Intuitiveness of geospatial uncertainty visualizations: a user study on point symbols

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ABSTRACT The understanding of uncertainty, or the difference between a real geographic phenomenon and the user's understanding of that phenomenon, is essential for those who work with spatial data. From this perspective, map symbols can be used as a tool for providing information about the level of uncertainty. Nevertheless, communicating uncertainty to the user in this way can be a challenging task. The main aim of the paper is to propose intuitive symbols to represent uncertainty. This goal is achieved by user testing of specially compiled point symbol sets. Emphasis is given to the intuitiveness and easy interpretation of proposed symbols. Symbols are part of a user-centered eye-tracking experiment designed to evaluate the suitability of the proposed solutions. Eye-tracking data is analyzed to determine the subject's performance in reading the map symbols. The analyses include the evaluation of observed parameters, user preferences, and cognitive metrics. Based on these, the most appropriate methods for designing point symbols are recommended and discussed.

KEY WORDS uncertainty – maps – eye-tracking – symbol set – visual perception – data quality

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1. Introduction

Even when spatial data are well described, users may not be aware of the inherent uncertainty in all the datasets they use. For this reason, it is crucial to evaluate the results of the analysis based on this data to understand the validity, limitations and conclusions. Moreover, many map readers, when they view a map based on results of spatial analysis, modeling or data manipulation, fail to understand that those results are affected by uncertainty. It is therefore of primary importance to design symbols and geovisualizations in a way which the user will intuitively understand. This problem is addressed in several research papers (Berjawi et al. 2014; Finger, Bisantz 2002; MacEachren et al. 2012). In addition, there has been significant research activity focused on visualizing uncertainty in particular detail. However, the use of such techniques in practice is still rare because standardized methods and guidelines are few and mostly untested. Nevertheless, the authors mentioned above do not take into consideration the measures available based on eye-tracking experiments. Therefore, our main ambition is to investigate, via eye-tracking, how individual symbol sets work on the map during reading tasks. We aim to bring new research findings to extend already published studies and to address several research questions: Is there any connection between user preferences and the effectiveness of symbols? Does the visual variable affect the perception of point symbols? Are there differences in the form of legends for point symbols? Can Geographic Information Science (GIScience) education change user interpretation (or preferences) or symbol effectiveness?

2. Background

2.1. The term uncertainty

Uncertainty implies that there is something we are not sure of in spatial data and analysis due to various reasons, such as ignorance of human knowledge, a generalization of geographic features, measurement errors, and incomplete representation of all factors in the analysis (Li 2017). A practical example where uncertainty has to be taken into consideration can be the delimitation of zones based on spatial data modeling (Machar et al. 2017; Pechanec, Burian, Kiliánová 2011). In our work, the definition by Longley et al. (2005) is adopted: "Uncertainty is the difference between a real geographic phenomenon and the user's understanding of the geographic phenomenon." It is distinct from concepts such as error or accuracy because it acknowledges an unknowable component of all geospatial information. For example, positional accuracy refers to the absolute and relative accuracy of the positions of geographic features. Attribute accuracy refers to the accuracy of the quantitative and qualitative information attached to each feature, and temporal accuracy refers to the coincidence between registered and actual time coordinate for the event. From our research perspective, the typology of uncertainty defined by MacEachren et al. (2005) is also essential, as it has received significant attention in the cartographic community. It can be used within the application of positional, temporal, and attribute uncertainties in geospatial data (Kinkeldey, Senaratne 2018). According to Brus (2014) the concept of uncertainty can be defined as the imperfection of users' knowledge about data, processes, or results. The uncertainties in spatial data and its analysis result from four major factors: (i) inherent uncertainty in the real world, (ii) the limitation of human knowledge in cognition of the real world, (iii) the limitation of the measurement technologies for obtaining spatial data, and (iv) the potential of generating and propagating uncertainty in the spatial data processing and analysis (Shi 2010).

In parallel with uncertainty, spatial data quality can be defined. There is now considerable agreement on the definition of quality in the literature, quality being defined as "fitness for use" (Veregin 1999). It can also be described as an evaluation of the similarity between spatial data and geographical truth, including both positional truth and attribute truth (Li 2017).

In the GIScience community, spatial data uncertainty has been a focus of research for the past several decades (Li 2017). In contrast with this statement was the concept of uncertainty in Czechia quite often neglected until last 10 years. This topic is of growing interest to the research community nowadays; we can find studies focused on cognitive aspects of uncertainty visualization (Kubíček, Šašinka, Stachoň 2014; Kubíček et al. 2017) or database quality (Hošková-Mayerová et al. 2013).

2.2. Visualization of uncertainty

Effective visualization should provide the appropriate visual metaphors to present information in a way that supports data comprehension. In this concept, data are primarily used to provide answers to specific questions, tests, hypotheses, or to explore relationships. In the case of GIScience, most of the data also have a spatial character, and the visual presentation must in this case also facilitate the achievement of the goals set. Most traditional visualization techniques have been created (and are often used), with the prerequisite that all available and user data are accurate and that the transfer of information is smooth. Even if there were a prerequisite in place, ensuring accurate, effective visualization of a data set, it would still be true that the displayed data contains a certain level of uncertainty (Brus, Pechanec, Machar 2018). In spite of these complications, the visualization of uncertainty as a way of communication can be traced back to initial studies dealing with uncertainty in general (Beard, Buttenfield, Clapham 1991). Afterwards a wide variety of visualization algorithms were used for the visualization of uncertainties, including geographic information systems, meteorology, oceanography and medical research (Lermusiaux et al. 2006; MacEachren 1995; Pang 2001; Pang, Wittenbrink, Lodha 1997). Even though the view on the visualization of uncertainty changes and it is slowly coming into a growing range of studies, including those environmental ones, the implementation is still a very slow process and a problematic area (Brus, Voženílek, Popelka 2013). Consequently, the visualization of uncertainty remains one of the most important challenges of visual analysis (Wong et al. 2012). From the cognitive point of view it is necessary to take into account the main concepts as visual search (Egeth, Dagenbach 1991) and research dealing with scene under increased attentional load (Brand, Johnson 2014). From the visualization point of view, many classification schemes were proposed in the field of GIScience and Information Visualisation (InfoVis). Perhaps the most comprehensive overview can be found in MacEachren's work (2005). In contrast to the GIScience community less emphasis is placed on the formalization of uncertainty within the InfoVis community (Aipperspach 2006). In the InfoVis community, the concept proposed by Pang, Wittenbrink, Lodha (1997), which probably describes the issue best and most comprehensively from the perspective of the visualization of uncertainty itself, is most commonly referred to. This model is by its nature based on the visualization model proposed by Haber and McNabb (1990). The whole scheme is based on the need to visualize a real phenomenon, from the process of collection and transformation to the final visualization of the phenomenon. However, in the author's conception, the visualization scheme primarily relies on real phenomena more than on abstract phenomena. Despite this fact, the scheme is also generally applicable for the visualization of information within the GIScience domain. From this model, uncertainty spreads throughout the whole process. Accordingly, there has been significant research activity focused on visualizing uncertainty in detail. Multiple typologies have been proposed to identify and quantify relevant types of uncertainty and a multitude of techniques to visualize uncertainty have been developed (Potter, Rosen, Johnson 2012). Despite the high number of methods proposed; many questions related to the visualization of uncertainty remain unanswered. Due to the myriad techniques available for different types of data, there is a lack of a comprehensive overview of all the methods, complex typology and predominantly tools that can efficiently work with the visualization of uncertainty. The fact that there is a lack of detailed recommendations and methodology for selecting individual methods is crucial, moreover, the lack of methodologies proven to be supported by user testing is the bottleneck of the whole research area.

2.3. Existing empirical studies

Over the years, there has been an increase in the number of studies that evaluate (rather than categorize or suggest methods for) uncertainty visualization, but the numbers are generally small with some variability (Kinkeldey et al. 2017). From our research, the work of MacEachren et al. (2012) is fundamental. The authors did not just focus on building a symbol set for one particular purpose. Instead, they aimed to design symbols that could be used universally in maps, tables, and in other forms in various scientific disciplines. The objective is to create a standardized graphic form of symbols for the visualization of uncertainty. They created symbols sets to express time, spatial, and attribute accuracy. They revealed their level using variable parameters of individual symbols. Specifically, it was each symbols's placement, its size, color tone, value, texture, orientation, shape, transparency, fuzziness rate, and image resolution. The suitability of the proposed symbols for this purpose was subsequently tested in an experiment consisting of two parts. In the first part, symbols sets with three levels of uncertainty contained were created. These were subsequently submitted to the participants for assessment of the subjective perceived suitability. In this way, information about the effect of individual symbols on the reader was acquired. In the second part, matrices (3×3 symbols) with different levels of overall accuracy were assembled from each symbol set. These were subsequently submitted to the participants in pairs. His task was to determine the total uncertainty levels contained in the matrix and to select the one with the higher value. The evaluation was based on the correctness of the responses and the time that respondents needed to decide. Therefore, the practical suitability and interpretation demand factor of each symbol set was assessed. The variable parameters of the symbols that were perceived to be best included fuzziness, location, and value. However, when using these symbols, it is necessary to keep their logical level order, where the increasing uncertainty increases the value of the used parameter. In the experimental section about the practical use of symbols, the highest number of correct responses was recorded with the shortest decision time for fuzziness and value methods. Thus, in the overall comparison, it is possible to recommend fuzziness, location and value as the most appropriate methods for the representation of uncertainty.

Other authors who addressed the problem of the representation of spatial data uncertainty were Berjawi et al. (2014). Their study was focused on showing the points of interest (POI) on the map. Individual POI corresponded to hotels, restaurants, and other attractive tourist destinations, for which the location and attribute information were tracked. The need to express the quality of the information was based on a data acquisition algorithm. This algorithm browsed through various data sources from which it took information about a destination. This information was subsequently appropriately combined, and the completeness and consistency of all the data obtained were evaluated. Based on this knowledge, the uncertainty was subsequently determined. The accuracy of location was determined based on Euclidean distance, an attribute based on the cluster analysis of similarity. Several symbol sets were created to represent the POI. Besides the newly designed ones, the best-rated symbols from the work of MacEachren et al. (2012) were used. They also examined a combination of multiple variable attributes to represent uncertainty within one symbol, such as location and fuzziness. If both correspond to one type of accuracy, then the possibility of misunderstanding the information quality levels is lowered. However, they can also be used to represent more types of accuracy in a one- symbol set, thereby increasing the information value, but at the cost of complicating the information acquisition process. In the test section, the symbols were first placed in pairs, which were then displayed in front of participants. Their task was to select a symbol with a higher level of accuracy. The assessment of the suitability of the symbol was based on monitoring the number of correct answers and the time needed for a decision. In the second part, the best-rated symbols were placed in the map to analyze the most appropriate form of how to represent the accuracy of the information, whether to use one symbol with a total accuracy level or more symbols corresponding to each type. The supplementation of an appropriate pop-up window was also tested. Based on the results, the option of one symbol set corresponding to the overall accuracy level with the sub-type displayed in the pop-up window was selected as the best. The map is not overloaded, while the maximum information value is maintained. Nevertheless, access to this data is more difficult.

3. Methodology

The study is based on the use of lessons learned from previous work aimed at the representation of point symbols to express the uncertainty. We followed the work of MacEachren et al. (2012) mainly by symbol set design. The whole workflow of the experiment is different. We perform one questionnaire with 100 respondents with a different background. We also mainly focus on simple questions about intuitiveness of designed symbols. In questionnaire we focused not only to point symbols but also to line and polygon ones and subsequently made several eye-tracking experiments. The whole finished study is nevertheless beyond the scope of a single paper and will be published in follow up work. The experiment reported in this paper is focused on point symbols consisting of an assembly of individual symbol sets suitable for expressing uncertainty. As already mentioned in addition to their assembly, their expected suitability was verified based on a questionnaire to determine perception and afterwards in practical use on the map. From this part of the experiment, information about symbol perception was obtained by

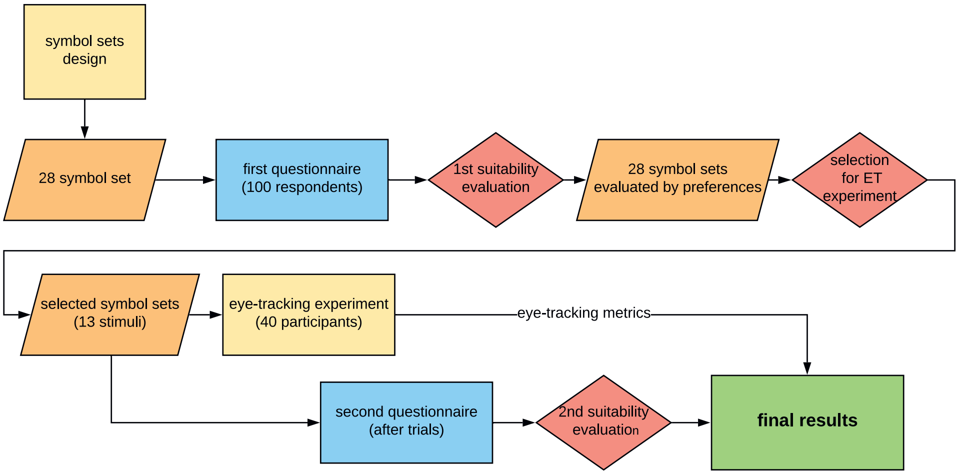


Fig. 1 – The design of the experiment

evaluating basic eye-tracking metrics such as scanpath length and trial duration. The eye-tracking experiment was conducted with a total of 40 respondents divided into two groups. The first group consisted of 20 students from the Department of Geoinformatics, Palacký University Olomouc who already had basic knowledge about the uncertainty of spatial phenomena. In this study, we considered them as cartographers. The second group consisted of 20 respondents without a GIScience background. We considered them as laypersons (non-cartographers). Answer choice was also used as a metric to assess whether the symbol set was correctly interpreted. Subsequently, the suitability was again evaluated via a second questionnaire. In addition to the symbols themselves, two variants of the legend were also proposed and the differences between respondents with and without GIScience background were observed. Our approach is therefore different from mentioned authors as we based our observation also on the eye-tracking experiment. This helps us to evaluate the real process of reading the map and gives a more realistic view of the process of getting information. The study design can be seen in Figure 1.

3.1. Symbol set design

At the beginning of the experiment, the symbol sets were designed to represent uncertainty. Their appearance was as already mentioned inspired by the results of the work done by MacEachren et al. (2012) and Berjawi et al. (2014). Initially 28 symbol sets were designed (Fig. 2). Symbol sets were created based on different

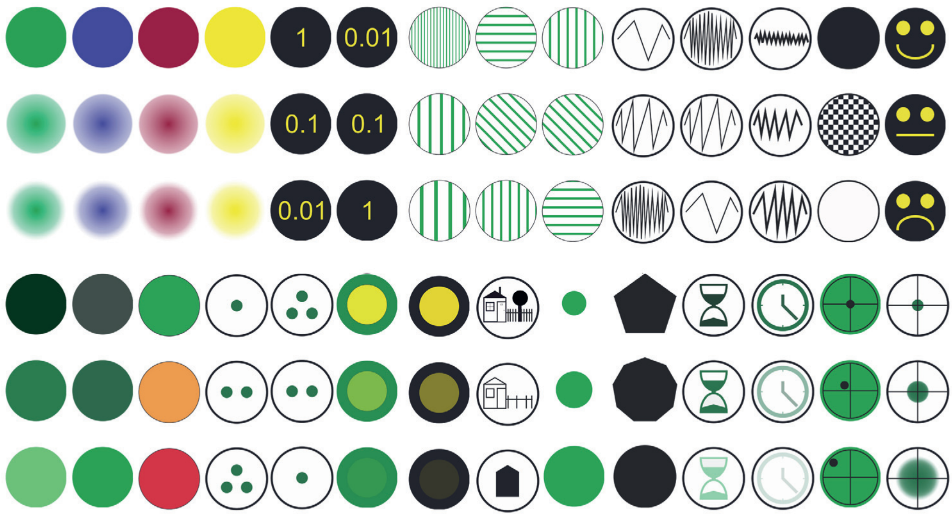


Fig. 2 – Main symbol set used in questionnaire (excluding modifications)

visual variable attributes to express uncertainty (fuzziness, size, saturation, color, and more). The selected sets were created in several color variations. Due to this, it was possible to compare the effect of the color preferences of the respondents on the result. Each symbol set represented three levels of uncertainty. Several point symbol sets were designed in two variants. This step was taken in consideration to verify the naturally perceived conjunction of the variable attribute level with a certain uncertainty level. In addition to the silhouette symbols also graphical forms were designed to measure differences in the perception of such symbol variations. The symbol sets can be also divided into groups showing different uncertainty issues (general uncertainty, accuracy, precision, and trustworthiness). Figure 3 shows a possible reflection of accuracy in the designed symbol sets. The symbols were designed for several followed-up eye-tracking experiments including combinations of symbols. In this paper, we introduce only one eye-tracking experiment, which focused on general uncertainty in a simple reading task.

3.2. Questionnaire

A questionnaire survey was put into the experiment to verify the suitability of the proposed symbol set before setup the eye-tracking experiment. The questionnaire was created in the Google Forms environment and contained 28 variants of point symbol sets with a corresponding legend of uncertainty level. In the questionnaire, each of them was also assigned a 7-point scale to express perceived suitability for

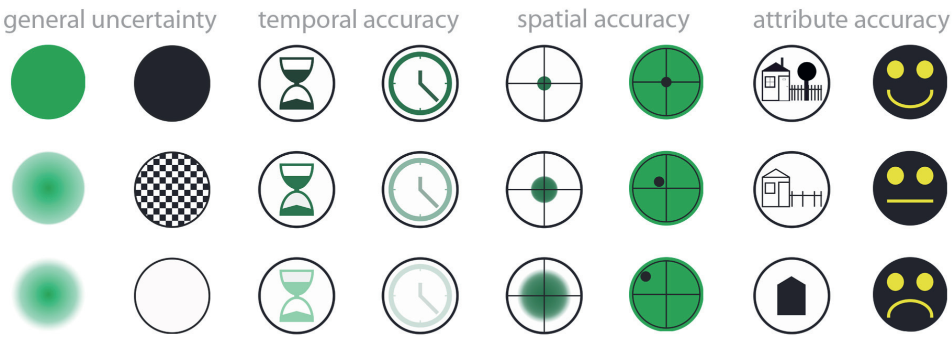


Fig. 3 – Reflection of accuracy in designed symbol sets

expressing uncertainty. The values vary on a scale from 1 to 7. Seven represented the maximum suitability. A detailed explanation of the term uncertainty was included in the introduction, as this term could have been unknown to some respondents. For many respondents, this was their first encounter with the term uncertainty. In addition, the questionnaire included several questions concerning respondent characterization. Namely, we asked for on age, gender, GIScience background including cartography and color perception deficiency. These personal oriented questions were on a voluntary basis. Information about possible congenital color perception deficiency was also included in the questionnaire.

3.3. Eye-tracking experiment

The main aim of the eye-tracking experiment was to verify whether the symbols with a high preference (suitability) score work in practical deployment. For the experiment, we chose highly preferred symbols, as well as those symbols with low scores. The aim of the experiment was to determine if low scored sets are also difficult to use during map reading tasks. All of these symbols were then placed in the map composition to illustrate the imaginary situation of the occurrence of a selected animal (fox). Figure 4 shows the finally selected symbol sets. In addition to the symbols, a legend was placed in the final stimuli. For testing, we designed two variants of legends: Variant "a" with uncertainty shown separately and variant "b" where uncertainty was incorporated directly in the symbol. The first one provides a simpler version, but in this case, the reader must apply the level of uncertainty to the symbol. However, its benefits may be noticeable in showing more phenomena, including information uncertainty expressed in a uniform style. In the second variant, the appearance of the symbol corresponding to individual levels of uncertainty is immediately apparent. Due to this, it is not possible to visualize some

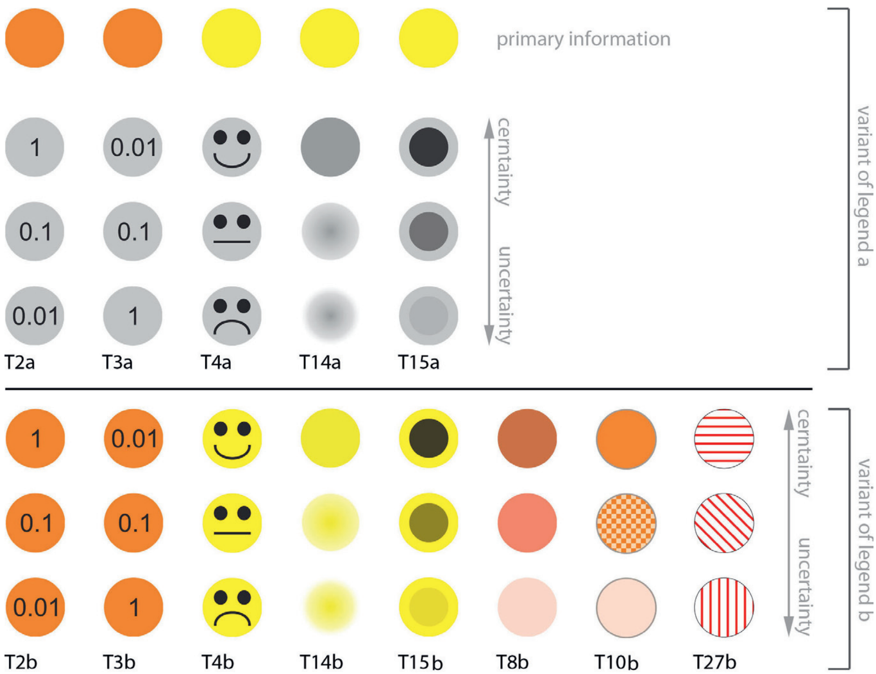


Fig. 4 – Symbol sets used in the eye-tracking experiment in two variants of the legend concept, variant a – the phenomenon and the uncertainty separately, variant b – a combination of both items of information

symbol sets using the method in variant "a". This is the reason why the number of symbol sets in variant "a" and "b" differs.

All map compositions used an orthoimage showing a forest landscape as the background. As we tried to incorporate the symbols in the map reading task, the chosen background helped us to minimize the complexity of map content. We avoided using topographic or thematic maps due to the mentioned map complexity and the possible influence of symbols by another map content. Moreover, to prevent its negative influence on the perception of the symbols themselves, the brightness and saturation of the colors were also adjusted. Before each stimulus (map), a sentence with a task to solve was shown to respondents.

3.4. "On the map choose the three most suitable locations to place the photo trap to record the occurrence of a fox"

The aim of the simple map reading task was to select places where the occurrence of the fox was likeliest. The respondents should incorporate uncertainty portrayed by point symbol sets and select one location represented by symbols showing most certain data. SensoMotoric Instruments (SMI) RED 250 eye-tracker was used in the study. The eye-tracker was arranged in the department's eye-tracking laboratory. The stimuli were displayed on a 24-inch screen with a resolution of 1,920×1,200 pixels. Eye positions were recorded at a frequency of 250 Hz. Data were analyzed using the applications Open Gaze and Mouse Analyzer (OGAMA) and SMI BeGaze. We used "trial duration" which represents the total observation time of the stimulus. Based on its value, it is possible to reveal the difficulty of the task or evaluate the attractiveness of the stimulus. Another used metric was scanpath length, which describes the length of the gaze trajectory in pixels and can be used for similar purposes. Fixation count metric is also used in the study. This metric indicates how many fixations were recorded in a particular Area of Interest. Similarities between participants were analyzed using the ScanGraph tool. The tool was developed at Palacký University in Olomouc, Czechia and is intended to find out similarities and differences between respondent's strategy of stimuli inspection. It works using the principle of the String-Edit-Distance method of Scanpath Comparison (Doležalová, Popelka 2016; Popelka, Doležalová, Beitlová 2018). The total number of 40 participants can be considered sufficient – it is consistent with many other studies. For example, Incoul et al. (2015) compared paper and digital maps, and a total of 32 respondents took part in the experiment. A similar number of respondents was also used by Çöltekin, Fabrikant, Lacayo (2010) when comparing map interface, or Fuhrmann, Komogortsev, Tamir (2009) when searching for differences between the map and its holographic equivalent.

4. Results

4.1. Questionnaire survey

A questionnaire survey aimed at the subjective evaluation of individual symbol sets was completed by 100 respondents. The age structure of the respondents was 18 to 60 years, and according to the gender structure, there were 60 men and 40 women. The results of the individual sets were arranged according to the median of their ratings. This statistical indicator was chosen due to resistance to the extreme value influence effect and its higher suitability for describing an unknown distribution. If the median matched for multiple sets, then the assessment of the distribution of the obtained suitability values using 1st and 3rd quartile followed. The final ranking of the symbol is shown in Figure 5. The best rating symbol set group was "fuzzy". This variant of the symbol set was elaborated in 4 color versions (symbol sets S11, S12, S13, and S14). The aim of this step was the effort to assess the influence of color on the result of the perceived suitability. That

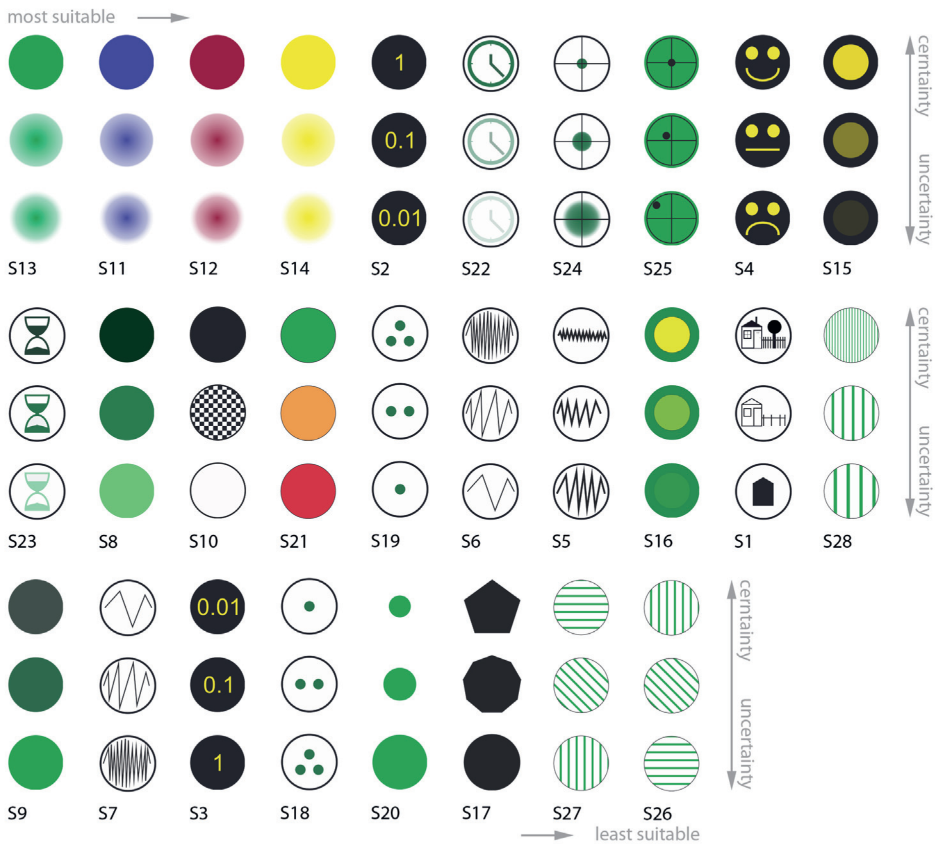


Fig. 5 – Final user rankings of the suitability of symbols from 1st questionnaire

is, whether the same symbols, just in a different color version, would be perceived differently. This hypothesis was not confirmed, and a similar result was achieved for all. Second most preferred was the symbol set S2. The uncertainty level is expressed by a numeric value located in the center of the symbol. The value of 1 corresponds to certain data and 0.01 to the uncertain data. The questionnaire also included a version which had the opposite uncertainty arrangement. This symbol set was not preferred and got the 23rd place. In the questionnaire, we also test symbols related to temporal accuracy. They were also evaluated as suitable. The S22 symbol only increases the transparency of the placed graphical form of the clock along with the increasing uncertainty. In addition to this variant, an hourglass version was also created with the identification S23 and was placed in 11th place.

Sets S24 and S25 were created for the positional uncertainty of the information. In the first variant, the accuracy in the space is induced using a variable point size. Its size should remind the reader of the localization in space. Therefore, with a higher level of inaccuracy, it is necessary to define a larger search area. In the case of high accuracy, it is possible to determine the destination place in much more detail, and it is not necessary to define such a large search area. The second set of symbols expresses uncertainty using a variable distance between the center of the character and the point location. The center represents the maximum possible accuracy, and the more distant the point is, the more it decreases and at the same time the uncertainty increases. The S4 symbol set, which uses the symbol of the human face to represent the uncertainty was very popular among the participants in the research. This set evokes a human mood in the reader, namely cheerful, neutral and sadness, through a different style of the mouth. These attributes are assigned a level of uncertainty that can stimulate these feelings. Specifically, a low level of uncertainty corresponds to the cheerful face and a high level to sadness. Sets S4 to S22 achieved the same result in the overall ratings.

The set using transparency as the variable parameter was placed in 10th place. Compared with the S13 set, it is an advantage that the background does not affect its perception because the variable part of the symbol is placed on a monochrome surface. However, in this questionnaire, the symbol was not placed on the map background. Therefore, it was not possible to evaluate the potential influence of the background on this symbol set.

The eye-tracking data allowed us to evaluate several parameters quantitatively. The main parameter was the correctness and structure of the answers to the questions included in the experiment which indicate whether the set was understood correctly. Also, the respondent's cognitive analysis was performed by evaluating the time spent on the trial (*trial duration*), the map reading process, and the overall eye trajectory length within the stimulus (*scanpath length*). These parameters can identify the complexity of the set for understanding and its level of intuitiveness. To assess the suitability of each legend type, a comparison of the time of eye sighting to the area of its location was also performed. A more appropriate variant should be easier to understand and therefore the respondent should spend less time interacting with it.

Overall, symbol sets showing certain data were best evaluated (Fig. 6). In all cases except symbol sets T8b and T15a were most certain data represented by one occurrence only. The trials T8b and T15a included two of these points to assess whether this anomaly is reflected in the overall results. That is, whether respondents will look for another symbol that shows certain data once one has already been selected. Each respondent had the task of selecting the three most appropriate symbols overall, so he also had to complement his selection appropriately with the symbols carrying less quality information. The T2a set was the best evaluated symbols. The representation of these symbols in the overall selection was 33.3%. It can be said that this graphic form appears to be the most intuitive. This is evidenced by the very low number of selected symbols showing high uncertainty,

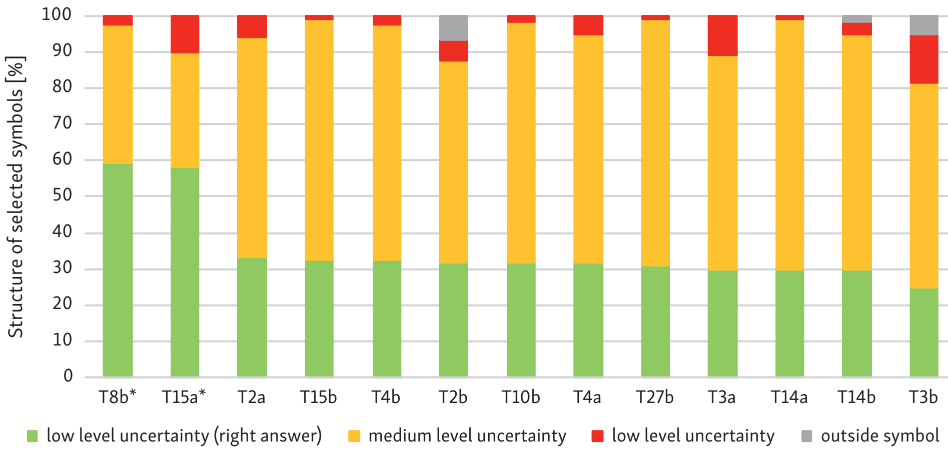


Fig. 6 – Structure of selected symbols by uncertainty level (the stimulus contained two symbols show certain data, the others only 1)

which reached 5.8% of the total number of representatives. A balanced result was achieved even in the comparison between the group of cartographers and laypersons. This symbol set could be suitable for wider usage.

Scanpath length was used to identify the difficulty or clarity of a given question (Fig. 7). The overall best result was recorded with the T10b set. This can be attributed to a rather distinctive graphical resolution of each level of uncertainty. The values of scanpath length are shown in Figure 6. In the second position was the T15b set and in third was the T8b. Scanpath length of the cartographers was

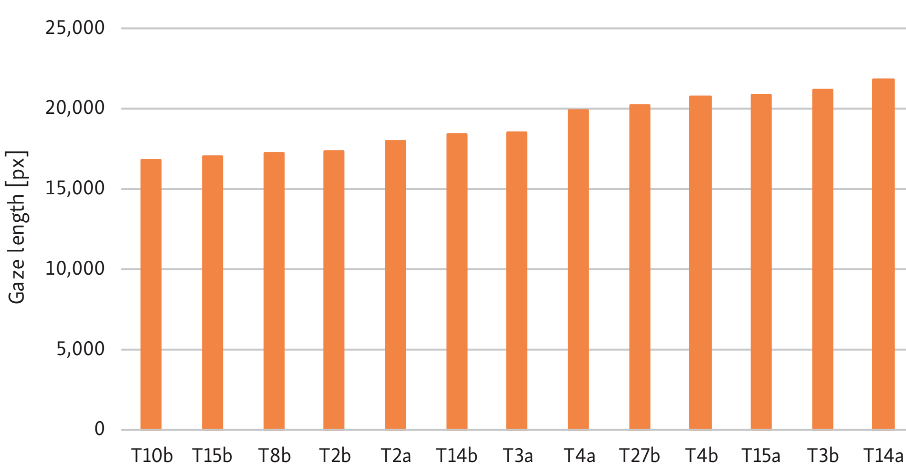


Fig. 7 – The scanpath length of the respondents' eye trajectory

Table 1 – The proportion of the total fixation time corresponding to individual parts of the map composition (gray tinted fields mean shorter fixation time)

	Total fixation time proportion (%)			
	Variant "a"		Variant "b"	
Comparative stimuli	Legend	Map field	Legend	Map field
T2	18.40	77.50	14.68	82.73
T3	18.70	77.14	18.04	78.63
T4	14.84	81.80	15.66	82.38
T14	20.16	75.39	14.46	82.76
T15	18.61	76.86	16.25	81.41

on average 2.2% longer, especially in the more complicated graphic design of the symbols, except the T3b, T14a, and T15b sets. A relatively significant difference is also evident in the placement of trials according to the chosen legend type. The first four places were occupied by the "b" variant of stimuli, which incorporates the level of uncertainty directly into the symbols of the phenomenon.

As mentioned above, we examined two types of symbols set legends (Fig. 3). Table 1 shows a list of the results of the compared trials incorporating different legend form. Each symbol set is assigned a value that corresponds to the proportion of the total fixation time spent in the legend area and the map field (Areas of Interest), always for the variants of legends "a" and "b" (Fig. 8). Thanks to this evaluation method, an objective result is achieved because the individual values determine the proportion of the total time on fixations of the given trial. This eliminates the effect of the various execution complexities that would occur when using absolute values such as fixation time. Based on the results, it is obvious that version "b" dominated, except for one case where a shorter fixation time in the legend area in favor of the map field was always found. Based on this, it can be concluded that this mode of sage was a more intuitive form of implementation. These results were compiled for all respondents, without a breakdown into groups by education. We examined the data and found only one significant difference between groups, and that was in the proportion of the fixation time found in the area of the legend, which was lower for laymen.

Due to the inconsistent result, it is not possible to determine the universally more appropriate implementation of the legend. It is always necessary to consider the plurality of phenomena which will be depicted in the map. In the case of one, it is more appropriate to choose variant "a". When more than one symbol is displayed, variant "b" is superior. Moreover in 2nd questionnaire the participants evaluated variant "b" as better perceived.

Sequences of the visited AOIs were imported into ScanGraph. For the analysis, the Levenshtein algorithm was used, and the parameter was set to 1.0 (similarity

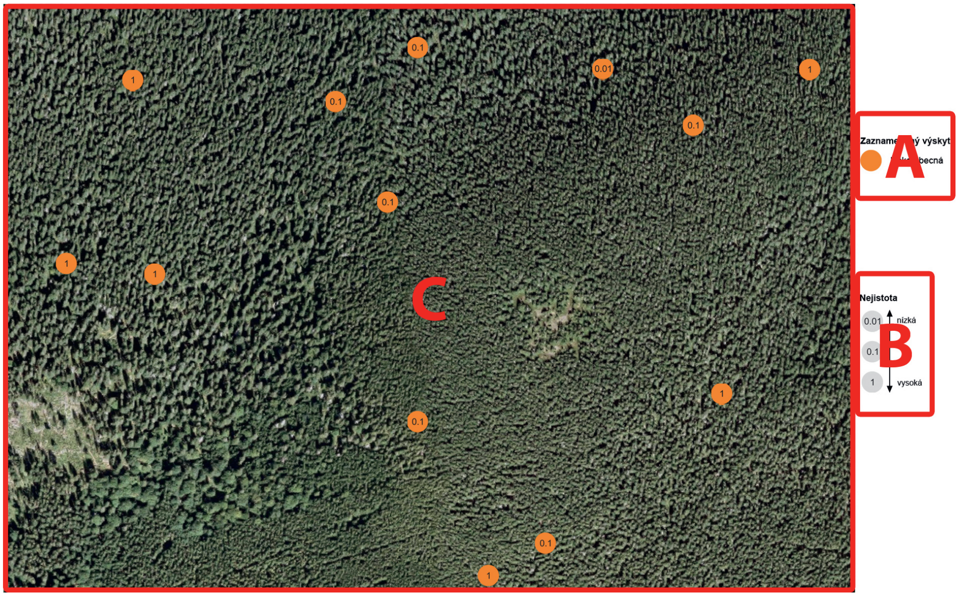


Fig. 8 – Places of interest marked on stimulus S2a

100%). That means that we were looking for participants with the same strategy of map reading. The important fact is that option "collapsed" was set, so there were no successive fixations in the sequences. For example, if a participant performed three fixations in each of the marked AOIs (AAABBBCCC), the sequence with the "collapsed" option will look like ABC. The tool's intended use is for finding similarities across different groups of participants (male/female; cartographer/non-cartographer). However, in this case, no such trend was found. So, it is not possible to say that for example, cartographers used a completely different strategy to non-cartographers. Figure 9 shows the groups' mixed nature (cartographers and non-cartographers). Cartographers are displayed as dark dots; non-cartographers are represented by bright dots.

For that reason, the tool was used in a slightly different way. Figure 10 is enhanced by the sequences that were recorded for found groups. It is evident that there is almost no "A" letter in these sequences. All sequences started with the letter "C" which means that the respondents investigated the map. It is logical because their gaze started from the center of the stimuli. In few cases, fixation in AOI "A" follows. However, respondents looked there only once, and no other fixation on this AOI is recorded.

This corresponds to the average number of fixations, which is 69 in the map (C), 16.5 in the part describing the uncertainty (B) and only 4 fixations in the first part of the legend (A).

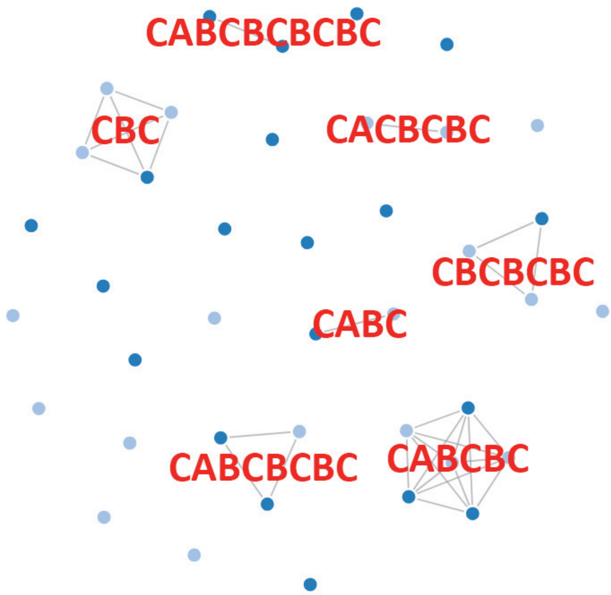


Fig. 9 – Groups of participants with the same sequence of visited AOIs on the example of stimulus 2A

In the next step, data for all five pairs of stimuli were combined, and similarity of the visual inspection strategy was analyzed across all stimuli. The graph now contains 200 nodes (40 participants × 5 stimuli) and their color does not represent if they are cartographers, but the belonging to the stimulus. Similar behavior as for the stimulus 2a was observed for all stimuli (with "a" variant of the legend). If the fixation in AOI "A" was recorded, it is only once at the beginning of the sequence.

The graph in Figure 11 depicts the average number of fixations recorded in the two legend AOIs. In the case of variant A – the total value was given as a sum of fixations in part A (grey) and part B (yellow).

4.2. The overall ranking of the symbol set

The final scoring of the tested symbol was based on ranking within the parameters gained by eye-tracking metrics and the second questionnaire which was held after the eye-tracking trials. Participants of experiment evaluated the user preferences of symbols via the 2nd questionnaire This evaluation was beneficial for T4b and T8b symbol sets (Table 2). These symbol sets achieved the same result with a median of the overall score of 6. This was followed by sets T15b and T10b, which also achieved a median of 6, but their scores included significantly lower marks of

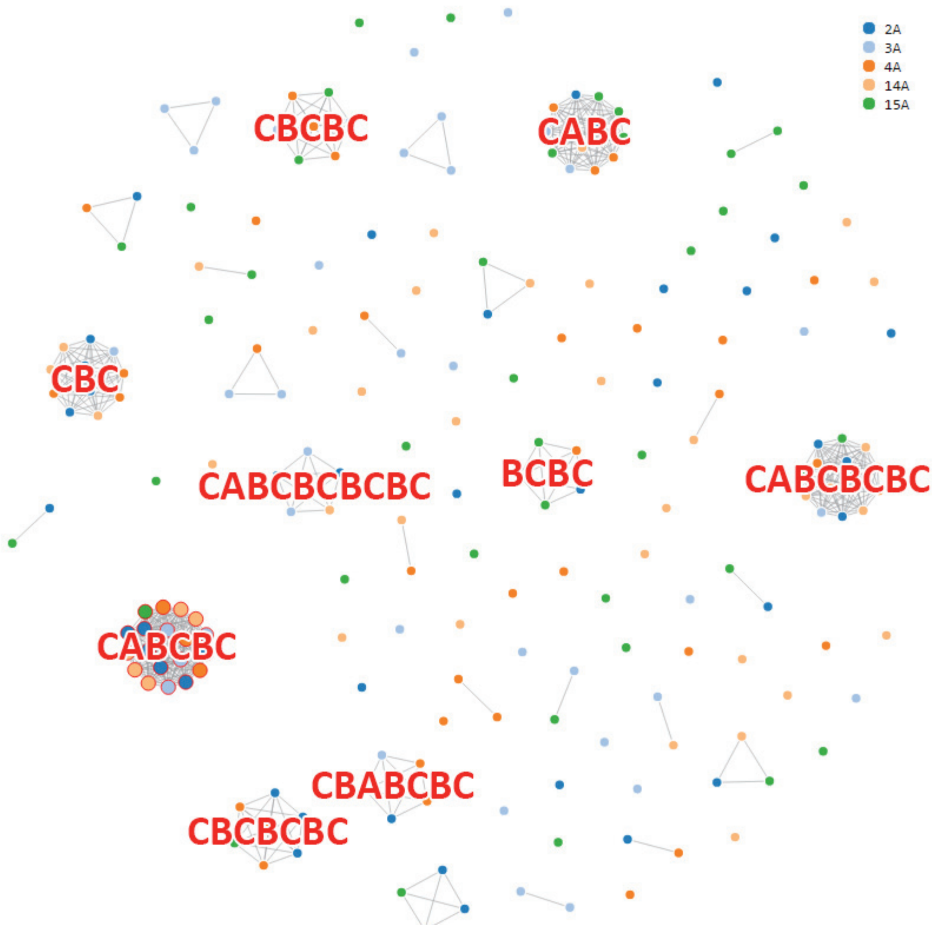


Fig. 10 – Groups of participants with the same sequence of visited AOIs across five stimuli with the "a" variant of the legend

perceived suitability, thus placing them in 3rd and 4th place. In a comparison of preferences of legend type, the first 6 places were occupied by the implementation of B legend variant. It can be said that users prefer this implementation and it can be recommended as a more suitable variant based on individual sub evaluations.

Table 2 contains the order of symbol sets within each evaluated criterion. The best result was achieved by the T8b, T10b and T15b sets. Again, it is necessary to draw attention to the possible distortion of the result for the T8b and T15a sets. In case of evaluating individual symbol sets by combining the results of both trials containing them and differing only in the chosen legend variant, then the best result would be achieved by the T2a/T2b pair. Results proved that users prefer

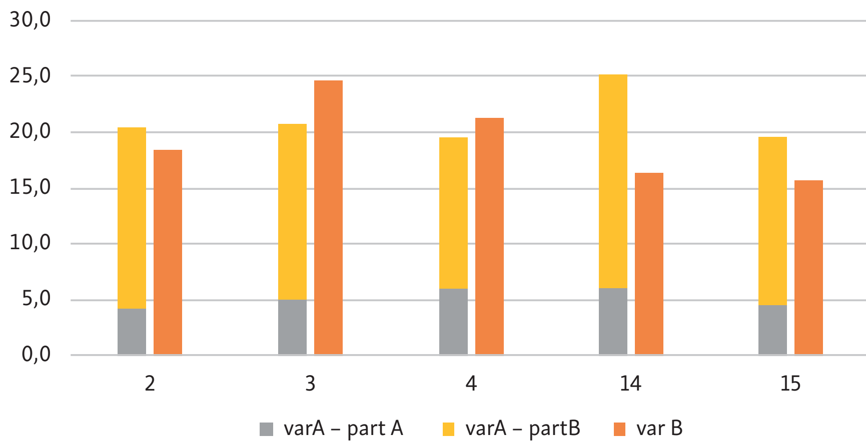


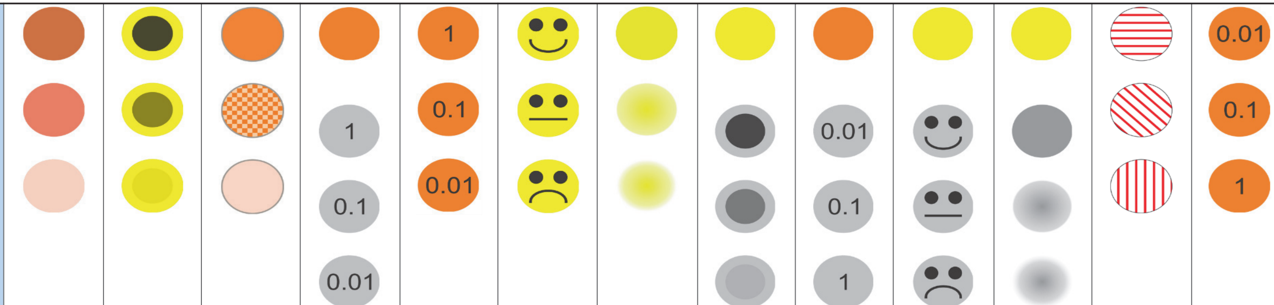
Fig. 11 – Average number of fixations in legend AOI

and intuitively work with symbols using saturation as information about the uncertainty. Interestingly, the same symbol set T15b and T15a work differently when using different legends. There are also differences between respondents' rankings of suitability and the overall performance of symbols in the eye-tracking task. The demonstrative example is T4b, which was chosen as most suitable, but during testing was in the middle of ranking.

5. Conclusion and discussion

During the experiment, we validate several theories. Simple user preference of symbols doesn't equate to their suitability for practical development. As an example, consider set T14b, which used fuzzification. Majority of respondents favored this symbol set and its modifications. Subsequently, they did not perform well during the eye-tracking task and were also ranked lower in the second questionnaire, mainly to the difficulty they presented in actual use. This finding is in contrast to the work of MacEachren et al. (2012) where fuzziness works particularly well. In this study the authors also do not recommend saturation. In our experiment, this symbol set was the best ranked. The main difference between the studies is with the parameters for ranking the symbols. The ranking parameters were the number of correct answers to the given question, the average trial tracking time, the average length of the eye trajectory, and the level of perceived suitability. We can also prove that there is a clear difference in intuitiveness for representing uncertainty among symbols based upon individual visual variables. In contrast to MacEachren et al., we considered the way the legend was implemented. The results showed

Table 2 – Final ranking of symbol sets

Symbol set													
	T8b	T15b	T10b	T2a	T2b	T4b	T14b	T15a	T3a	T4a	T14a	T27b	T3b
Correctness of question	1	4	7	3	6	5	12	2	10	8	11	9	13
Trial duration	1	4	3	7	8	12	6	5	2	9	10	13	11
Gaze length	3	2	1	5	4	10	6	11	7	8	13	9	12
Evaluation of suitability	2	3	4	8	6	1	5	11	12	7	10	13	9
Final ranking	1	2, 3		4	5	6	7, 8		9	10	11, 12		13

that symbols which directly incorporate uncertainty in the visual variable work better than legends with separation of uncertainty and symbols. This is mainly because its appearance can significantly affect the speed and accuracy of the interpretation of the results. Even more in all parts of the work, the results were compared between groups of respondents with and without GIScience education. This step aimed to evaluate the impact of this knowledge on the process of reading a map with a representation of uncertainty. The cartographers represent an expert opinion, and a group of laymen then provides a way of understanding how people without GIScience background get the information from the map. Thanks to this knowledge, it is possible to design symbol sets in such a way that their practicability can target a wider audience. In fact, our results suggest that with reference to the particular symbol sets we examined, those with GIScience background and laypersons utilize each legend type similarly. More research in different map environments can build on these initial findings.

Additionally, the experimental setup can be biased by several in-text mentioned problems. A continuing area of concern is in the understanding of the term 'uncertainty', even in the GIScience community. It remains relatively unusual to find users with knowledge about spatial data uncertainty. Due to this general naivety to the term 'uncertainty', we were concerned that the results could be affected if we were show examples to participants at the start of the eye-tracking study. For this reason, we provide an explanation but not show visual form of uncertainty visualization before the experiment, in order to prevent possible bias.

Nonetheless, we believe that the presented study will aid in the understanding of user preferences and to show a possible direction of research to assess user preferences through quantitative methods.

References

AIPPERSPACH, R. (2006): Categorization and Toolkit Support for Uncertainty Visualization. Retrieved from http://vis.berkeley.edu/courses/cs294-10-sp06/wiki/images/2/21/AipperspachFinalReport.pdf (5.5.2019).

BEARD, M.K., BUTTENFIELD, B.P., CLAPHAM, S.B. (1991): NCGIA Research Initiative 7: Visualization of Spatial Data Quality: Scientific Report for the Specialist Meeting 8–12 June 1991, Castine, Maine. Retrieved from Santa Barbara.

BERJAWI, B., DUCHATEAU, F., CHESNEAU, E., FAVETTA, F., SECCIA, G., CUNTY, C., MIQUEL, M., LAURINI, R. (2014): Uncertainty visualization of multi-providers cartographic integration. Journal of Visual Languages and Computing, 25, 6, 995–1002, doi:10.1016/j.jvlc.2014.10.033.

BRAND, J., JOHNSON, A.P. (2014): Attention to local and global levels of hierarchical Navon figures affects rapid scene categorization. Frontiers in psychology, 5, 1274.

BRUS, J. (2014): Vizualizace nejistoty v environmentálních studiích (1st edition ed.). Univerzita Palackého v Olomouci, Olomouc.

BRUS, J., PECHANEC, V., MACHAR, I. (2018): Depiction of uncertainty in the visually interpreted land cover data. Ecological Informatics, 47, 10–13, doi:10.1016/j.ecoinf.2017.10.015.

BRUS, J., VOŽENÍLEK, V., POPELKA, S. (2013): An Assessment of Quantitative Uncertainty Visualization Methods for Interpolated Meteorological Data. In: Murgante, B., Misra, S., Carlini, M., Torre, C.M., Nguyen, H.Q., Taniar, D., Apduhan, B.O., Gervasi, O. (eds.): Computational Science and Its Applications – Iccsa 2013, Pt Iv 7974, 166–178.

ÇÖLTEKIN, A., FABRIKANT, S.I., LACAYO, M. (2010): Exploring the efficiency of users' visual analytics strategies based on sequence analysis of eye movement recordings. International Journal of Geographical Information Science, 24, 10, 1559–1575.

DOLEŽALOVÁ, J., POPELKA, S. (2016): ScanGraph: A Novel Scanpath Comparison Method Using Visualisation of Graph Cliques. Journal of Eye Movement Research, 9, 4, doi:ARTN 510.16910/jemr.9.4.5.

EGETH, H., DAGENBACH, D. (1991): Parallel versus serial processing in visual search: Further evidence from subadditive effects of visual quality. Journal of Experimental Psychology: Human Perception and Performance, 17, 2, 551.

FINGER, R., BISANTZ, A.M. (2002): Utilizing graphical formats to convey uncertainty in a decision-making task. Theoretical Issues in Ergonomics Science, 3, 1, 1–25.

FUHRMANN, S., KOMOGORTSEV, O., TAMIR, D. (2009): Investigating hologram-based route planning. Transactions in GIS, 13, 177–196.

HABER, R.B., MCNABB, D.A. (1990): Visualization idioms: A conceptual model for scientific visualization systems. Visualization in scientific computing, 74, 93.

HOŠKOVÁ-MAYEROVÁ, Š. et al. (2013): Spatial Database Quality and the Potential Uncertainty Sources. In: Proto, A.N., Squillante, M., Kacprzyk, J. (eds): Advanced Dynamic Modeling of Economic and Social Systems, Springer, 127–142.

INCOUL, A. et al. (2015): Comparing paper and digital topographic maps using eye tracking. In: Brus, J., Vondráková, A., Voženílek, V. (eds): Modern Trends in Cartography, Springer, 339–356.

KINKELDEY, C., MACEACHREN, A.M., RIVEIRO, M., SCHIEWE, J. (2017): Evaluating the effect of visually represented geodata uncertainty on decision-making: systematic review, lessons learned, and recommendations. Cartography and Geographic Information Science, 44, 1, 1–21, doi:10.1080/15230406.2015.1089792.

KINKELDEY, C., SENARATNE, H. (2018). Representing Uncertainty. The Geographic Information Science & Technology Body of Knowledge.

KUBÍČEK, P., ŠAŠINKA, Č., STACHOŇ, Z. (2014): Vybrané kognitivní aspekty vizualizace polohové nejistoty v geografických datech. Geografie, 119, 1, 67–90.

KUBÍČEK, P., ŠAŠINKA, Č., STACHOŇ, Z., ŠTĚRBA, Z., APELTAUER, J., URBÁNEK, T. (2017): Cartographic design and usability of visual variables for linear features. The Cartographic Journal, 54, 1, 91–102.

LERMUSIAUX, P.F., CHIU, C.S., GAWARKIEWICZ, G., ABBOT, P., ROBINSON, A.R., MILLER, R.N., HALEY, P.J., LESLIE, W.G., MAJUMDAR, S.J., PANG, A., LEKIEN, F. (2006): Quantifying uncertainties in ocean predictions. Oceanography, 19, 1, 90–103.

LI, L. (2017): Spatial data uncertainty. The Geographic Information Science & Technology Body of Knowledge, 4th Quarter 2017 Edition.

LONGLEY, P.A., GOODCHILD, M., MAGUIRE, D.J., RHIND, D.W. (2005): Geographic information systems and science: John Wiley & Sons.

MACEACHREN, A.M. (1995): How maps work : representation, visualization, and design. New York: Guilford Press.

MACEACHREN, A.M., ROBINSON, A., HOPPER, S., GARDNER, S., MURRAY, R., GAHEGAN, M., HETZLER, E. (2005): Visualizing geospatial information uncertainty: What we know and what we need to know. Cartography and Geographic Information Science, 32, 3, 139–160.
MACEACHREN, A.M., ROTH, R.E., O'BRIEN, J., LI, B., SWINGLEY, D., GAHEGAN, M. (2012): Visual Semiotics & Uncertainty Visualization: An Empirical Study. Visualization and Computer Graphics, IEEE Transactions on, 18, 12, 2496–2505.
MACHAR, I., VOŽENÍLEK, V., KIRCHNER, K., VLČKOVÁ, V., BUČEK, A. (2017): Biogeographic model of climate conditions for vegetation zones in Czechia. Geografie, 122, 1, 64–82.
PANG, A. (2001): Visualizing uncertainty in geo-spatial data. Paper presented at the Workshop on the Intersections between Geospatial Information and Information Technology.
PANG, A.T., WITTENBRINK, C.M., LODHA, S.K. (1997): Approaches to uncertainty visualization. The Visual Computer, 13, 8, 370–390.
PECHANEC, V., BURIAN, J., KILIANOVÁ, H. (2011): Geospatial analysis of the spatial conflicts of flood hazard in urban planning. Moravian Geographical Reports, 19, 1, 41–49.
POPELKA, S., DOLEŽALOVÁ, J., BEITLOVÁ, M. (2018): New features of scangraph: a tool for revealing participants' strategy from eye-movement data. Paper presented at the Proceedings of the 2018 ACM Symposium on Eye Tracking Research & Applications.
POTTER, K., ROSEN, P., JOHNSON, C.R. (2012): From quantification to visualization: A taxonomy of uncertainty visualization approaches Uncertainty Quantification in Scientific Computing, Springer, 226–249.
SHI, W. (2010): Principles of modeling uncertainties in spatial data and spatial analyses. Boca Raton: CRC Press/Taylor & Francis.
VEREGIN, H. (1999): Data quality parameters. Geographical information systems, 1, 177–189.
WONG, P.C., SHEN, H.W., JOHNSON, C.R., CHEN, C., ROSS, R.B. (2012): The top 10 challenges in extreme-scale visual analytics. Computer Graphics and Applications, IEEE, 32, 4, 63–67.

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The content of this Special Issue of Geografie Journal has been prepared together with the International Cartographic Association, namely with the Commission on Cognitive Issues in Geographic Information Visualization, the Commission on Use, User and Usability Issues, and the Commission on Atlases. Selected authors were contacted during the ICA Commissions' joint workshop "Atlases, Cognition, Usability" held in Olomouc (Czechia) at Palacký University in April 2018. The content of the Special Issue reflects the current topics handled by the Commissions and we hope that the special issue increases awareness and knowledge of cognitive and usability issues with geographic information among the broader geographic community. Preliminary selection of manuscripts and pre-submission communication with authors was done by Petr Kubíček (Masaryk University, proposed incoming co-Chair of the Cognitive Issues in Geographic Information Visualization Commission) and Amy Griffin (RMIT University, current co-chair of the Cognitive Issues in Geographic Information Visualization Commission). We thank all of the authors who contributed their research to this special issue.