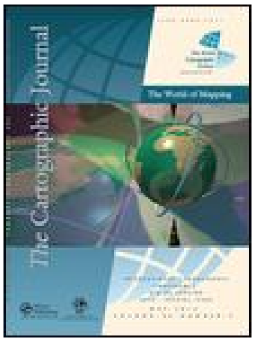

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SURVEY PAPER

Cartographic Design and Usability of Visual Variables for Linear Features

Petr Kubíček[1], Čeněk Šašinka[2], Zdeněk Stachoň[1], Zbyněk Štěrba[1], Jiří Apeltauer[3] and Tomáš Urbánek[2]

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This article addresses the measurement and assessment of response times and error rates in map-reading tasks relative to various modes of linear feature visualization. In a between-subject design study, participants completed a set of map-reading tasks generated by approaches to a traffic problem. These entailed quick and correct decoding of graphically represented quantitative and qualitative spatial information. The tasks first involved the decoding of one graphic variable, then of two variables simultaneously. While alternative representations of qualitative information included colour hue and symbol shape, the quantitative information was communicated either through symbol size or colour value. In bivariate tasks, quantitative and qualitative graphical elements were combined in a single display. Individual differences were also examined. The concept of cognitive style partially explains the variability in people's perception and thinking, describing individual preferences in object representation and problem-solving strategies. The data obtained in the experiment suggest that alternative forms of visualization may have different impacts on performance in map-reading tasks: colour hue and size proved more efficient in communicating information than shape and colour value. Apart from this, it was shown that individual facets of cognitive style may affect task performance, depending on the type of visualization employed.

Keywords: cartographic design; usability; transport; cognitive style

INTRODUCTION

The representation of geographic information and its usability constitute an important part of the research agendas in both the geovisualization (MacEachren and Kraak, 2001) and the GIScience cognition communities (Montello, 2009). The importance of cognitive adequacy for successful analysis and decision-making has also been pointed out by Andrienko *et al*. (2007).

Transportation applications, including navigation, have always been a challenging area of visualization, with several contexts to be addressed. An emergency dispatch centre responsible for rapid response to traffic incidents may be considered one such particular context. As pointed out by Goldsberry (2008), many current traffic maps violate cartographic conventions and create gaps between the traffic information database and the ability of users to read the map. Despite the broad acceptance of such conventions both in textbooks (Slocum *et al*., 2009; Voženílek *et al*., 2011) and within different application communities, there is still a lack of empirical evidence for an effective and efficient use of such conventions. The system of seven visual variables proposed by Bertin (1983) is among the often discussed conventions (Fabrikant and Goldsberry, 2005; Garlandini and Fabrikant, 2009; Griffin, 2008; MacEachren *et al*., 2012). Bertin suggested that these variables are logically correct for communication. However, neither map designers nor map users are aware of cognitive processes involved in the decisions based on these variables. Moreover, Bertin mentioned the employment of these variables for individual use only, while in real situations they are combined in maps for a multivariate display (MacEachren, 1995). Following the original Bertin's hypothesis, Nelson (1999, 2000) studied how groupings of visual variables influence the ability of map users to read and infer information from complex visual representations. She particularly focused on bivariate point symbol design and provided an empirical background for effective choice of combination of graphic variables. Choosing an effective method of symbolization for bivariate map is also connected with the data type (qualitative and quantitative) and Nelson (2000) proposed a typology of

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visual variables combination based on geometric representation (point, line, and area), data type, and preferred combination. Hue and size combination was proposed as the most effective for qualitative/quantitative data mixture visualization.

The specificity of traffic maps was studied by Goldsberry (2008), who explored how variable symbolization influenced the perception of traffic maps. Among others he also proposed and tested the possibility of using cultural metaphor (traffic light) to optimize the intuitiveness of the map despite violating cartography rules. The results of empirical test demonstrated that the tested map-readers seem to decode the map's stoplight symbology with ease regardless of the absence of a legend. Dong *et al*. (2012) evaluated dynamic symbols for traffic flow data, comparing size and colour as two most prominent graphic variables. They found that variable size (line thickness) outperformed colour in both effectiveness and efficiency. Just recently, Lautenschütz (2012) used the traffic light metaphor for speed depiction on linear symbols. The combination of line thickness and colour representing speed was used to visually highlight line elements and make them perceptually salient.

The issue of cartographic visualization is also closely related to visual cognition research, which has a long tradition in psychology (for overview see Wolfe, 1994, 1998; Pinker, 1984). The results from this field have naturally been applied in the field of cartography (Ciołkosz-Styk, 2012). However, it must be noted that the applicability of such findings is quite limited since the stimulus material employed in most psychological studies is very simple. In contrast, maps always represent very complex types of stimuli (Edler *et al*., 2014; Thorndyke and Stasz, 1979), carrying specific information and quite often combination of graphic and textual information in case of labels placed with a varying level of efficiency (Ooms *et al*., 2012). During map-reading tasks many different types of cognitive processes are progressively engaged, depending on the kind of instruction used, and the researcher has little means of separating and studying them in isolation. The effect of cartographic sign attributes thus cannot be studied irrespective of the actual meaning of the signs. Ogao (2002) attempts to describe the different map tasks and activities in cartography from a psychological perspective by employing Neisser's (1967) conceptualization of cognition, understood as the complete set of processes responsible for the transformation, reduction, processing, storage, retrieval, and application of sensory input. According to Ogao (2002), all the sensory inputs provided by maps can be explained by these processes. In cartography, they are defined in relation to localization and attributes of objects in space. Medyckyj-Scott and Board (1991) pointed out that, in cartography, cognition research revolves around the issue of active processing of maps by the individual, especially addressing the question of how cognitive-based structures and processes such as memory, reasoning, imagination, motivation, and attention contribute to this kind of processing. The application of psychological concepts to the area of cartographic research is presented e.g. in the work by Allen *et al*. (2006), who studied how information is derived from simple meteorological maps, focusing not only on the domain-specific knowledge of the user, but mainly on deeper understanding of the actual cognitive processes employed (e.g. spatial scanning or flexibility of closure). A different approach was chosen by Popelka *et al*. (2013), who created a typology of map-readers based on their eye movements when completing map-related tasks. In the study, a device for recording eye movements (an eye-tracker) was used. Confirming that users read maps in varying ways, the study divided the participants into several groups, based on the procedures they chose.

The results of the above studies stress the importance of taking into account between-participant differences (in map reading) during the evaluation process.

INDIVIDUAL DIFFERENCES BETWEEN MAP-READERS

Individuals vary not only with respect to the level of their cognitive abilities – for instance, their working memory capacity (Daneman and Carpenter, 1980) – but also with respect to the way these abilities are organized within the brain. In the present study, individual differences in the participants' performance with respect to map tasks were examined in terms of cognitive style. Isaksen and Puccio (2008) note that research on cognitive styles derives from the study of perception and personality. Gardner *et al*. (1959) define cognitive style as a developmentally stable form of cognitive control which remains invariant across different situations. Kozhevnikov (2007) describes cognitive styles as heuristics that is used by the individual when processing information about the environment and which can be detected at both elementary (automated) as well as complex (conscious) levels of perception and cognition. Riding and Cheema (1991) argue that today's research is primarily directed at two specific dimensions of cognitive style – the verbal-imagery dimension, which refers to the preference for information that is presented either verbally or in the form of visual images, and the global (wholistic)-analytic dimension, which reflects information structuring preferences.

Sadler-Smith (2001) makes a distinction between 'verbalizers', individuals who prefer encoding information in the form of verbal associations, and 'imaginers' (also called visualizers), those who prefer information in the form of mental images. In addition to this, Blazhenkova and Kozhevnikov (2009) differentiate within the traditional visual-verbal dimension between 'object imaginers' and 'spatial imaginer'. Object imagery orientation is determined by the preference of the individual for generating vivid, concrete, and detailed images. On the other hand, spatial imagery uses images to generate quite schematic representations of spatial relationships between objects. Blajenkova *et al.* (2006) add that object imaginers pay more attention to individual objects and recognize specific attributes such as shape, size, colour, etc. In contrast, spatial imaginers tend to focus on relatively abstract representations of spatial objects and their parts, are better at localizing objects in space and motion, and are also generally more effective in performing complex spatial transformations. Kozhevnikov *et al*. (2005) argue that object imaginers encode and process images more holistically, as a single perceptual unit, whereas spatial visualizers generate and process images analytically.

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In terms of the wholistic-analytic dimension, individuals of the global type tend to perceive the given situation in a comprehensive manner, considering a broader perspective and the context of what is happening. Analytically oriented individuals, on the other hand, perceive the situation as an aggregate of discrete elements, typically concentrating upon only one or two of them at the expense of others (Rezaei and Katz, 2004). Graff (2003) points out that a wholistic-analytic cognitive approach can be defined as describing the tendency of the individual to process information either as an integrated whole or as a set of discrete components. Analyzers are able to grasp the individual parts of ideas, but they might have problems integrating these partial concepts into complete units. By contrast, holistically oriented individuals are able to approach concepts as wholes, but they may have difficulties separating individual ideas into discrete components.

Taking into account the above, the objective of this study was to propose an effective and efficient method for the decoding of bivariate linear symbols. In addition, the study sought to empirically evaluate the suitability of the graphic variables combinations for practical tasks of varying complexity. Selected combinations of linear symbols were designed and tested within traffic map settings in order to ensure the applicability of the results.

We assume that various combinations of the four forms of visualization used in our study represent different levels of cognitive load for discrete parts of the cognitive system, and hence might vary in their compatibility with the cognitive styles that were described above.

EXPERIMENT

Stimuli

The basic stimulus material consisted of cartographic visualizations and supplementary psychological tests that could divide the test battery into three main parts (see Figure 1). The stimulus material, its design (including graphic variables used) and the structure of the psychological tests are described in this section.

In our study, we faced the problem of visualization of alternative routes (detours) which have two mandatory variables to be visualized – road passability and available road capacity. Since road passability is a qualitative variable (car, lorry, truck) and road capacity is a quantitative, we resolved the issue of bivariate visualization of linear features by combining both qualitative and quantitative characteristics in a single display. Two versions of visualization were selected, based on Bertin's (1983) visual variable categories (selective, associative, ordered, and quantitative) and justification given in a previous work addressing 2D map assessment (Garlandini and Fabrikant, 2009). A combination of *colour hue* and *size* was used for version A, whereas line *shape* and *colour value* were combined for version B. Both methods are frequently used for bivariate visualization (Nelson, 2000) in transportation applications. All variables were classified into three intervals: the road passability variable distinguishes routes for (a) *personal cars*, (b) *lorries*, and (c) *trucks*, while the road capacity variable was divided into intervals (a) *0–300 vehicles per hour*, (b) *301–600 vehicles per hour*, and (c) *601 and more vehicles per hour*. Each stimulus contains a map field with a cartographic visualization corresponding to either version A or B, and a map legend clarifying the meaning of the linear symbols. Combinations of graphical variables and the composition of the final maps used in the two versions of map-reading tests are shown in Figure 2.

The cartographic stimulus material was designed as a simplified visualization which can minimize the influence of selected area. It consisted of, first, only the univariate (Figure 1 – A.1–2; B.1–2; see Figure 3 for design description) visualization and, second, the bivariate visualization (Figure 1 – A.3 and B.3) that represent both qualitative and quantitative variables. These stimuli formed two sections of the map-reading test (section 1 and section 2), starting with the simpler tasks but progressing with the more complex ones (the bivariate visualizations). The design of all maps was the same through the whole experiment in order not to distract the users' attention. In addition to the linear symbols visualizing the information about detours, some simple background information was included, consisting of urban areas and green areas representing forests. These

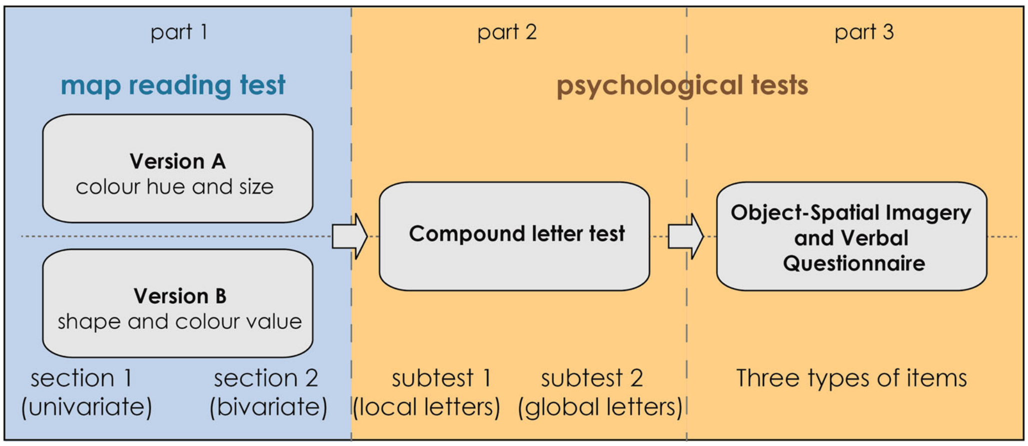

Figure 1. Experimental design used for the study

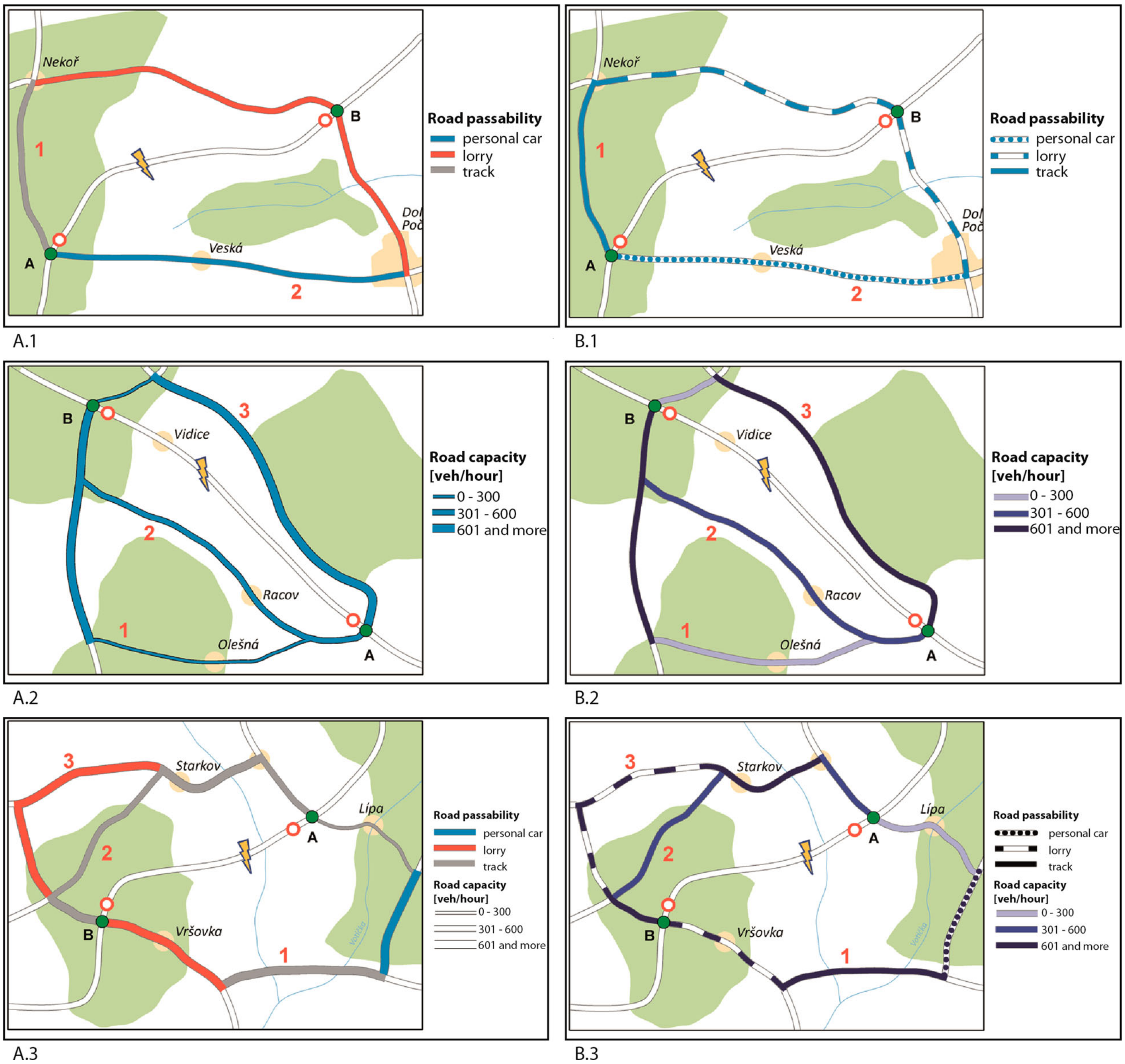

Figure 2. Examples of linear symbols for (A.1) qualitative variable – colour hue used in version A, (A.2) quantitative variable – colour value used in version A, (A.3) bivariate linear symbols with the combination of colour hue and size in version A and corresponding variants for the version B (B.1–B.3)

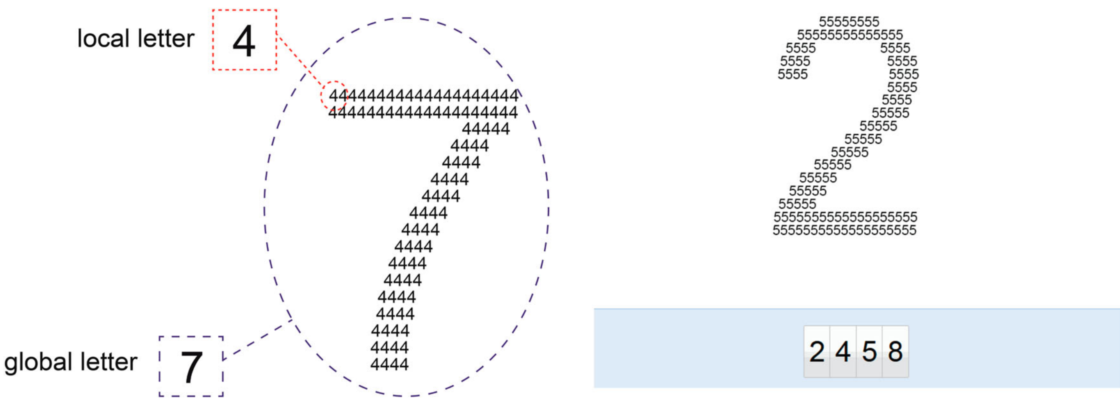

Figure 3. Detailed structure of map-reading test (part 1 see Figure 1) – sections and subsections in the first part of the test battery

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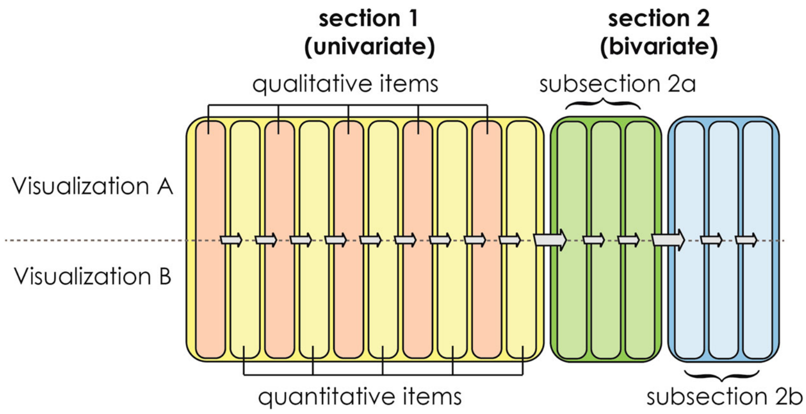

Figure 4. Principle of a compound stimuli (left); an item from the Compound letter test adapted into the MuTeP environment (right)

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elements were visualized to increase the representativeness of the experimental design (Brunswik, 1955).

The last part of the test battery consisted of psychological tests. It contained a variation of Navon's hierarchical figures test (Navon, 1977), Object-Spatial Imagery and Verbal Questionnaire (OSIVQ, Blazhenkova and Kozhevnikov, 2009). For the purposes of this study, a compound letter test (see e.g. Figure 4 right) was designed within the MuTeP virtual workspace, as a variation of Navon's hierarchical figures test. Navon's test (Navon, 1977) is one of the most frequently used methods for the measurement of the global-analytic dimension of cognitive processing (e.g. Brand and Johnson, 2014; Duchaine *et al.*, 2007; Yovel *et al.*, 2005). Our study employed a tool based on Navon's hierarchical figures task, used for the measurement of a person's ability to direct attention either to the local level of visual stimulus material or to the global level (see Figure 4 left).

Object imagery *vs.* spatial imagery *vs.* verbalizer cognitive styles were measured using OSIVQ (see e.g. Table 1), an adaptation of the OSIVQ questionnaire by Vidláková (2010), who translated the OSIQ (object-spatial imagery questionnaire; see Blajenkova *et al.* 2006) into Czech and expanded it later by adding the verbal dimension (OSIVQ; see Blazhenkova and Kozhevnikov, 2009). Thus, the measure involves three dimensions of cognitive style.

Research questions

The aim of the present study was to investigate a set of hypotheses based on the theoretical background presented in the introduction. The hypotheses focused in part on the comparison of the cartographic visualization methods employed in the experiment; in addition, the experiment examined the level of correlation between the participants' performance regarding alternative cartographic visualizations and the participants' scores in the test of cognitive styles. For alternative visualizations, we hypothesized that the A version will result in lower reaction times. The hypothesis was based on the characteristics of basic graphic primitives and the concept of similarity. Map reading requires parallel activation of low-level cognitive processes respectively early vision processes (Henderson and Hollingworth, 1999) and higher-level processing related to symbols and their meaning (e.g. Horz and Schnotz, 2010). It has been suggested (Bertin, 1983; Lautenschütz, 2012; Nelson, 2000) that, of basic graphic primitives, colour hue and size can be expected to aid visual processing. In addition, we drew on the concept of similarity in the communication of meaning. Hahn *et al.* (2003) describe their new theoretical approach to similarity – 'representational distortion'. Hahn *et al.* (2003, p. 2) stating that "the similarity between two entities is a function of the 'complexity' required to 'distort' or 'transform' the representation of one into the representation of the other". In the context of map reading, the similarity in question concerns the relationship between a mental representation of a given phenomenon (i.e. its meaning) and its objective representation (i.e. graphic visualization). We suggest that the concept of road capacity is more readily understandable if its mental representation is supported by the size (line width) of the objective representation. The mental transformation may then proceed as follows: The wider the road, the more cars it can hold (meaning, the greater capacity it has). By analogy then, the wider the line in the map, the greater the capacity of the road it represents. However, the employment of a varying colour hue instead of line width to symbolize road capacity can be assumed to require an additional transformation, whereby colour is translated as representing size. Two transformations are then performed: from colour hue to size (deeper colour represents wider lines) and from size (width) of the line in the map to the

Table 1. Examples of items in the OSIVQ; Blazhenkova and Kozhevnikov (2009)

Measured dimension	Used statements in the questionnaire
Spatial imagery	I was very good in 3D geometry as a student.
Object imagery	My images are very colourful and bright.
Verbalisers	My verbal abilities would make a career in language arts relatively easy for me.

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capacity of the road it represents. The employment of qualitative variables does not lead to a substantial difference: neither colour hue nor line shape bear analogy to the phenomena they stand for.

Our expectations respecting the relationship between an individuals' cognitive style and his/her performance were grounded in relevant theory; in addition, we drew on the results of our previous studies. The two alternative sets of symbols intended for crisis management were experimentally compared by Stachoň *et al*. (see Stachoň *et al*., 2013). The A set was characterized as more iconic (colours are used in a contrasting way, affixes are more robust, pictorial or associative clues are employed), while the B set was described as schematic (colours in individual symbols as well as in the entire set are more balanced and conservative, numbers are employed for expressing quantity and letters to increase the representativeness of symbols, e.g. 'V'). The iconic set has been found to increase reaction times in spatial imaginers (i.e. more time was needed to find target objects). No such effect has been observed for object imaginers and the schematic set. Another study investigated the relationship between global/local bias in map-readers and their performance with respect to avalanche danger maps. The study sought to compare the intrinsic and extrinsic methods of cartographic visualization (Šašinka, 2013; Štěrba *et al*., 2014). It revealed a significantly positive correlation between task times for bivariate visualization (the intrinsic method) and reaction times in the local letter subtest. At the same time, no correlation has been found between the intrinsic method and the global letter subtest. For the extrinsic method (combination of colour and shape), reverse trends have been observed: the participants with low reaction times in the global letter subtest exhibited low task times in map-reading tasks, while no effect has been found for the local letter subtest.

We hypothesized that analytically oriented map-readers and spatial imaginers will receive better times for the B map version, which was regarded as schematic and abstract because the graphic primitives it employed can be viewed as less linked to the actual phenomena the primitives represent, and successful decoding of these primitives (e.g. line shape) requires the activation of analytical brain processes. By contrast, version A, which employed hue-based phenomenon categorization, was deemed as more straightforward, and it was assumed to lend itself more readily to the wholistic cognitive style and object imagery.

Participants

In total, 147 individuals participated in the study, aged between 16 and 60. The sample consisted of 88 (60%) men and 59 women, of whom eight had finished school at the elementary level, 45 at secondary, and 94 had higher (university) education. The expertise of the group was manifold since the respondents came from diverse fields: one-third of respondents were students from the Department of Geography; the rest of them included students with technical education and novice users who attended our laboratory. We presume that this group composition represents a suitable sample that increases the external validity of the experiment. The map-reading experience criterion was further represented by the self-reported frequency of map reading: daily ($N = 15$), every week ($N = 66$), occasionally ($N = 54$), or rarely ($N = 12$). The computer proficiency criterion, which was a precondition for dealing with the task requirements and completing the test battery in an electronic form, was met by all participants. All the respondents participated in the experiment on a voluntary basis.

Setup and procedure

The study was conducted in air-conditioned computer rooms of Masaryk University and the University of Technology in Brno. All experiments were performed in controlled conditions with maximum exclusion of potentially interfering factors. The screen resolution was constant for all individuals and for all measurements taken. All the test batteries were administered in the virtual workspace of the MuTeP Software developed at the Department of Geography of Masaryk University. The MuTeP Software was launched using the Google Chrome browser and recorded every activity undertaken by the respondent, including response time and correctness of the response (for more information on the MuTeP Software, see Koláčný *et al*., 2011). Sample of both tests are available upon request.

The participants were randomly divided into two groups, completing either version A or version B of the test. Altogether, there were 77 administrations of the whole test battery of version A and 70 administrations of version B. At the beginning of the experiment, the participants were first informed about the purpose of the testing and that their participation in the study was voluntary. Next, they were asked to provide their basic personal data (gender, education, etc.), which served to divide the respondents into groups. This part also contained examples of the presentations and the geographic visualizations used in the experiment. It ended with an explanation of the cartographic methods.

The first part (map-reading test) consisted of a set of tasks regarding the cartographic stimulus material. Similar tasks were presented in two versions of cartographic visualization (version A and version B, see above): single variable (road passability and available road capacity in two separate displays) – univariate visualization decoding (marked as 'section 1') and two variables (road passability and available road capacity in a single display) – bivariate visualization decoding (marked as 'section 2'). In total, 16 test items were presented to each respondent in a systematic order on a computer screen. The first section contained 10 tasks where the visualizations of qualitative and quantitative variables were ordered alternately. The second section consisted of six tasks that included the bivariate visualizations. These tasks were also systematically ordered. Each of the tasks consisted of two consecutive slides: the first one included a task question, after that a cartographic stimulus was shown to the user. The second slide contained again the task question that was written above the cartographic stimulus. The user was asked to answer the question by clicking on the corresponding button at the bottom of the slide. The task questions differed depending on the part of the test. The first section contained questions or tasks concerning just single variable (such as 'What is the way from the point A to B that could be used by more than 300 vehicles per hour?'

Table 2. Mean values of average response time (in seconds) with statistical comparison of the two parts of the test (m – mean value; s – standard deviation; t – t-value, df – degrees of freedom, p – statistical significance).

	Visualization A		Visualization B		Welch t-test		
	m	s	m	s	t	df	p
Univariate – quality	*15.4*	*5.8*	*16.2*	*7.0*	*−0.788*	*134.1*	*0.432*
Univariate – quantity	*12.7*	*3.9*	*13.2*	*4.8*	*−0.613*	*134.1*	*0.541*
univariate – all	14.0	4.6	14.7	5.6	−0.764	133.7	0.446
Bivariate – multi-choice	*18.6*	*7.1*	*22.4*	*11.1*	*−2.456*	*115.6*	*0.016**
Bivariate – yes/no question	*18.3*	*8.3*	*19.2*	*8.3*	*−0.658*	*143.6*	*0.512*
Bivariate – all	18.5	6.6	20.8	9.0	−1.803	125.8	0.074

At the 0.01 level (2-tailed); exlude cases pairwise. Italic values represent results of particular subtests.

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for the single quantity variable, and 'Which detour from the point A to B that could be used by lorries?' for the single quality variable – see Figure 1 – A.1, B.1). All detours were always marked by a number right next to the visualized communication on the map.

The second section included questions regarding both variables; this part could be further subdivided into two subsections, characterized by two types of questions, marked as 2a and 2b. The former included three 'multiple-choice question' tasks that required determining and labelling a particular route choice (such as 'Find the way from the point A to B that could be used by more than 300 personal cars per hour', see Figure 1 – A.3, B.3). In contrast, subsection 2b employed Yes/No questions, again involving three tasks ('Is there any detour from the point A to B that could be used by more than 300 lorries per hour?'). The questions in all sections of the map-reading test were evenly distributed among all variable intervals.

The final part of the experiment consisted of a psychological test to determine cognitive styles and other personal characteristics with the compound letter test and the OSIVQ. The compound letter test included instructions, several training items, and 32 test items. The stimulus material consisted of a set of large, single-digit numbers compounded of small numbers. There were two subtests, local and global, each comprising 16 items. Participants were instructed to identify correctly the small numbers in the first subtest and the large numbers in the second subtest by clicking on one of four available buttons as quickly as possible (see Figure 2 right). The overall response time of the respondent was recorded electronically, and the average response time per item calculated. The internal consistencies (Cronbach's alpha) of both subtests were found to be high ($\alpha = 0.82$ and $\alpha = 0.89$ respectively). Finally, each respondent also took the OSIVQ test by filling in a questionnaire. In total, it consists of 45 items, with participants responding on a 5-point Likert-type scale. The questionnaire is currently in the process of standardization, conducted by the author of the adaptation. The internal consistencies of all dimensions were found to be high too (object imaginers: $\alpha = 0.77$; spatial imaginers: $\alpha = 0.84$; verbalisers: $\alpha = 0.76$).

RESULTS

The data analysis concentrated in particular on the impact of the individual visual variables on map readability, efficiency of qualitative and quantitative information processing, and overall understanding. Apart from that, we were also interested in the effects of cognitive style. At the level of descriptive statistics, we found certain general differences between participant performance in version A and version B tasks.

Overall efficiency

User efficiency was represented by the response times necessary for error-free accomplishment of a particular task. The results show slightly better scores for most tasks of version A, though the Welsch t-test revealed only one task of the map-reading test to be significantly different (*. – at the 5% level of significance) – see Table 2.

In the first section of the map-reading test (single variable tasks), six tasks received lower median response times in version A than in version B; however, the overall average difference between the two versions did not prove significant. Tasks in the first section of the map-reading test could be further divided into two groups, each consisting of tasks using either qualitative or quantitative types of question. In any case, response times in these subcategories in version A and B were not found to be significantly different either (see Table 2).

The second section of the map-reading test consisted of more complex types of task that imposed higher cognitive loads on the participants. Tasks in this section could be further divided into two subsections, characterized by two types of questions. The former included three 'multi-choice question' tasks that required determining and labelling a particular route choice. Differences between the two versions in this subsection proved significant as the average response time in version A was almost by four seconds faster than the average time in version B. By contrast, the second subsection, constructed with Yes/No questions (and again involving three tasks), did not yield any significant differences, even though response times in version A appeared to be somewhat shorter again, by almost one second. The lack of statistical significance in this subsection may be attributed to the inverse pattern of difference in one of the tasks where participants showed better scores in version B (though not significant – see the graph in Figure 5, task 14).

Although the last two subsections of the map-reading test (containing bivariate visualization) differed in the question type, the nature of the tasks remained the same for both subsections. This allowed us to group these two consecutive subsections together into a single score. For this combination we did not find any significant differences in response times

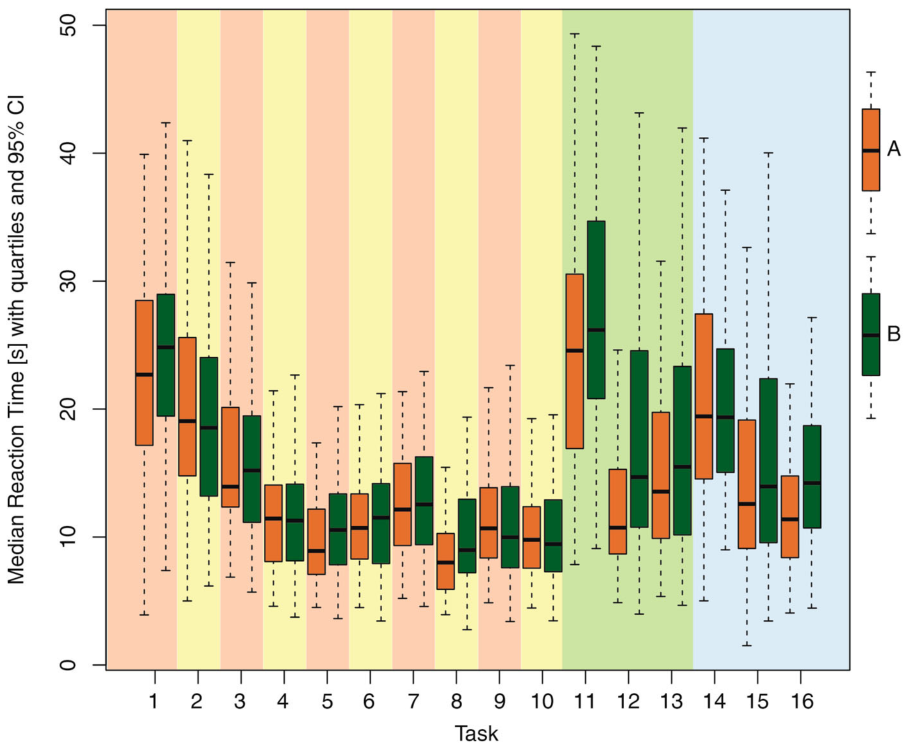

Figure 5. Mean values of response time in all sections of the map-reading test (parts 1, 2a, and 2b) with 95% confidence interval (CI) – versions A and B. (Note: Background colours correspond to the structure of the test battery described in detail on the Figure 3)

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between both versions. This insignificancy of the differences might have been caused by the combination of both subsections where the contradictory results influence the overall score of the whole section.

In summary, slight differences were found between the two versions in most of the tasks (see Figure 5). Each section of the test also indicates a clear tendency towards decreasing response times in the progress of the subset, which was probably due to the effect of learning. Since this pattern was very similar for both versions, we derived no implications for further interpretation.

Overall effectiveness

User effectiveness in completing the test was also monitored. In each task, there was only one correct answer, with all the others regarded as incorrect. Differences in effectiveness were examined using the non-parametric Kruskal–Wallis tests.

In the first section of the test, virtually no differences in effectiveness emerged between version A and version B. The average error rate for qualitative tasks was 2.1% for version A and 2.3% for version B ($H = 0.004$; *ns*). Quantitative tasks produced somewhat better results with average error rates of 0.5% for version A and 0.71% for version B ($H = 0.240$; *ns*). The overall error rate for the first part was 2.6% for version A and 3% for version B ($H = 0.340$; *ns*). None of the single error rates (for the individual tasks) was statistically significant.

The results were similar for the second section of the test. None of the variables tested showed any significant difference. For multiple-choice question tasks, the average error rate was 4.3% in version A and 6.6% in version B ($H = 2.656$; *ns*). Only one task (number 11) produced significantly different error rates in the two versions, i.e. 2.6% in version A and 11.4% in version B ($H = 4.510$; $p < 0.05$). The results were even more comparable for the Yes/No questions, with error rates of 12.9% in version A and 11.9% in version B ($H = 0.226$; *ns*).

Effects of cognitive style

Tables 3 and 4 show correlations between response times achieved in the map-reading tasks and all psychological measures completed by participants. The compound letter test score is represented by the average response times achieved in the various subtests featuring compound *vs*. local letters. Hence, lower scores actually mean higher levels of the corresponding processing style or ability (Wholistic *vs*. Analytical). With the OSIVQ questionnaire, the values represent the actual scores in the three independent cognitive styles resp. dimensions – verbal, object imagery, and spatial imagery. Higher scores thus represent higher levels of the trait in this section.

DISCUSSION

This experimental study investigated the effects of different visual variables used for linear feature cartographic visualizations on the ability of map users to perceive visual information and infer further data from it. In this section, the results are further discussed from various perspectives,

Table 3. Correlation between achievements in the A version of cartographic tasks and psychological tests (OSIVQ and compound letter test)

Spearman's rho	OSIVQ			Compound letter test	
Visualization A	*Object*	*Spatial*	*Verbal*	*Local letters*	*Global letters*
Univariate – quality	*−0.17*	*−0.08*	*−0.11*	*.30***	*0.14*
Univariate – quantity	*−.26**	*−0.02*	*−0.08*	*.29**	*0.09*
Univariate – all	−0.21	−0.05	−0.11	.30**	0.10
Bivariate – multi-choice	*−.28**	*0.06*	*−0.15*	*.29**	*0.11*
Bivariate – yes/no question	*−0.01*	*−0.05*	*−0.04*	*0.20*	*0.01*
Bivariate – all	−.24*	0.02	−0.10	.32**	0.09

*The correlation is significant at the 0.05 level (2-tailed); **The correlation is significant at the 0.01 level (2-tailed); exlude cases pairwise.

starting with the general level of effectiveness and efficiency of different visual representations and then placing the results in the context of previous studies. The results are discussed at two levels, beginning with perception issues regarding qualitative and quantitative variables separately (section 1), followed by an analysis of more complex tasks (subsection 2a and 2b). Individual differences are also addressed in terms of the results of two psychological tests (OSIVQ and Compound letter test), stressing the role of cognitive styles. Finally, the research design itself is reflected upon, together with its shortcomings and essential limitations.

The study revealed differences in the response time to individual variants of cartographic visualization even they were mostly not statistically significant. In general the version A, combining size and colour hue to communicate key information, promoted better performance in respondents than the version B, which used shape and colour value. This difference was particularly marked in performance efficiency and could be observed in both section 1 and section 2 of the map-reading test. In section 1, statistically significant differences were found only in one of the ten tasks, and there were no significant differences identified in section 2. These results still slightly indicate that size and colour hue might be somewhat better information carriers in cartographic visualizations than shape and colour value combinations. This finding tallies with Hegarty *et al*. (2010), who stressed the role of visual salience principles in task-relevant information display. The results for single variable displays support the existing ordering of visual variables (Bertin, 1983; Garlandini and Fabrikant, 2009). Specifically, in qualitative perceptual tasks, displays using colour hue yielded better performance than displays using shape, and size proved to be a more efficient communicator of meaning in quantitative tasks than colour value. Average response times show that quantitative visual variables were easier to perceive, and participant's responses were quickest when symbol size was used to communicate the target information (*cf.* Dong *et al*. 2012; Garlandini and Fabrikant, 2009). Not only did size and colour perform better as single variables (section 1) but also in combination (section 2). Colour hue and size thus confirmed an attention-guiding role for linear graphical features (Bertin, 1983; Wolfe and Horowitz, 2004). On the other hand, differences in map design did not seem to have any significant impact on task accuracy (effectiveness) either in section 1 or section 2 of the map-reading test. This is again in agreement with the original findings of Hegarty *et al*. (2010), who observed that changes in visual salience played only a marginal role in the accuracy of user choices.

Our hypotheses about cognitive styles were not fully supported by the results of the experiment. For version A, weak negative correlations were found between the object imagery dimension of OSIVQ and some of the cartographic subsections, and moderate positive correlations were found between the local letter subtest of the compound letter test and almost all cartographic subsections (with the exception of the bivariate 'yes/no' subsection). This means that the participants who achieved better response times in analytical tasks were on average slightly faster to complete tasks in the map-reading test. Further, object imaginers showed lower response times in the map-reading tasks of the following subsections of the test: univariate (quantity) and bivariate (multiple-choice). In version B, no significant effects were found relating to the OSIVQ dimensions. Nevertheless, moderate positive correlations were found between the participants' performance in all the subsections and their scores

Table 4. Correlation between achievements in the B version of cartographic tasks and psychological tests (OSIVQ and compound letter test)

Spearman's rho	OSIVQ			Compound letter test	
Visualization B	*Object*	*Spatial*	*Verbal*	*Local letters*	*Global letters*
Univariate – quality	*−0.12*	*−0.05*	*−0.17*	***.33*****	***.39*****
Univariate – quantity	*−0.04*	*0.08*	*−0.13*	***.26****	*0.15*
Univariate – all	−0.07	−0.03	−0.16	**.33****	**.32****
Bivariate – multi-choice	*0.01*	*0.10*	*−0.08*	***.37*****	***.30****
Bivariate – yes/no question	*0.03*	*0.14*	*−0.13*	***.26****	*0.15*
Bivariate – all	0.02	0.11	−0.11	**.37****	**.28***

*Correlation is significant at the 0.05 level (2-tailed); **Correlation is significant at the 0.01 level (2-tailed); exlude cases pairwise.

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in the local letter subtests of the CLT. In addition, a moderate positive correlation was found between the participants' performance in some of the subsections of cartographic part (specifically univariate-quantity and bivariate – multi-choice) and the global dimension of CLT. These results appear to indicate that analytical processes probably played an important role in dealing with both version A and version B display variants. Particularly with respect to version B, the participants' performance appears to have been more dependent on their ability to distinguish and analyse different colour values or different line types, and thus the correlation with the local dimension of CLT was slightly stronger. We also suggest that the connection between efficiency in version B map-reading tasks and the score in the global letter subtest might indicate that the participants' performance with respect to the version B map depended partly upon the ability to simultaneously register and process the two types of variable, i.e. the shape and colour value. An alternative explanation would be that map-reading performance is merely related to the general psychomotor speed (White *et al*., 1997) of the individual, which also influences one's performance in both subtests of the compound letter test. However, this argument is somewhat weakened by the fact that no correlations were found between the global letter subtest scores and performance in version A. The absence of any connection between version A and the global letter score, as well as the weaker correlation between version A and the local letter score, indicate that performance in version A is not particularly affected by increased employment of decoding processes or a thorough analysis of individual variable values. Parallel processing of size and colour hue thus seems to involve less cognitive load than that entailed in version B variable combination.

A closer look at the correlations between subsections bivariate – multi-choice and bivariate – yes/no in both display versions, as well as their relation to the global and local letter scores, reveals an interesting pattern. The bivariate – multi-choice and bivariate – yes/no tasks can be distinguished by an explicit change in task instructions. This change also leads to a decrease in the size of effect, i.e. it cancels the correlation with the CLT scores. This leads us to the idea that, when working on different map-reading tasks, different component cognitive processes may have been employed to varying extents. This conclusion may have important implications for the interpretation of research findings in general, indicating that such interpretation should always try to focus on the role of individual cognitive functions involved in the processing of a particular task. In our own experiment, we assume that the following functions and operations have been involved: understanding the instructions; decoding the legend and storing the values and their graphic representations in the memory; visual search for elementary graphic objects in the map and discrimination between them; visual comparison of these elements with the legend (recall from memory); and deciding whether the localized alternative (route) meets the requirement(s) listed in the instructions. Performance differences in sections bivariate – multi-choice and bivariate – yes/no, very probably arising out of the change of instructions, direct our attention to the fundamental methodological issues and principles of designing studies in this area of research. Brunswik (1955) critically revised the potential of laboratory experiments, which by all means represent a lasting and essential tool of general science. By postulating an original concept for representative design he stressed, highly importantly, the serious interpretation limitations of findings obtained through experimental designs. An intentional effort on the part of the researcher to eliminate or control all extraneous variables inevitably leads to a decreased external validity of the study as well. An example of this could possibly be seen in our study, where the changes in task instructions probably resulted in switching to a different level of cognitive processing, manifesting as marked changes in statistical effects of different measures of cognitive style on the map-reading task performance.

CONCLUSION

In presented experimental study effects of different visual variables used for linear feature cartographic visualizations were measured and compared and the relationship between map-related tasks and user's cognitive style was verified. We found out that visualization A (combination of colour hue and size) in comparison with visualization B was (colour value and symbol shape) more efficient in all type of tasks but only in one case was significant. There were found no significant differences in the effectiveness of visualizations. Significant relationships between map-related tasks and explored cognitive styles of users were verified. In case of the visualization A, efficiency in map-reading tasks correlates with the level of object imagery and performance in local letter subtest. There were not found any relationship between map-reading task in the visualization B and object or spatial imagery. On the other hand, we found out that the performance in the visualization A correlates with the local and global letter subtests at the same time. Conclusions from the bivariate subsections indicate importance of focus on the role of individual cognitive functions involved in the processing of a particular task.

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