy	Impocasi	YR.no	Wundermap	Darksky	Windy	Impocasi	YR.no	Wundermap	Darksky	Windy	Impocasi	YR.no	Wundermap	Darksky	Windy	Impocasi	YR.no	Wundermap	Darksky	Windy	Impocasi	YR.no	Wundermap	Darksky	Windy	Impocasi	YR.no	Wundermap
P01	OK	OK	OK	OK	X	YES	YES	YES	YES	YES	NO	YES	NO	NO	NO	OK	OK	OK	OK	X	OK	OK	OK	OK	OK	NA	NA	-8	-3	21
P02	OK	OK	OK	OK	X	YES	YES	NO	YES	X	NO	NO	NO	YES	X	OK	OK	OK	OK	X	OK	OK	OK	OK	OK	16	-9	-6	-4	16
P03	OK	X	OK	X	X	YES	YES	NO	YES	X	NO	NO	NO	YES	X	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	18	-9	-6	-4	20
P04	OK	X	OK	OK	X	YES	YES	YES	YES	YES	NO	NO	NO	NO	YES	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	18	-9	-6	-1	19
P05	X	X	X	OK	X	YES	YES	YES	YES	X	YES	NO	NO	YES	X	X	OK	OK	OK	X	OK	OK	OK	OK	OK	21	-9	-6	-3	16
P06	X	OK	X	X	X	NO	YES	YES	NO	YES	NO	NO	NO	YES	NO	X	X	OK	OK	X	OK	OK	OK	OK	OK	20	-9	-30	-5	20
P07	OK	OK	OK	X	X	NO	NO	NO	NO	X	NO	NO	YES	YES	X	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	18	-9	-6	-3	20
P08	OK	OK	OK	X	X	NO	NO	NO	NO	NO	NO	YES	NO	NO	NO	OK	OK	X	OK	OK	OK	OK	OK	OK	OK	18	-11	-15	-2	19
P09	OK	OK	OK	OK	X	YES!	NO!	NO	NO	X	NO	YES	NO	YES	X	X	OK	OK	OK	OK	OK	OK	OK	OK	OK	18	-9	-15	-8	16
P10	X	OK	OK	OK	X	YES	NO	NO	YES	X!	NO	YES	YES	YES	NO	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	22	-9	8	-3	20
P11	OK	OK	OK	OK	X	NO	NO	NO	NO	X	NO	X	YES	YES	X	OK	OK	X	OK	X	OK	OK	OK	OK	OK	18	-9	-15	-4	20
P12	X	OK	OK	OK	X	NO	NO	NO	X	NO	NO	NO	YES	YES	X	OK	OK	X	OK	OK	OK	OK	OK	OK	OK	18	-9	-4	-3	21
P13	OK	X	OK	OK	X	YES	YES	NO	NO	NO!	NO	NO!	YES	NO!	X	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	21	-9	-6	-3	21
P14	OK	OK	OK	OK	X	YES	YES	NO	NO	X!	NO	YES	YES	NO	NO	OK	OK	X	OK	X	OK	OK	OK	OK	OK	18	-9	-4	-4	21
P15	OK	OK	OK	OK	OK	YES	YES	YES	X	X	NO	NO	YES	NO	X	OK	OK	OK	OK	X	OK	OK	OK	OK	OK	18	-9	-15	-3	21
P16	OK	OK	OK	OK	OK	YES	NO	YES	NO	X	NO	YES	YES	YES	X	OK	OK	OK	OK	X	OK	OK	OK	OK	OK	18	-9	-15	-9	19
P17	OK	X	X	OK	X	YES	YES	NO	NO	X	NO	NO	NO	NO	X!	OK	OK	OK	OK	X	OK	OK	OK	OK	OK	20	-9	-6	-4	16
P18	OK	OK	OK	OK	X	NO	NO	NO	NO	X!	NO	NO	YES	NO	X	OK	OK	OK	OK	X	OK	OK	OK	OK	OK	20	-9	-6	-3	19
P19	OK	OK	X	X	X	YES	NO	NO	NO	X	NO	NO	YES	YES	X!	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	22	-9	-4	-4	20
P20	OK	OK	OK	OK	X	YES	NO	YES	YES	NO	YES	NO	NO	YES	X	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	18	-9	-6	NA	23
P21	OK	OK	OK	OK	OK	NO	NO	YES	YES	X	YES	YES	YES	NO	NO	OK	OK	X	OK	OK	OK	OK	OK	OK	OK	18	-9	-8	-4	18
P22	OK	OK	OK	OK	OK	NO	NO	NO	NO	YES	NO	YES	YES	NO	X	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	18	-9	-6	-4	19
P23	OK	OK	OK	OK	X	YES	YES	YES	NO	YES	YES	NO	YES	X	X	OK	OK	OK	OK	X	OK	OK	OK	OK	OK	18	-9	-6	-3	19
P24	OK	OK	OK	OK	X	NO	NO	NO!	YES	X!	X	YES	YES	YES	X!	OK	OK	OK	OK	X	OK	OK	OK	OK	OK	NA	-9	-6	-3	16
P25	OK	OK	X	OK	OK	YES	NO	X!	YES	X!	YES	YES	YES	YES	X!	OK	OK	OK	OK	X	OK	OK	OK	OK	OK	23	-9	-6	-3	19
P26	OK	OK	OK	OK	X	YES	YES	YES	YES	X!	NO	YES	YES	YES	X!	OK	OK	X	OK	OK	OK	OK	OK	OK	OK	2	-9	-15	-3	20
P27	OK	OK	OK	OK	X	YES	YES	YES	NO	X!	NO	YES	YES	NO	X!	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	21	-9	-6	-4	16
P28	OK	X	X	OK	X	NO	NO	YES	YES!	X!	YES	NO	YES	YES	X!	OK	OK	X	OK	X	OK	OK	OK	OK	X	16	-9	-8	-3	16
P29	OK	OK	OK	OK	X	NO	NO	YES	NO!	X	NO	NO	NO	NO	X!	OK	OK	OK	OK	X	OK	OK	OK	OK	OK	24	-9	-6	-3	21
P30	OK	X	OK	OK	X	YES	NO	YES	YES	X	NO	YES	YES	YES	X	OK	OK	OK	OK	X	OK	OK	OK	OK	OK	18	-9	-4	-3	16
P31	OK	OK	OK	OK	X	YES!	NO!	YES!	NO!	X!	NO!	NO!	NO!	YES!	X!	OK	X	OK	OK	X	OK	OK	OK	OK	OK	21	-9	-6	0	21
P32	OK	OK	OK	OK	X	NO	YES	NO	YES	X!	YES	YES	NO	YES	NO!	OK	OK	OK	OK	X	OK	OK	OK	OK	OK	21	-9	-8	-4	16
P33	OK	OK	OK	OK	OK	NO	YES	X!	NO	X!	NO	NO	YES	YES	X!	OK	OK	OK	OK	X	OK	OK	OK	OK	OK	18	-9	-15	-3	16
P34	OK	X	OK	OK	X	YES	NO	YES	NO	X!	NO	YES	YES	YES	X!	X	OK	OK	OK	X	OK	OK	OK	OK	OK	23	-9	-6	-3	18
Correct	30	26	28	29	6	34	34	32	32	9	33	33	34	33	8	30	33	27	34	14	34	34	34	34	33	16	32	17	27	0
Wrong	4	8	6	5	28	0	0	2	2	25	1	1	0	1	26	4	1	7	0	20	0	0	0	0	1	18	2	17	7	34
LEGEND		<div><div></div>Correct answer</div>										<div><div></div>Wrong answer</div>										<div><div></div>Bold</div>		Assistance needed						

## LEGEND

 Correct answer

 Wrong answer

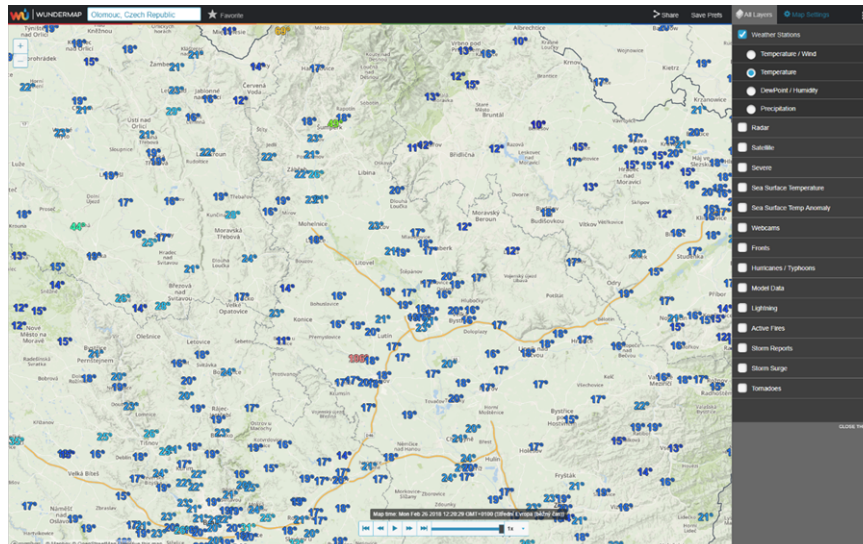
 Assistance needed

In the Static section of the experiment, respondents were required to first indicate where the time interval on the map could be switched (task 1). To evaluate the correctness of the responses, areas of interest in the stimulus around the correct answers had to be created to detect whether respondents had clicked on the field. The most significant problems again occurred with Wundermap (Figure 8). In the second question, respondents were required to indicate where the thematic layer could be switched. In this situation, almost all of the answers on all maps were correct; only one respondent (P28) on the Wundermap answered incorrectly. In the final question of the static section, respondents answered what temperature it would be at certain times in certain cities.

It was immediately apparent that users had the most significant problems finding the correct answers in the Wundermap weather web map; all the respondents' answers were incorrect due to the unreadability and misstatement of the presented phenomenon. The authors of the map had chosen an inappropriate cartographic method for visualizing temperature, and respondents were not able to state the temperature in a given city with any certainty. Figure 8 shows a screen capture of the Wundermap in which test respondents were asked to find the temperature in Olomouc.

Most of the respondents correctly responded to the tasks on YR.no and Windy weather web maps and could orient themselves to find the correct answer quickly. On the In-Počasi web map, respondents had problems finding the interval to which the correct answer belonged. The colour range of the

displayed values is extensive, and the colour spacing between individual colours is difficult to discern. Respondents found it difficult to assign the colours depicted on the map to the correct interval in the legend. On the DarkSky web map, respondents had to make a greater effort than on previous maps to find the temperature, which was not highlighted in the map but only indicated in the information text located above the map field.



**Figure 8.** Image of the Wundermap weather web map from the test.

### 3.2. Eye-tracking Results

#### 3.2.1. Introductory Test Section Results

As described above, the first part of the eye-tracking test was free viewing of selected weather web maps. In this section, respondents were required to view the maps they would work with throughout the test in five minutes. This section was not evaluated in detail, as it was aimed at orientating primary users with the selected web maps. For this task, only the essential characteristics of each evaluated web map were summarized and are explained below.

Respondents in the novice group worked differently with the maps. Novices viewed the map itself, zoomed in on their place of residence, viewed the contents of the map and then focused on switching thematic layers, etc. Respondents in the group of experts, however, immediately focused on map functionality after the maps were loaded. They looked for available thematic layers, switched timescales and attempted to find out whether it was possible to switch units where the forecast was displayed and whether it was possible to look into the legend. These basic findings confirmed the appropriate separation of respondents into groups of novices and experts. More than 70 percent of respondents thus had typical behaviors corresponding to their inclusion in the group of novices/experts, and less than 30 percent of respondents did not demonstrate this typical behavior.

During free viewing of the DarkSky web map, respondents focused mainly on switching thematic layers, switching the time for displaying the forecast and observing the headline of the web map, where the current temperature was written with large digits (set by default to Fahrenheit). While browsing, respondents had no problems finding basic controls.

The Windy web map is the most attractive at a glance. Each respondent navigated differently through the map, as it was possible to select and display many different thematic layers and show different units and time intervals. The possibilities are almost countless, and respondents, therefore, moved around the map field with considerable difference. Interestingly, most respondents used the mouse wheel to zoom in/out, not the button specified in the map box.



Respondents did not encounter any problems while viewing the In-Počasi web map. Control and understanding of the map were intuitive, and free viewing therefore did not present any unexpected conclusions. Test respondents attempted switching thematic layers, zooming in and out, switching predictions and looked for primary or detailed viewing.

Free viewing of the Norwegian web map YR.no also demonstrated that respondents had no problems handling the map. As in other maps, they attempted basic web map control. Some respondents selected interactive map features, mainly graphs showing additional weather information. The unique feature of this map is the possibility of displaying different thematic layers for Scandinavian countries than other European countries. No peculiarities in controlling the map were observed.

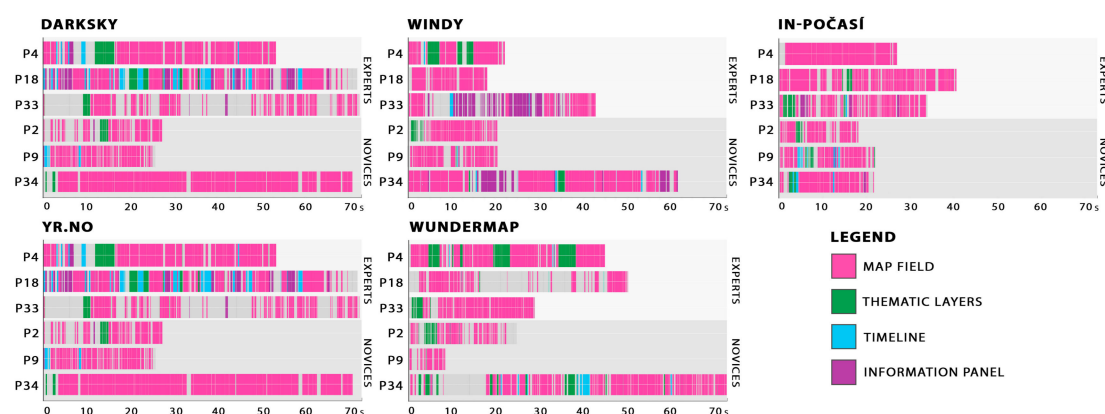
As the final map in the free viewing section, the Wundermap web map provided the most significant difficulties for respondents. All of the respondents attempted switching thematic layers, but over 50% experienced problems with loading thematic layers (slow loading of content during zoom in/out). Problems were also encountered with switching prediction timing, and some respondents mentioned that they did not understand the method of data visualization, suggesting that their interpretation of the map's information was problematic.

No unpredictable conclusions were discovered from the free viewing. Respondents always explored the basic functionality of the web maps, how to control them and the possibility of displaying thematic layers or additional functions. As mentioned above, the main reason for the free viewing section was to for respondents to gain familiarity with the maps. Respondents who had worked with web maps previously (experts) focused more on the functionality of the web map and the display options the web map offered. By contrast, users with less experience of web maps (novices) were primarily interested in the map's content (viewing places on the map or attempting to find their place of residence).

### 3.2.2. Dynamic Test Section Results

The dynamic section of the eye-tracking experiment immediately followed the introductory section. The objective of this section was to monitor and identify how respondents worked with the maps, whether they used all the available elements, used the map interactively or otherwise. In this part of the test, each web map consisted of three tasks.

The first task required: *Locate and click to highlight the area with the lowest/highest real-time wind speed in the Czech Republic*. This question was evaluated by creating dynamic AOIs and then visualized using an AOI Sequence Chart. Sequence Charts were created for six respondents—three experts and three novices. In the following charts (Figure 9), six respondents and their work with the web maps to find an answer to the given question can be seen. One chart was created for each test web map.



**Figure 9.** Areas of Interest (AOI) Sequence Chart for all evaluated maps for six selected respondents (selection of illustrative examples).



While searching for a solution to this task, respondents spent the most time on the DarkSky web map. Novices had significantly longer response times than experts (except P34) (Figure 9). P34 was not sure of the answer and thoroughly explored the map to properly identify the place he wanted. All of the maps showed that experts needed much less time to find the answers than novices. Ideally, a respondent would orient themselves, look into the thematic layers, activate the thematic layer for wind and then look back to the map field to find the desired area, i.e., depicted in a sequence of pink-green-pink colours. This sequence was observed for the YR.no web map, where searching was most effective. If several colours alternated in the graph in succession, it indicated that the respondent was confused about finding the correct answer on the screen or that the map controls were inappropriately divided. The AOI Sequence Chart of a Wundermap web map could be misled by assuming that searching on this map would be efficient and fast. However, in reality, it was different. Respondents mentioned that searching on this map was too complicated and did not even attempt to locate the right answer on it.

In addition to visualizing the Sequence Chart of selected respondents, three eye-tracking metrics were analysed—Fixation Count, Trial Duration and Scanpath Length. In all three cases, the identified trend was similar. The In-Počasi web map offered the fastest solution, respondents very quickly finding the button to switch to the thematic layer for wind information and reading the scale colour. The least effective in terms of Scanpath Length, though, were observed with the Wundermap web map, where information about wind speed and direction was incomprehensible. Surprisingly, a relatively low Scanpath Length value on the Windy web map was observed (Figure 10). Wind speed and direction information in this map are processed in a very detailed way using animation. Therefore, the solution to the given task was more demanding than in a static visualization. It is important to note that wind information was presented in a much more detailed and accurate manner than information in other maps on the Windy web portal.

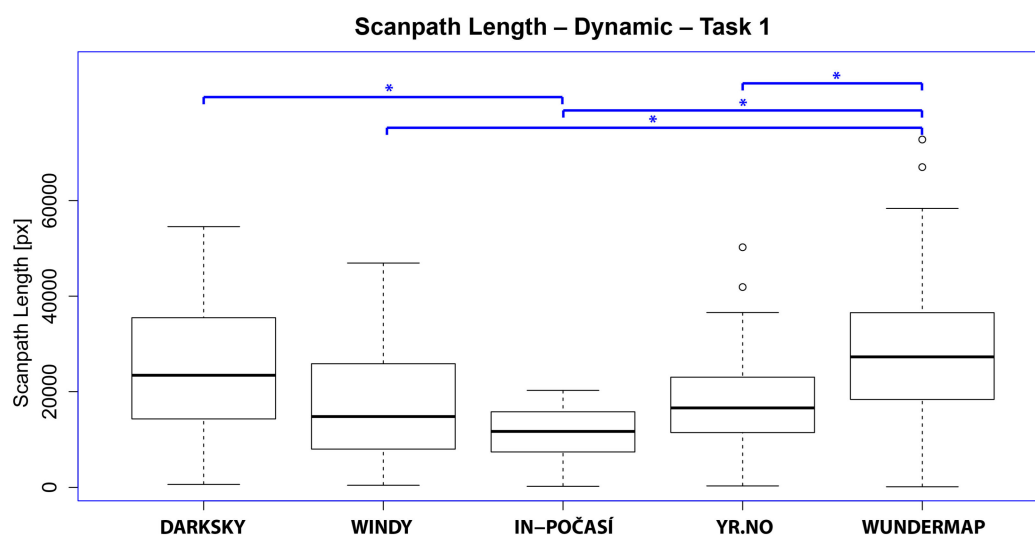
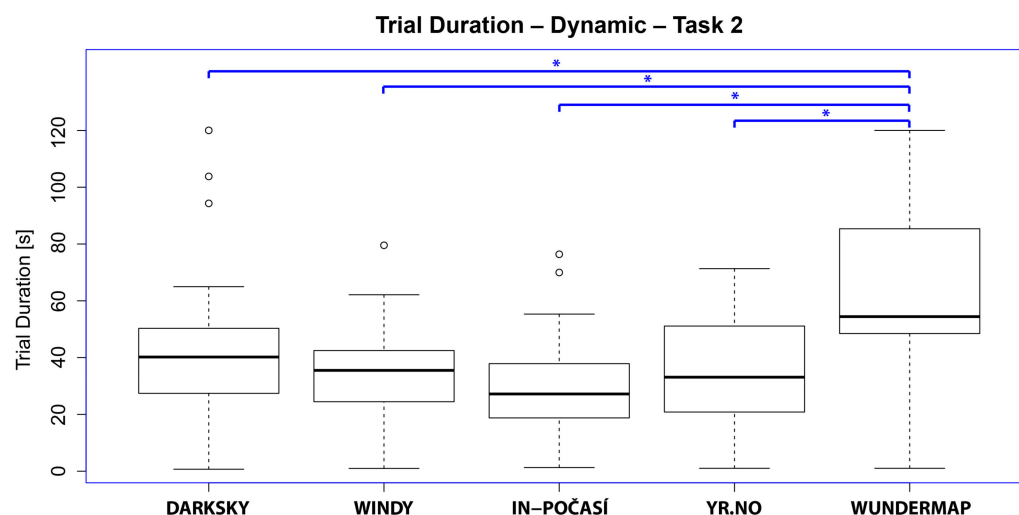


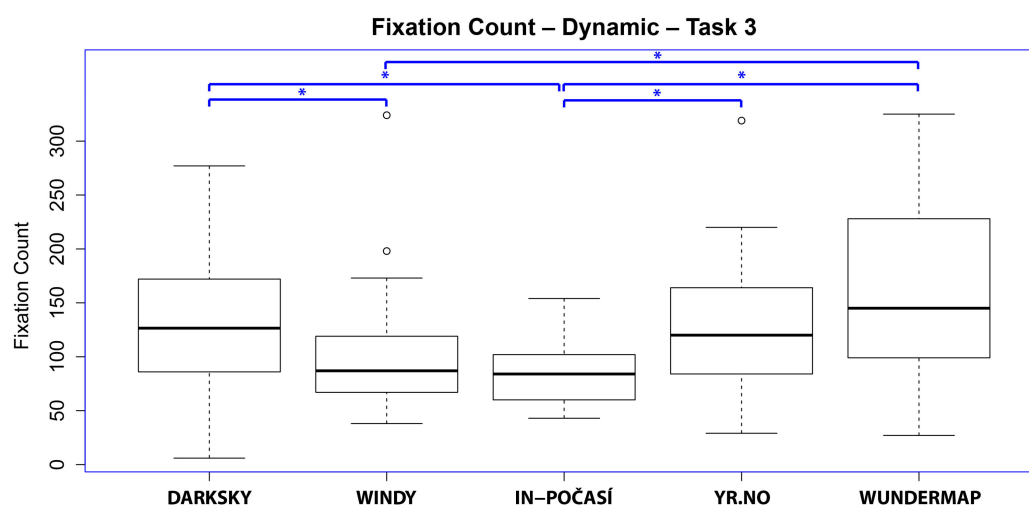
Figure 10. Scanpath Length analysis for the Dynamic Section—Task 1.

The second task asked: *Will it be cloudy today at [time] in [location]?* The objective of this task was to analyse the amount of time a respondent needed to find the answer (Figure 11). The longest response time was observed with the Wundermap web map, where respondents spent on average 65 s. (median 54.4 s) The shortest response time was observed with the In-Počasi web map, respondents spending on average 30 s (median 27 s), which is approximately half that of the Wundermap web map. As mentioned above, some respondents refused to use the Wundermap web map to find the correct answer because of thematic layers loading slowly and not being able to understand the cartographic method of the web map.



**Figure 11.** Trial Duration to find the answer in the Dynamic Section—Task 2.

The third and final task in the dynamic section asked: *Will it rain tomorrow in [location]?* This task concerned the occurrence of precipitation on the next day. The first evaluation method used was Fixation Count or the average number of fixations (Figure 12). This method shows how effective a user's search is in the stimulus, or whether the user interface of the tested stimulus (web map) is poorly defined. The greater the number of fixation counts, the less user-friendly the web map and the less effective the user search. The highest fixation median values were observed with the Wundermap web map (145) and DarkSky web map (126). The In-Počasí web map achieved the best results (84).



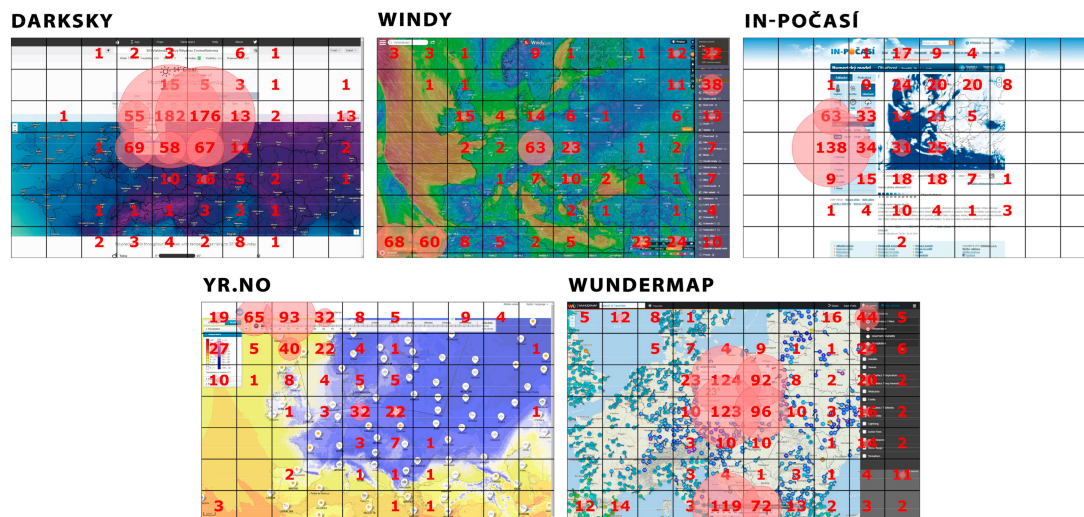
**Figure 12.** Fixation Count analysis in the Dynamic Section—Task 3.

From these conclusions and evaluations, it is clear that the Wundermap web map was the worst of all evaluation means and procedures, while the In-Počasí web map had the best features for interactivity, user-friendliness, convenience and adaptation to different user groups.

### 3.2.3. Static Test Section Results

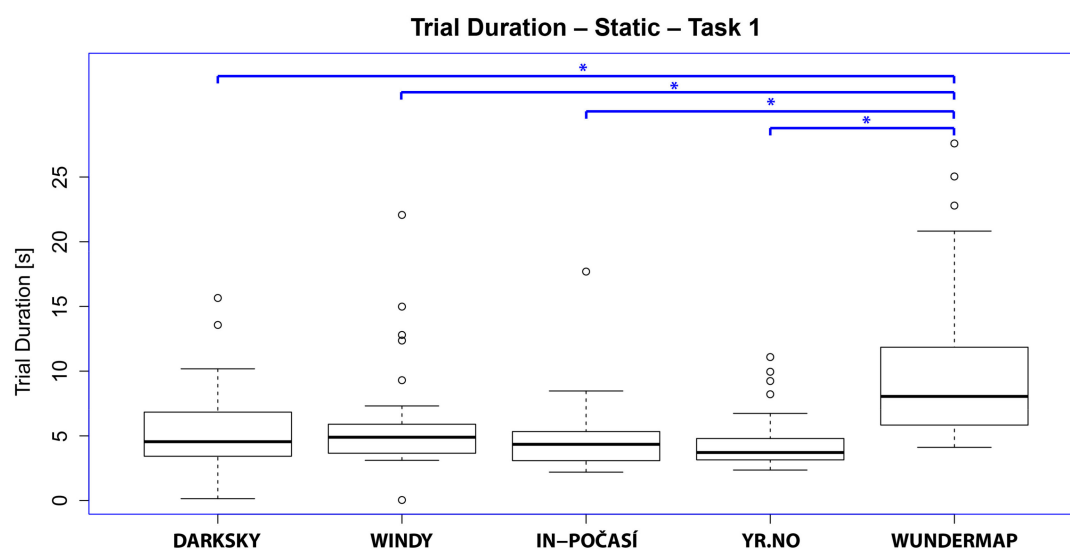
The following section evaluates the static section of the eye-tracking experiment and provides corresponding conclusions. Processing this section was not dynamic or time-consuming. Each web map is evaluated and then compared to others at the end of this section.

The first task required: *Find and click where the weather forecast can be switched to another day.* A visual evaluation of this question was performed using the Gridded AOI method. This method was selected to facilitate the comparison of stimuli, regardless of their content. The resulting output is shown in Figure 13. Analysis showed that the Windy and In-Počasi web maps were intuitive to respondents, as they almost immediately found the required location on the map. In contrast, respondents searched for the required button on Wundermap. This analysis showed that despite the very colourful and graphically rich content of this map, the button to switch the weather forecast to another day is not conveniently or intuitively positioned. In the case of the In-Počasi web map, a simple and clean design with basic content and no unnecessary features proved to be user-friendly.



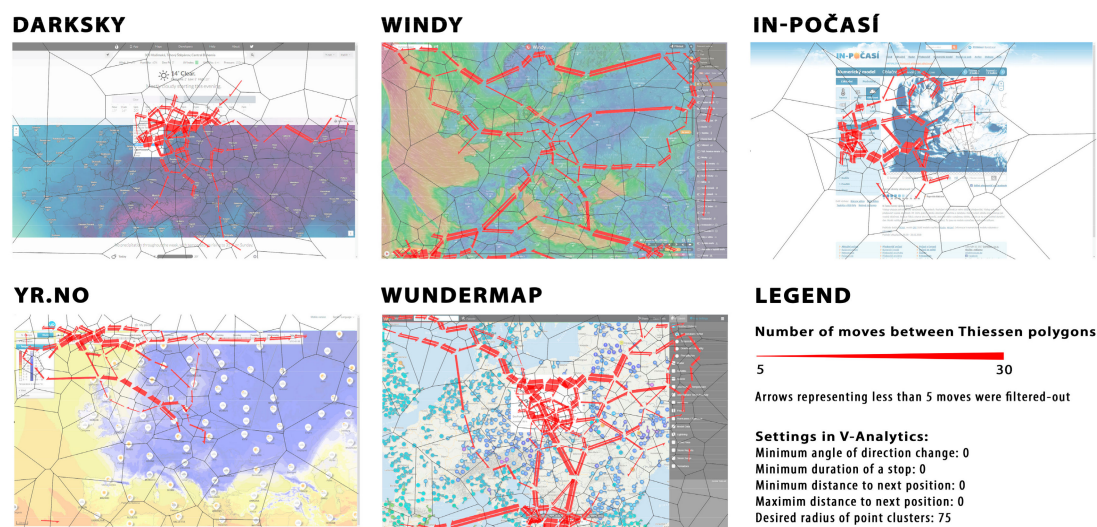
**Figure 13.** Number of fixations recorded in the regular grid overlaying the stimuli in Static – Task 1. The size of the circle and number represent the number of fixations recorded in each cell of the grid.

Another interesting indicator is Trial Duration (Figure 14). From the box plot, it is evident that respondents spent the most time finding the correct answer on the Wundermap web map and the least time on the Norwegian YR.no. Statistically significant differences were found between the Wundermap and all other maps.



**Figure 14.** Trial Duration analysis in the Static Section—Task 1.

The other method of visualizing the results mentioned above was carried is a FlowMap (Figure 15). Similar lines of sight of respondents' eyes were observed. Only arrows with five or more moves between places were plotted. Where arrows are thicker and closer together, respondents were more efficient in searching for a result and knew where to search for an element to find and pinpoint it accurately. This is evident on the DarkSky web site, where respondents did not search the whole screen and found the time switching layer directly. The most confused searches were seen on the Windy and Wundermap web maps. The arrows on the Wundermap web map show high-frequency eye movements across the entire map. This means that respondents searched the entire screen and were distracted by the other elements displayed on the map, their search, therefore, being ineffective



**Figure 15.** FlowMap analysis of evaluated web maps. The visualization displays aggregated eye-movements of all respondents as arrows between generated Thiessen polygons.

When combined with the two above-mentioned evaluation methods, DarkSky demonstrated the best-defined control for switching web map time scales. Both evaluations showed that this web map was best. The Windy web map is a little ambiguous, having the most significant number of fixations in the right place, although respondents only found it by searching the entire screen. The Windy web map is well-arranged, and the controls are intuitive. This contradictory evaluation could be attributed to the arrangement of its controls. These are located in the corners and sides of the map field; the controls are spaced apart, and a user has to navigate the entire screen to find out where the desired element is. A comparison of the average time respondents needed to find the data switch control showed that despite the far-reaching controls on the Windy map, the time required to find them was still less than on the Wundermap web map.

The second task also dealt with the web map and its controls, asking: *Find the place where the theme layers can be switched and click to mark it.* This presented a very similar situation to the third task of the dynamic section. The least fixations required to solve the task was recorded for the In-Počasí web map (Figure 16). A statistically significant difference was found between this map and the DarkSky, Wundermap and YR.no maps. Thematic layer switching on the In-Počasí web map is implemented through intuitive symbols, and respondents found it less complicated. Similar symbols are also used on Windy web map, but they are located in the top right corner of the screen, and are much smaller and less pronounced.

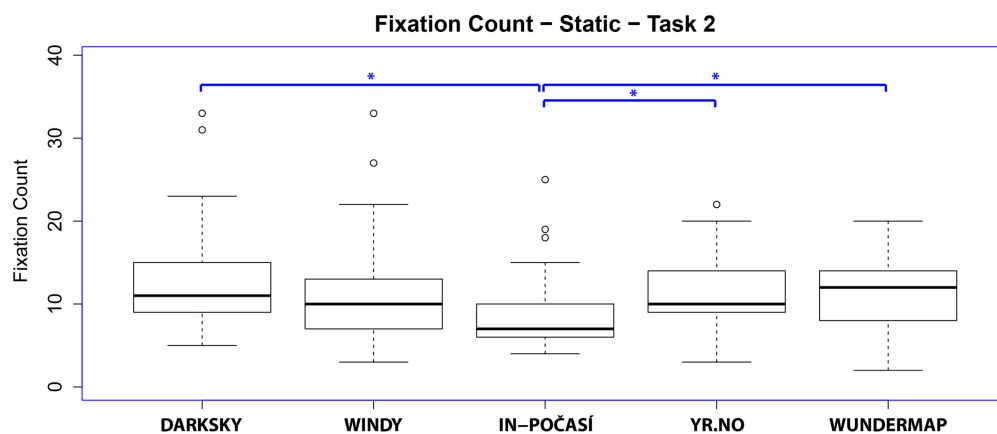


Figure 16. Fixation Count analysis in the Static Section—Task 2.

The final task in the static section of the eye-tracking test asked: *What is the temperature (in Celsius) in [location]?* The Windy web map provided the quickest solution, listing temperature values directly at each city. Between this map and all others, statistically significant differences were found in the Fixation Count and Trial Duration metrics (Figure 17). On the DarkSky web map, however, the temperature near Prague was missing, and a large number of incorrect answers were therefore recorded, and the time required to solve this task was the longest of all evaluated maps.

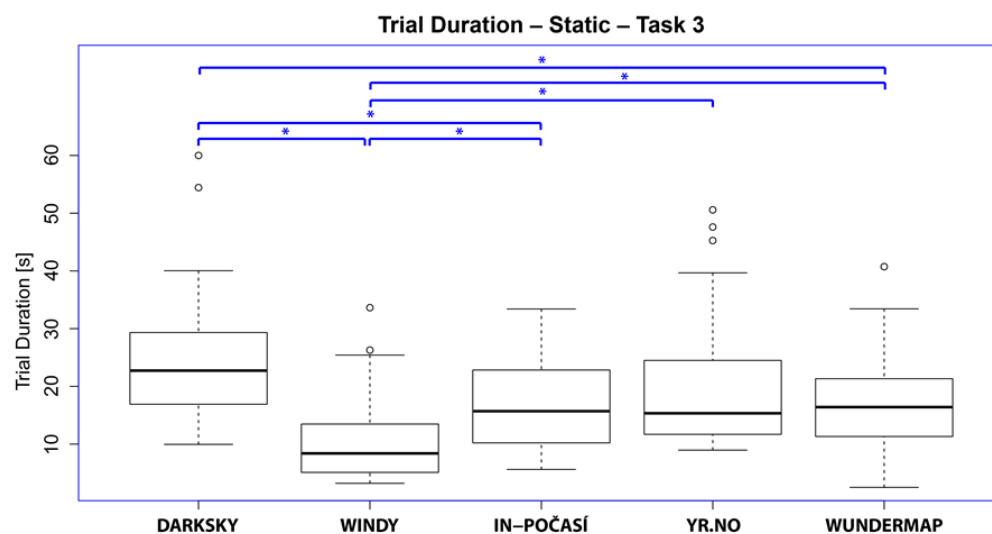


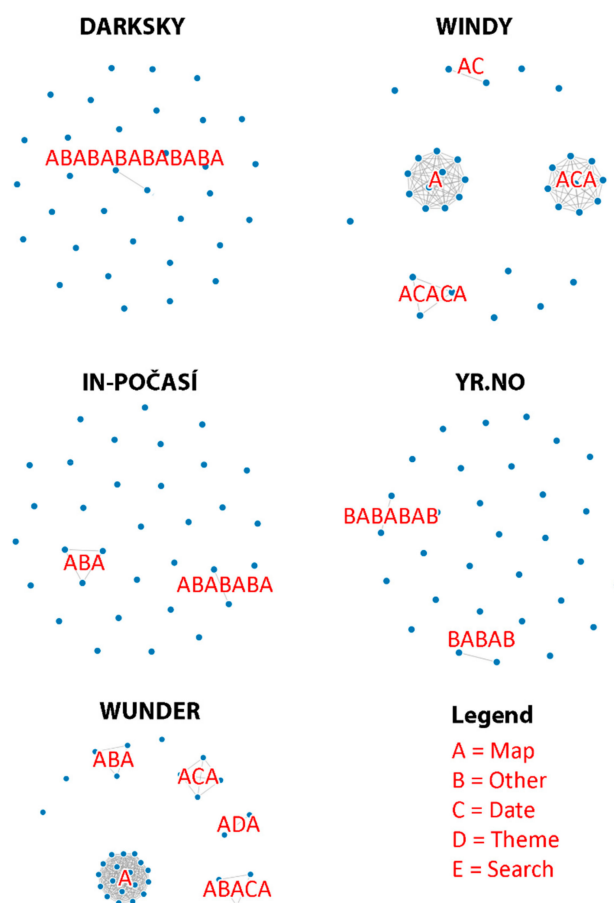
Figure 17. Trial Duration in the Static Section—Task 3.

ScanGraph was another method used to study the above task, because it can help to find similarities in the strategy of stimulus inspection. In this case, no significant differences were found between the expert and novice groups. ScanGraph was nevertheless used, only in a slightly different manner, in order to tease out similarities and differences in strategy between respondents. Distribution into groups of experts and novices was not considered, and parameter  $p$  indicating the degree of similarity was set to 100%; therefore, only those respondents whose order of visited areas of interest were the same became visible. At the same time, “collapsed” was selected so that repeated fixations in one area of interest were not considered. The resulting graphs for all five maps are shown in Figure 18. Each dot represents one respondent. The order of visited areas of interest is shown in red letters.

This analysis can show how difficult it was to find the right answer on individual maps and whether respondents chose the same strategy. On the DarkSky web map, only two respondents were observed utilizing the same strategy. This was at the transition between the areas of interest around the map field and the information text above the map that indicated the temperature for



Prague, which represented the correct solution to the task. Respondents could, therefore, look at this element (labelled B) to find the correct answer. However, it is clear that respondents did not realize this and did not apply this strategy. In a more in-depth data analysis, respondents needed to see at least three AOI (P17 – BAB), but no more than 60 (P24 – BABABABACBCDABADBABACBACACABACABACBABABCDABABACABABABABCABAC), with an average of 15 respondents in the area of interest.



**Figure 18.** Graphic outcome of the ScanGraph analysis. Each dot represents one respondent Dots connected by an edge form a group based on the same order of visited Areas of Interest.

A diametrically different situation occurred with the Windy web map, with clearly identified groups of respondents applying the same strategy. The largest group consisted of eleven respondents, who looked at only the map field. Other groups of nine, three and two members looked at the date switch panel in addition to the map, where the weather forecast for the following days was also presented in the form of a meteogram.

On the In-Počasí web map, the most crucial area of interest was the colour gamut contained in the B-marked element. As shown in the boxplot in Figure 18, the third task on the In-Počasí web map was more demanding than the previous two, and respondents took longer to find the answer. This is confirmed by the ScanGraph analysis, which showed only two small groups of respondents with the same strategy.

A similar situation was observed with the YR.no web map, where the forecast for the following days was also displayed as a meteogram (labelled B). Even with this map, only two groups of respondents adopted the same strategy.

The largest group of respondents who adopted the same strategy to complete the task was observed with the Wundermap web map. This group consisted of 18 respondents, all of whom only

looked at the map field. Unfortunately, the visualization of temperature on this map is very unclear, and in Olomouc, the temperature data overlapped, and it was difficult for respondents to find the correct answer.

### 3.3. Think-Aloud Results

The Think-Aloud method is one of the oldest research methods [46]. Since the analysis of eye-tracking data alone does not provide an answer to the question "Why does the user behave as he/she behaves", the application of the Think-Aloud method can bring new insights and justification of the acquired findings.

Although this method was planned to be applied to all respondents, most of the data collected were not relevant since, as already mentioned, respondents said it was difficult for them to describe what they were doing and why, and it interfered with their concentration. Therefore, they were often interviewed after the experiment was completed, so that the information gained could still be used for further analysis (but not as Think-Aloud results). In the text below is an example of a respondent who was able to cooperate 100%. It was an expert who commented on his actions and his reasons without any problems.

Because it is not a synthesis of knowledge based on the data from all respondents, but merely an illustrative example of how to use the method, it does not present the majority respondents' opinions or approaches. The commentary of one of the respondents was translated and transcribed into text as follows:

Question 1: Locate and click to highlight the area with the highest/lowest real-time wind speed in the Czech Republic.

DarkSky: *"I'm trying to zoom in, but it's not possible using a mouse. Well, here I found some information on the map that's in Hradec Králové, because there are lower numbers than everywhere else, but I can't read it from the colours. However, do you want general information or rather point values? As a map user, I would go after that number, so I clicked on Hradec Kralove."*

Windy: *"I'll find the wind. So, the information here is in degrees, and it's in the cities, and I would have to go here by colour and click somewhere near Olomouc. Also, when I click on it, I'll get the information with the exact number."*

In-Počasí: *"Here, I would go to the border of the three regions, finding it by colour."*

YR: *"Here, I have to study this strange colour scale for a long time to find out that it's the lightest green, and I'd like to see it somewhere near Zlín."*

Wundermap: *"The wind is hidden somehow strangely here in the layer. So, I want to find the highest number, but what does that number show? Well, it's according to Fahrenheit, but it is the temperature, yet it's strange. Trying to right-click the legend, but I just can't see it. Well, look at this, I'm missing the legend, and it's been redrawn on another layer. Well, I can't find the highest one, so let's say here, because it's so green and there has to be that temperature. It's totally stupid to me."*

The quotes clearly show where the user found the answer quickly and where not. For example, the knowledge of the user's ability to read and understand colours on the maps is very beneficial.

Question 2: Will it be cloudy today at [time] in [location]?

DarkSky: *"So, cloud cover can be clicked here. I wrote Prague into the search here, it's even listed here. So today at 10 pm, it will be cloudy and partly cloudy. I ignored the map and found it up there in that information."*

Windy: *"So I switch to clouds. Here, I switched to clouds, and here found ten o'clock, and now I'm going to look at the map. Well, the answer is that it won't be overcast, but there will be some cloud."*

In-Počasi: *"Clouds are already there, here, it doesn't lead me to a location, but when I load it, there is not much of a base layer here, so I'm looking for a location not very well and estimate it will be covered by 50% or so, clouds will be there."*

YR: *"So precipitation, here, I'm misled and cannot find the clouds, but it is right in the icons, so that I can find the time and the place. Now I thought it would hit me and the meteogram would start, and at 8 o'clock it won't be cloudy. Clouds only arrive later."*

Wundermap: *"Help me. Here there might be a clue, I could find it there. Why does it load so slowly that I have to wait? We want it for 7 pm, but the map only shows now. How does the timescale change there, probably not. It may be because it is slow. So, when I click on the map, it will probably not work out anything. It stopped me from looking, so I won't even look for it."*

The task required work with layers/topics and quotes show that this has appropriately verified user credibility within map functionality. Sub-comments lead to knowledge of shortcomings occurring in the evaluated maps and provide the basis for better interpretation of the results.

Question 3: Will it rain tomorrow in [location]?

DarkSky: *"I see that I'm not the first to find it through search. So here I am, switching the date to tomorrow after I found the place. Well, it will rain there, but I'm not quite sure now if that's tomorrow. Well, I'm only a little bit confident that the contents of the map will switch to tomorrow, but not at all with the strip above with information. So, I have to look at the map, and it won't rain tomorrow. However, I'm not quite sure."*

Windy: *"So we want tomorrow again. So, it makes me think of the maps as they move, and yes it will rain."*

In-Počasi: *"I'm clicking on Friday and crashing. I know roughly where Paris is, but I would rather write it, and now I see it. Again, the times go through, and I can see that the showers will come, and more rain will come in the evening."*

YR: *"I'm starting to move here on that timeline, and I see that tomorrow it should be raining."*

Wundermap: *"I have to find it here, but there is a very slow server here. I was trying to select it, but the menu has been stuck. So, disappear. This is a pain. I want to know if it's going to rain. Well, here I can see only the current, and here's just a chart for today. I won't find out about tomorrow. I have a feeling I'm not going to find out about tomorrow."*

Again, the ability to work with web map features, including change of layer/topic and time, was evaluated in this task. Quotes show how the user obtained the information (from map movement, layer switching and time change, etc.) and what was easier for him.

### 3.4. Summary of Results

Users worked with web maps in the simplest form; they did not look for hidden functions in the menu or attempt to find any advanced functionality. They primarily looked at the controls on the main screen of the web map. If expandable control panels were available, the respondents only looked at them after they had examined other elements. Therefore, interactive map elements were only explored by respondents after they had become acquainted with the map. Map interactivity was not an obstacle unless it contained too much information or options to choose from. Searching was still quicker in static menus that respondents did not have to switch on or off. Static menus were available on Windy, In-Počasi and Yr.No; it was necessary to switch the menu on/off in DarkSky and Wundermap; Figures 10–13 show the better results for the maps with static menus. For example, the average value of Scanpath Length (Figure 10) for maps with static menus was 14,350px; for those with dynamic menus the average Scanpath Length value was 25,355px.

After evaluating how users worked with weather web maps, novices were identified as being disinterested in web map functionality and primarily interested in map content and what they could see on the map (for example, whether they could find their place of residence). Experts, though, were interested in exploring web map functionality, such as display capabilities, thematic layers, additional analysis, zooming in/out, switching timescales and other features (based on the comparison of ScanGraph analyses and qualitative evaluation). Mapmakers (cartographers and GIScience experts) should, therefore, consider the target user group when designing a map. Given that weather information is accessed by complete cartographic novices with minimal web map experience, weather web maps should be as simple as possible. The importance of this statement is paramount if the map is intended for the public. If mapmakers expect the map to be mainly for experts and the web map content will contain not only basic weather indicators but also extensive meteorological indicators and indexes of meteorological phenomena, the choice of more sophisticated interactive elements is advisable.

User issues are of relevance to many aspects of mapmaking, such as historical, sociological, psychological, conceptual, and others. One of the most important issues is adapting to the needs of different user groups. User issues in cartography are determined by map users and represent the most important influence in the process of map creation [47]. It is such an important aspect that map makers should pay great attention to it.

Much research is involved in discovering user interests and preferences. In some studies, however, user preferences have been shown as not very accurate regarding the quality of assessed geovisualizations and maps and the suitability of their respective purpose and user target group [48]. This finding was confirmed in this study, specifically in the combined evaluation of the Think-Aloud method with the results of eye-tracking testing (despite the limitations and problems that accompanied the use of the Think-Aloud). For example, one respondent liked a certain map at first glance (mentioned during map viewing in the Think-Aloud record), but it was difficult for him to complete the task. Conversely, in a map that the respondent did not take any interest in at first and would be rated as average in the preference rating, the correct solution was much more accessible. Unfortunately, because this respondent needed to concentrate on solving the task and did not attempt to comment on the process, it was not possible to substantiate this claim with statistical indicators.

The differences between experts and novices are evident from the evaluation of the experiment. The group of experts worked much more efficiently and could find the correct answers to the required tasks. The differences between respondents were also visible in the Sequence Chart evaluation (Figure 9), where it is clear that experts moved their eyes with more concentration on the goal and did not revise or search. Despite the striking differences in the individual evaluation methods compared to the similarity of fixation strings, novices and experts did not differ significantly. No significant differences in trajectories and movements between AOI areas were found (Figure 18).

Evaluation of the dynamic section of eye-tracking testing clearly showed that respondents had a complex map composition problem, mainly in that controls were on different sides of the map field rather than in one place. This problem arose, though, only during the first use of a web map. As soon as the respondents learned a map's functionality, they found this map element easily. Assessing the factors influencing a new user is very different from assessing the factors influencing an experienced user. This was detected while respondents were monitored as they worked with the Windy web map. At first, respondents had great difficulty finding the required controls, as the elements were distributed along the sides of the map field and set very far apart. In the final task, users no longer demonstrated the problem of finding map composition elements and used them more efficiently than in the first task.

The user aspect was mainly measured as user-friendliness and showed how a respondent felt while using a web map, what worked best for the respondent and what their preferences were. This assessment was subjective and very much depended on the respondent and their habits. This user aspect is closely related to all other user issues mentioned above. During the Think-Aloud assessment, some respondents mentioned the map that was best for them to control and which one they would like to use. Testing also showed that the concept of user comfort introduces the notion of intuitive map

control and modern map design. Some respondents did not need a modern design, but they required functionality, simplicity and high-speed web map loading. For this reason, it was very complicated to evaluate the user aspect. Testing showed, however, that if a web map did not contain modern visualization elements, had very complex layouts and was very slow to load, it was very inconvenient to the respondent (for example, the Wundermap web map).

Lastly, graphic design significantly influenced respondents and their work with the web maps. Modern depiction enhances the attractiveness of maps and empowers a user's vision, even if they do not have flawless control and cartographic visualization methods are sometimes incorrect. Graphic map design, therefore, adds to the overall impression of a web map, portal or application. Respondents identified the Windy web map as attractive, but after the final task, some described this webpage as excessively detailed and cluttered with unnecessary information and suggested the possibility of changing thematic content. Most respondents identified the In-Počasí web map as balanced in map content and graphic design.

#### 4. Discussion

This study assessed selected aspects of weather maps and focused on the degree of interactivity of these maps and user perception. Several works have already evaluated web maps, but only in a few cases at the level of user interpretation, perception, and cognition or general analysis of selected web maps.

The evaluated maps were selected based on an online survey, which was used to garner information on the most frequently used maps and adding a selection of different map types (known but less used maps). As most of the respondents had used international web resources in their work and personal life, the selection included the very frequently used weather web map YR.no. Another important aspect considered was that the respondents in the present study would be of Czech nationality. Therefore, the frequently used Czech weather web map In-Počasí, which includes only the territory of the Czech Republic, was included in the selection. Another Czech weather web map included was Windy map, developed by the owner of the most popular web map application in the Czech Republic Mapy.cz. The final maps selected were the Wundermap map and the DarkSky map, because their interfaces differ from the interfaces of the other maps.

The stimuli were presented in a fixed order because the analysis of dynamic stimuli combined with random order would be problematic. The analysis of dynamic stimuli will be very problematic when they will be randomized. In the static section of the experiment, it is possible to randomize the stimuli, but we did not do so in order to remain consistent within the experimental structure. We hope that the learning effect did not affect results, since different maps have different control mechanisms and are use different cartographic methods.

The eye-tracking experiment dataset was also analysed with Sequence Charts, using dynamic areas of interest. For the analysis, only six respondents (three experts and three novices) were selected. This was due to the clarity of the resulting visualization and extreme demands on time for creating dynamic areas of interest. The authors are aware that viewing the order of visited areas of interest for all 34 respondents might be interesting, but it would be necessary to manually create dynamic areas of interest for all respondents and all stimuli. However, this question may be a part of future research that could address weather web maps and their use.

User issues in map creation are determined by the target users and represent the most significant influence in the process of geovisualization. Therefore, considerable attention is addressed toward the user's needs, requirements, and preferences. Experiments, as presented in this article, allow inspecting in more detail the specifics that relate to different types of maps. Closely related topics enable detailed analysis of the experimental data and permit to draw relevant conclusions.

It is necessary to evaluate geovisualizations not only in terms of the correctness of the methods used and their compliance to cartographic principles, but also in their aesthetics and the user perception and interpretation of perceived information. The results above demonstrate that user preferences and user needs can be different. This conclusion is based on the Think-Aloud data analysis. The research



outcomes show that it is crucial to implement map user testing into the geovisualization process, including a functional evaluation of interactive maps.

## 5. Conclusions

Weather maps were evaluated by combining research methods with a core eye-tracking experiment that focused on analysing the behaviour of respondents as they worked with the selected maps. The experiment was divided into three parts: a free viewing section, a dynamic section, and a static section. Five selected web maps with meteorological themes were employed in testing. Thirty-four respondents performed the test, separated into two map user groups of experts and novices.

The main aim of the presented research was to find out how users work with selected weather web maps. There are many map characteristics and parameters that affect the metrics being evaluated. All weather web maps are complex cartographic works; they differ in map composition, map symbology, map interactivity, map content, etc. Therefore, it is not possible to conclude which weather web maps were the best and worst overall. It can only be concluded that some maps are easier to understand and use (Windy, In-Počasí, YR.no) and some maps are not (Wundermap).

Partial results are presented in the task evaluation (Section 3.2). The acquired knowledge can be used to further discussion of weather web maps and their implementation. Our results include the findings that if expandable control panels were available, the respondents only looked at them after they had examined other elements; map interactivity was not an obstacle unless it contained too much information or too many options to choose from; searching was quicker in static menus that respondents did not have to switch on or off; and that the Think-Aloud method has significant limits in the case of dynamic testing due to high user demands.

Each web map is different, and both major and minor differences were identified. Further related research may focus on the impact of these differences on the user perception and cognition. Analysis can also be focused on different thematic maps and, thus, differences in attitudes of experts and general public (novices) can be evaluated. To that need, one of the planned future experiments will focus on the analysis of web maps intended for archaeologists.

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