MASARYK UNIVERSITY

FACULTY OF SCIENCE

DEPARTMENT OF GEOGRAPHY

Experimental Research in Cartographic Visualization

HABILITATION THESIS

ZDENĚK STACHOŇ

BRNO 2022

THE GOOD CARTOGRAPHER IS BOTH A SCIENTIST AND AN ARTIST. HE MUST HAVE A THOROUGH KNOWLEDGE OF HIS SUBJECT AND MODEL, THE EARTH.

ERWIN RAISZ

ACKNOWLEDGEMENTS

At this point, I would like to thank the supervisor of my Ph.D. studies, Professor Konečný, for his guidance in my professional and personal life. Furthermore, to Professor Kubíček, the Director of the Department of Geography, Faculty of Science, Masaryk University for his support and professional feedback and Professor Dobrovolný for the conditions created for my professional activities. To Dr. Šašinka for inspiring discussions over hectolitres of coffee and to his wife Alžběta for her understanding.

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Last but not least, I thank my wife Barbara for her patience and support and my parents, Eva and Zdeněk, for their support.

COMMENTARY

This habilitation thesis contains twelve research articles which represent long-term research in the field of cartographic visualization. The research component of the thesis is divided into two parts, consisting in (i) the design and configuration of tools for use in experimental cartographic research and publication of research studies in cartographic visualization, and (ii) studies on differences in visual perception, differences in bivariate cartographic visualization, and complex spatial tasks. The results were subsequently applied to advance theoretical knowledge in cartography, more generally for practical application in creating maps, and specifically for application in geographic support during crisis management. Based on the results, the thesis presents a discussion and proposal for a modified scheme of cartographic communication and the forms which potentially affect this process in theoretical cartography. Possible applications lie in generating cartographic visualizations according to the user's characteristics (map literacy, familiarity with the environment, cultural background, etc.) or applying recommendations to geographic visualizations designed to support crisis management, where time is a significant factor. Detailed results and discussions are included in the attached research articles.

The following list of publications specifies the author's role in the experimental work, supervision, writing and editing of the manuscript and research direction.

Paper 1

Popelka, S., **Stachoň, Z.,** Šašinka, Č., & Doležalová, J. (2016). Eyetribe Tracker Data Accuracy Evaluation and Its Interconnection with Hypothesis Software for Cartographic Purposes. Computational Intelligence and Neuroscience, Vol. 2016, Special Issue, February, Article ID 9172506. https://doi.org/10.1155/2016/9172506. (WoS JIF QUARTILE: Q2)

Author's contribution:

Experimental work (%)	Supervision (%)	Manuscript (%)	Research direction (%)
25	25	25	25

Paper 2

Šašinka, Č., Morong, K., & **Stachoň, Z.** (2017). The Hypothesis Platform : An Online Tool for Experimental Research into Work with Maps and Behavior in Electronic Environments. ISPRS International Journal of Geo-Information, 6(12). https://doi.org/10.3390/ijgi6120407. (WoS JIF QUARTILE: Q2)

Author’s contribution:

Experimental work (%)	Supervision (%)	Manuscript (%)	Research direction (%)
40	30	40	40

Paper 3

Šašinka, Č., **Stachoň, Z. (corresponding author),** Sedlák, M., Chmelík, J., Herman, L., Kubíček, P., Strnadová, A., Doležal, M., Tejkl, H., Urbánek, T., Svatoňová, H., Ugwitz, P., & Juřík, V. (2019). Collaborative Immersive Virtual Environments for Education in Geography. ISPRS International Journal of Geo-Information, 8(1). https://doi.org/10.3390/ijgi8010003. (WoS JIF QUARTILE: Q2)

Author’s contribution:

Experimental work (%)	Supervision (%)	Manuscript (%)	Research direction (%)
30	45	10	50

Paper 4

Konečný, M., Kubíček, P., **Stachoň, Z. (corresponding author),** & Šašinka Č. (2011). The usability of selected base maps for crises management: users' perspectives. SpringerLink, Applied Geomatics. Springer, 2011/3, pp. 189–198. ISSN 1866-9298. https://doi.org/10.1007/s12518-011-0053-1. (WoS JIF QUARTILE: Q3)

Author’s contribution:

Experimental work (%)	Supervision (%)	Manuscript (%)	Research direction (%)
70	40	70	60

Paper 5

Stachoň, Z., Šašinka, Č., Čeněk, J., Angsüesser, S. Kubíček, P., Štěrba, Z., Bilíková, M. (2018). Effect of Size, Shape and Map Background in Cartographic Visualization: Experimental Study on Czech and Chinese Populations. ISPRS International Journal of Geo-Information, 7/427, pp. 1-15. ISSN 2220-9964. https://doi.org/10.3390/ijgi7110427. (WoS JIF QUARTILE: Q2)

Author’s contribution:

Experimental work (%)	Supervision (%)	Manuscript (%)	Research direction (%)
70	95	60	80

Paper 6

Stachoň, Z., Šašinka, Č., Čeněk, J., Štěrba, Z., Angsüesser, S., Fabrikant, S., I., Štampach, R., & Morong, K. (2019). Cross-cultural differences in figure–ground perception of cartographic stimuli. Cartography and Geographic Information Science, 46(1), 82-94. https://doi.org/10.1080/15230406.2018.1470575. (WoS JIF QUARTILE: Q3)

Author's contribution:

Experimental work (%)	Supervision (%)	Manuscript (%)	Research direction (%)
50	50	70	50

Paper 7

Kubíček, P., Šašinka, Č., **Stachoň, Z.,** Štěrba, Z., Apeltauer, J., & Urbánek, T. (2017). Cartographic Design and Usability of Visual Variables for Linear Features. Cartographic Journal, 54(1), 91-102. https://doi.org/10.1080/00087041.2016.1168141. (WoS JIF QUARTILE: Q4)

Author's contribution:

Experimental work (%)	Supervision (%)	Manuscript (%)	Research direction (%)
50	30	30	50

Paper 8

Šašinka, Č., **Stachoň, Z.,** Kubíček, P., Tamm, S., Matas, A., & Kukaňová, M. (2018). The Impact of Global/Local Bias on Task-solving in Map-related Tasks Employing Extrinsic and Intrinsic Visualization of Risk Uncertainty Maps. The Cartographic Journal, ISSN 0008-7041. https://doi.org/10.1080/00087041.2017.1414018. (WoS JIF QUARTILE: Q4)

Author's contribution:

Experimental work (%)	Supervision (%)	Manuscript (%)	Research direction (%)
70	40	40	60

Paper 9

Šašinka, Č., **Stachoň, Z. (corresponding author),** Čeněk, J., Šašinková, A., Popelka, S., Ugwitz, P., & Lacko, D. (2021). A Comparison of the Performance on Extrinsic and Intrinsic Cartographic Visualizations through Correctness, Response Time and Cognitive Processing. PLoS ONE, 16(4). https://doi.org/10.1371/journal.pone.0250164. (WoS JIF QUARTILE: Q2)

Author’s contribution:

Experimental work (%)	Supervision (%)	Manuscript (%)	Research direction (%)
40	20	40	40

Paper 10

Lacko, D., Šašinka, Č., Čeněk, J., **Stachoň, Z.**, & Lu W.-L. (2020). Cross-Cultural Differences in Cognitive Style, Individualism/Collectivism and Map Reading between Central European and East Asian University Students. Studia Psychologica, 62(1), 23-42. http://dx.doi.org/10.31577/sp.2020.01.789. (WoS JIF QUARTILE: Q4)

Author’s contribution:

Experimental work (%)	Supervision (%)	Manuscript (%)	Research direction (%)
30	50	10	40

Paper 11

Kubíček, P., Šašinka, Č., **Stachoň, Z.,** Herman, L., Juřík, V., Urbánek, T., & Chmelík, J. (2019). Identification of altitude profiles in 3D geovisualizations: the role of interaction and spatial abilities. International Journal of Digital Earth, 12(2), 156-172. https://doi.org/10.1080/17538947.2017.1382581. (WoS JIF QUARTILE: Q1)

Author’s contribution:

Experimental work (%)	Supervision (%)	Manuscript (%)	Research direction (%)
60	60	30	50

Paper 12

Zhu, L., Shen, J., Zhou, J., **Stachoň, Z.,** Hong, S., & Wang, X., (2022). Personalized landmark adaptive visualization method for pedestrian navigation maps: Considering user familiarity. Transactions in GIS. Wiley, 26/2, pp. 669-690. ISSN 1361-1682. https://doi.org/10.1111/tgis.12877. (WoS JIF QUARTILE: Q3)

Author’s contribution:

Experimental work (%)	Supervision (%)	Manuscript (%)	Research direction (%)
10	50	10	60

Contents

1. Introduction

Cartographic visualizations can potentially play a key role in many everyday human experiences such as emergency management, military purposes, landscape management, regional planning, education, and so on. Some methods are suboptimal or misleading in specific contexts or not suitable for certain users or technology (Kraak et al., 2020b). A detailed understanding of the fundamental principles of cartographic visualization is therefore vital.

The fundamentals employed in our research are outlined by the International Cartographic Association (ICA), which is a key umbrella organization for cartographers at the international level. In 2009, the ICA published its Research Agenda (RA) for Cartography and GI Science (Virrantaus et al., 2009), specifying ten key future research areas in cartography. Two main areas relate significantly to the research presented here: (i) the usability of maps and GI and (ii) cartographic Theory (Figure 1). Both areas contain a number of subtopics which link to the remainder of the defined research areas.

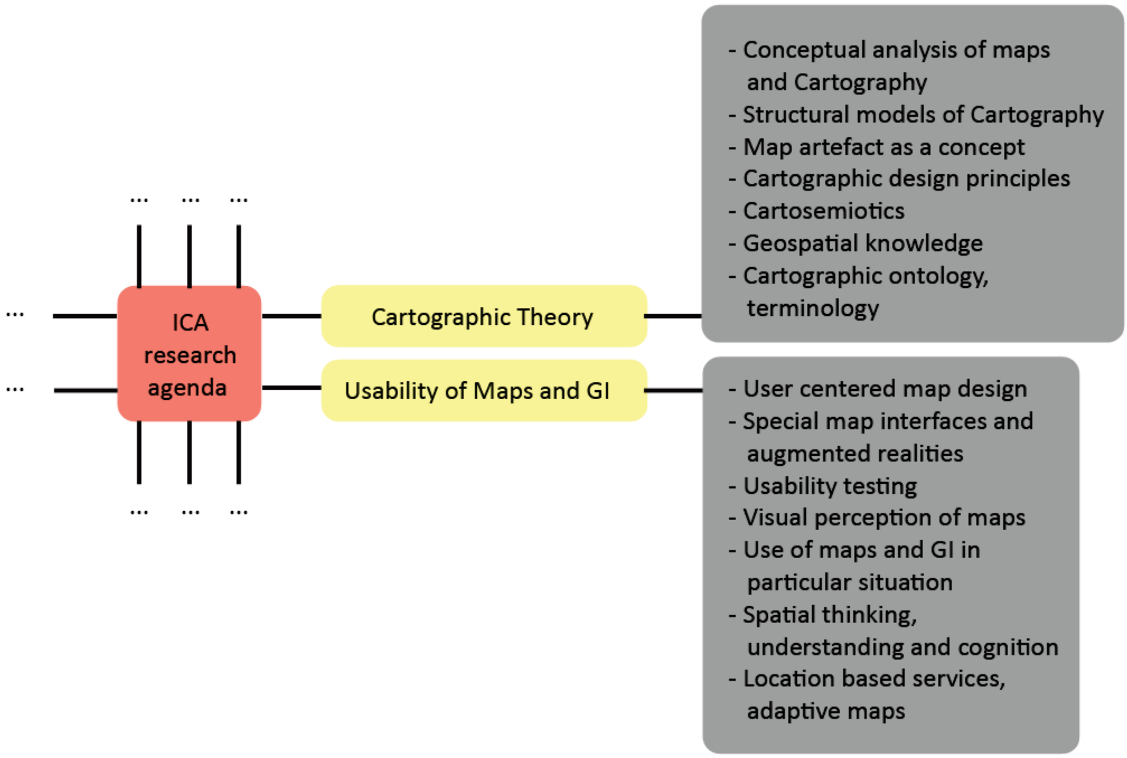

Figure 1: Selected research areas (yellow) and subtopics (grey) in the ICA's research agenda (adapted from Virrantaus et al., 2009).

These two cartographic research areas relate to the cartographic communication process in that experimental studies are able to verify theoretical background and vice versa; knowledge of the principles of cartographic communication is able to improve the methods and approaches applied in experimental studies.

Empirical research which investigates the knowledge contained within the principles of cartographic communication has been the subject of cartographic research since the publication of Robinson's work – *The Look of Maps: An Examination of Cartographic Design in 1952* (Robinson, 1952). Initially, only cartographers (see below) attempted to describe and explain the processes of cartographic communication. Cartography and other research focused on cartographic visualization as stimuli is highly multidisciplinary, for example Worth (1989), Konečný & Švancara (1996), MacEachren (1995), and Montello & Freundschuh (2004); collaboration with experts in fields such as psychology, cognitive sciences, neurosciences and related disciplines mentioned by MacEachren (1995) and Griffin et al. (2017) is therefore essential. The importance of this approach is already mentioned in the work by Eckert – *Die Kartenwischenschaft* (1925) – and emphasized by key organizations such as the ICA, first in the Commission on User Experience (before 2019, the Commission on Use, User and Usability Issues) – http://cartogis.ugent.be/kooms/UUI/), http://use.icaci.org – which has been active since 1984 (Roth, 2021), and then in the Commission on Visualization, established in 1995 (MacEachren & Kraak, 1997), and the contemporary Commission on Cognitive Issues in Geographic Information Visualization – https://cogvis.icaci.org/.

The ICA's commission helps promote research directions in the above-mentioned areas through the publication of relevant books (e.g., *Mapping for a Sustainable World* by Kraak et al., 2020b), establishment of research agendas (e.g., Roth et al., 2017; Griffin et al., 2017; Roth et al., 2022), creation of educational materials (e.g., chapters in the GIS Body of Knowledge: Roth, 2017); Ooms & Skarlatidou, 2018; Stachoň et al., 2020), organization of themed workshops (e.g., Stachoň & Kubíček, 2021; Griffin et al., 2021; Stachoň, 2022) and other related activities.

1.1 Concept

The scope of this work is based on several goals highlighted in the ICA's commission materials: the Commission on Cognitive Issues in Geographic Information Visualization (https://cogvis.icaci.org/) promotes *"the development of human-centred cartographic theory and practice based on sound empirical findings on the use of cartographic displays for spatiotemporal inference and decision-making";* the Commission on User eXperience (http://use.icaci.org) emphasizes *"the map user's importance and involvement in evaluating cartographic products for the improvement of usability".* The research presented here was framed according to these goals and contains twelve studies which have two distinct research areas according to specific content (Figure 2). The selected content aligns with the need to converge cartographic theory and practice, emphasized by Kent (2018).

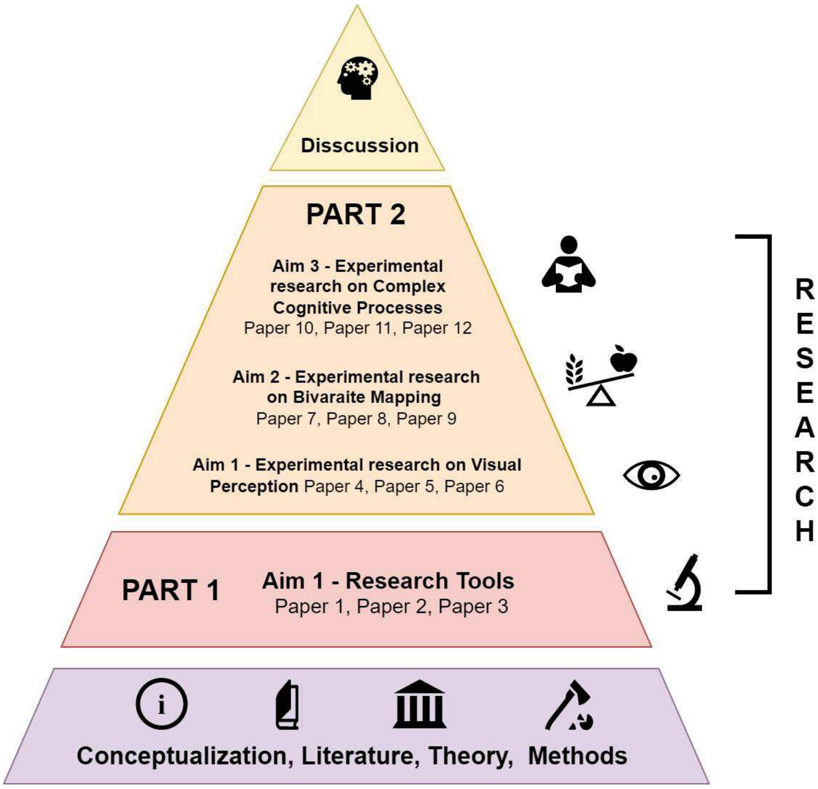

Figure 2: Schema of general research.

The research component consists of two parts. PART 1 discusses the aim to **develop new research tools suitable for collecting experimental data** in user studies which apply a variety of methodological approaches with respect to the unique nature of cartography and related disciplines in cartographic visualization (Paper 1, Paper 2) and visualization of spatial information for immersive virtual environments (IVEs) (Paper 3).

PART 2 pursues three main aims. Aim 1 – **experimental research on the visual perception of maps** (Paper 4, Paper 5, Paper 6); Aim 2 – **experimental research on bivariate mapping** (Paper 7, Paper 8, Paper 9); Aim 3 – **experimental research on complex spatial tasks** focused on individual user and group performance using 2D or 3D cartographic visualization methods and associations (Paper 10, Paper 11, Paper 12). These three aims were not worked towards in isolation but linked through several aspects.

The structure illustrated in Figure 2 is discussed in subsequent chapters.

1.2 Motivation

Research in this area is highly interdisciplinary and aligned with increasing interest in experimental approaches to maps and cartography from cartographers, psychologists, geographers, designers, information scientists, data specialists and other researchers. This is evident from the increasing number of papers published in reputable research databases – Web of Science and Scopus (Figure 3).

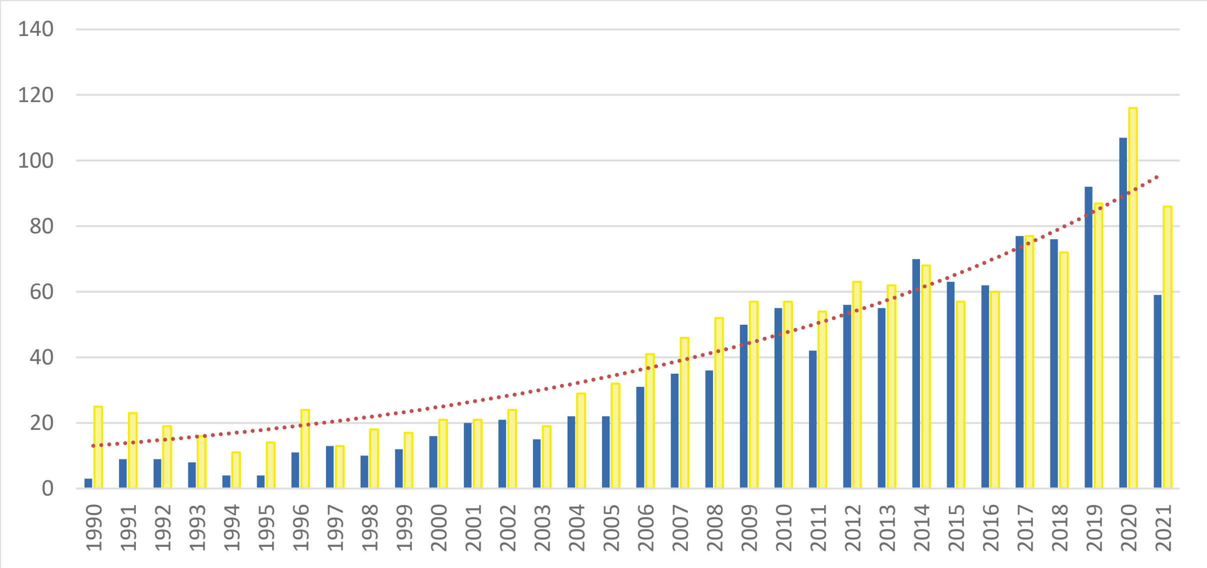

Figure 3: Number of papers featuring experiments in cartography, published in Web of Science (blue) and Scopus (yellow) since 1990.

Experimental research is just one of the possible approaches of studying usability in cartography. Roth & Harrower (2008) presented a continuum of controlled experimentation and usability testing. The research presented in this thesis focuses mainly on the controlled experimentation area of the schema.

Experimental research in cartographic visualization primarily investigates the perceptual and cognitive aspects of human interaction with cartographic visualizations (Konečný & Švancara, 1996). This area falls under the cognitive cartography research subdiscipline (Fabrikant & Lobben, 2009). Montello (2002) conceptualized three main cognitive cartography research areas: map design research (improving maps), map-psychology research (using simplified cartographic visualizations as stimuli), and map-education research. To a large extent, cognitive cartography adopts similar approaches and designs to psychology.

The research team at the Masaryk University (MUNI) Department of Geography, Faculty of Science has been cooperating for a long time in this area with staff at the Department of Psychology at the Faculty of Arts, Cabinet of Information Sciences and Librarianship (KISK), Faculty of Informatics, and Department of Visual Computing. The team is also involved in international collaboration with University of Zurich, Freie University of Berlin, University of Wageningen, and Palacký University Olomouc. Work with these external partners has brought together several original research projects and solutions, which are presented and discussed in this text.

Linked to several international and national research activities, the research was conducted under the national Research plan (2005–2011) – ***Dynamic Geovisualization in Crisis***

ⓘ

Management (MSM0021622418), led by principal investigator (PI) prof. RNDr. Milan Konečný, CSc., followed by the international project ***Dynamic Mapping Methods for Risk and Disaster Management in the Era of Big Data*** (LTACH-17002, 2017–2019, PI prof. Konečný) and ***The Effects of Socio-Cultural Factors and Writing Systems on Perception and Cognition of Complex Visual Stimuli*** (GC19-09265J, 2018–2021, PI dr. Šašinka). Two projects focused on education were conducted at the national level – ***Effects of Cartographic Visualizations in Solving Practical and Instructional Spatial Tasks*** (MUNI/M/0846/2015, 2016–2018, PI assoc. prof. Svatoňová) and ***Education in Collaborative Immersive Virtual Reality*** (TL03000346, 2020–2023, PI dr. Šašinka).

2. Theoretical background

Controlled experimentation delivers repeatable, generalizable findings in various scientific fields and is associated more with theoretical research. The theoretical background for cartography (and cartographic visualization) can be traced to the work by German geographer Max Eckert (Eckert, 1925), yet to date it has not been fully explored. Even the general theoretical framework of six visual variables postulated by Bertin (1967/1983) has not been fully verified, and sometimes it has even been misinterpreted. Research into the process of communicating spatial information to the map user from a map (cartographic visualization in general) is a significant area of theoretical cartography. The work by Koláčný (1969) and Ratajski (1972) established a new paradigm for cartographic communication/transmission (Figure 4).

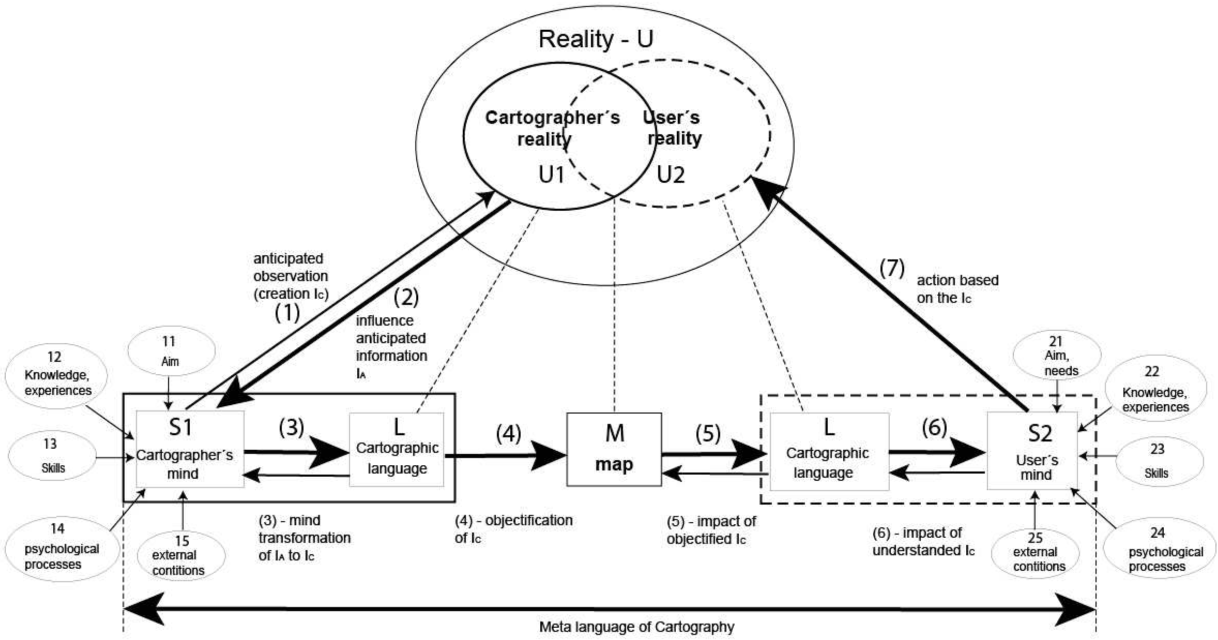

Figure 4: Theoretical model of the cartographic communication process in cartography (adapted from Koláčný, 1969).

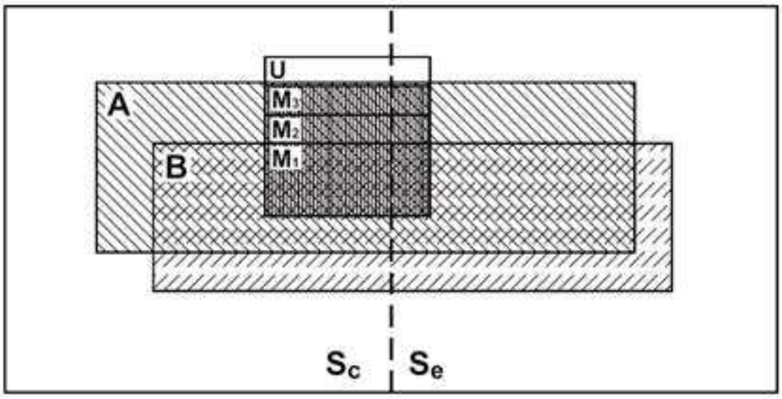

Figure 5: Cognitive elements in cartographic communication (Robinson & Petchenik, 1976)

A and B represent the map maker's and map user's general idea of reality, respectively.
The square area M represents the cartographer's map viewed by the percipient.
M_1 is the fraction of M already known to the map user.
M_2 is the fraction of M that is newly comprehended by the map user.
M_3 is the fraction that is not comprehended by the map user.
U is the increase in the map user's notion of reality, unintended by the map maker.

The approach was later developed by Morrison (1976), Robinson & Petchenik (1976) (Figure 5), Board (1978), MacEachren (1995), Ormeling (1997) (Figure 7) and Morita (2004) and also modified, discussed and criticized by Keates (1982) (Figure 6), Morrison (1976), MacEachren (1995), Griffin (2021) and others.

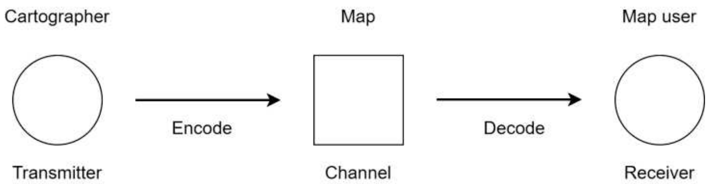

Figure 6: Map communication model (Keates, 1982).

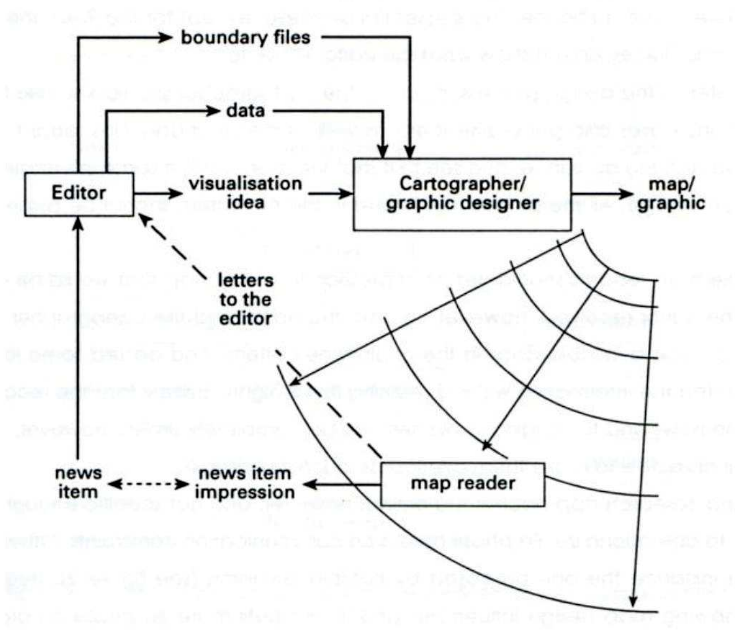

Figure 7: Model of spatial information transfer procedure published by (Ormeling, 1997).

The approaches by Konečný et al. (2006) and Griffin et al. (2017) incorporate the effects of context in all parts of the process (Figure 8); Kent (2018) focuses on user feedback (Figure 9); Kitchin et al. (2012) shift the attention from the map to the mapping process itself.

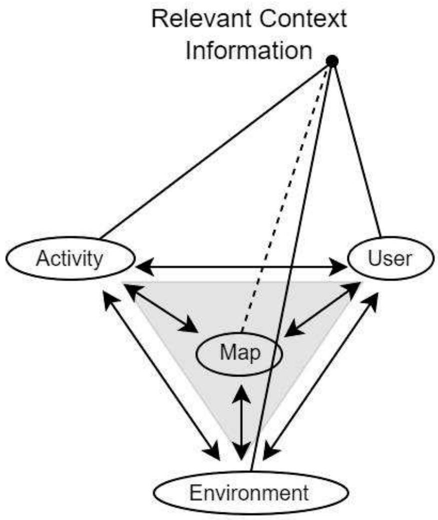

Figure 8: Model for operationalizing context in map use (adapted from Griffin et al., 2017).

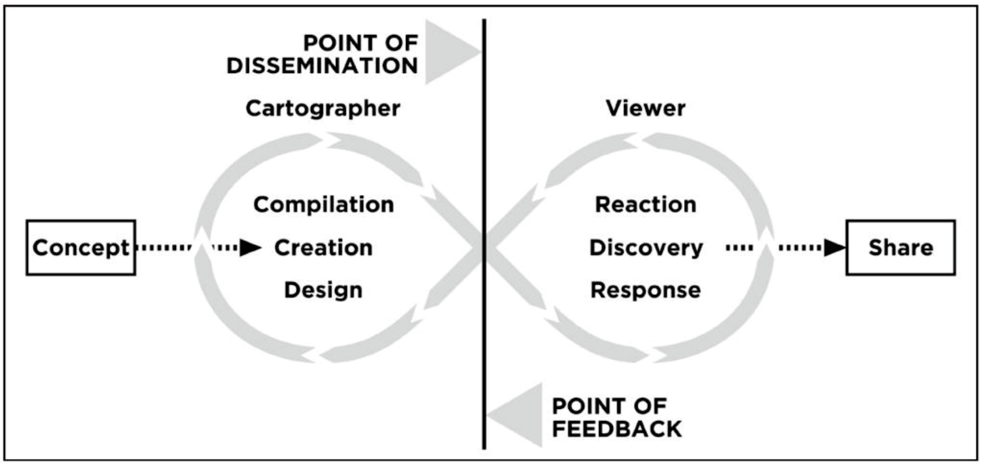

Figure 9: Map communication model conceived by Kent (2018).

The most recent approaches explore new perspectives, but they cover only specific aspects, not the full spectrum of cartographic characteristics. A detailed overview and classification of theoretical approaches in cartography is presented by Griffin (2021).

One irrefutable aspect of cartography is its interdisciplinary nature. Cartographers address matters linked to geography, physics, mathematics, statistics, informatics, psychology and other fields of science. Cartography could be viewed as a behavioural science since it involves the human aspect (Worth, 1989). Experimental cartography uses many methods and techniques (Bandrova, T., Konečný, M., Zlatanova, 2014) which are normally applied in sociology, human geography, and psychology (especially cognitive psychology) to investigate specific information about human perception and cognition.

Despite drawing some criticisms, the communication model above is a universal and robust theoretical concept. Its lack of experimental evidence, however, is its main weakness (Keates, 1982), although experimental research and development would be able to bring this approach up to date.

3. Research Methods

To achieve our aims in the research, we applied a range of methods. This chapter first defines the basic terminology of cartographic research, then describes the methods we applied and any cultural aspects which affected our research results.

3.1 Terminology

Contemporary cartographic literature has an extensive terminology for traditional and commonly applied methods and approaches. However, cartography must respond to new challenges posed mainly by developments in technology. New technologies introduce new environments that require modification or extension of the existing terminology. 3D visualizations and immersive virtual environments are areas of great interest to cartographers and entail cartographic challenges in presenting spatial information.

The text here uses various terms, some which are still under consideration in the (cartographic) community. The main source for cartographic terminology is the *Cartography & Visualization* section in the *GIS&T Body of Knowledge* (https://gistbok.ucgis.org/knowledge-area/cartography-and-visualization). However, selected terms are presented in a form which is commonly used and understood.

Cartographic communication

The cartographic communication/transmission paradigm established in the 1960s is often considered obsolete (see Chapter 2). Nevertheless, this paradigm is considered the most successful in terms of unifying cartographic theory and practice (Kent, 2018), and it is still mentioned in expert publications.

Cartographic communication/transmission of spatial information in our research is understood in the broader sense noted by Ratajski (1972), constituting a process of transmitting information about the spatial distribution of phenomena.

Cartographic visualization

Cartographic visualization generally deals with the visualization of spatial data. Alternative terms such as geographic visualization, geovisualization (MacEachren & Kraak, 2001) and others are frequently seen. For cartographic visualization, the definition of the term is sufficient. The term geovisualization may be understood as a general umbrella term that covers all aspects of the "*visualization of geographic information (spatial, temporal or attribute or a combination of all three), the process of creating interactive visualizations for geographic analysis, using maps, map-like displays, multimedia, plots and graphs (also in* *combination) to aid visual thinking and insight/hypotheses generation, and a perspective on cartography*" (Çöltekin et al., 2018). The term geovisualization is understood in the broader sense described by Goodchild (2009), and the terms geographic visualization, geovisualization, and cartographic visualization are considered synonymous.

Immersive Virtual Environments

The matter of terminology in immersive virtual environments in cartography is addressed in Chapter CV-17 of the *GIS Body Of Knowledge* (BOK) (Stachoň et al., 2020) and the paper *Extended Reality in Spatial Sciences: A Review of Research Challenges and Future Directions* by Çöltekin et al. (2020). These publications are used as a terminological base for our current research (Figure 10).

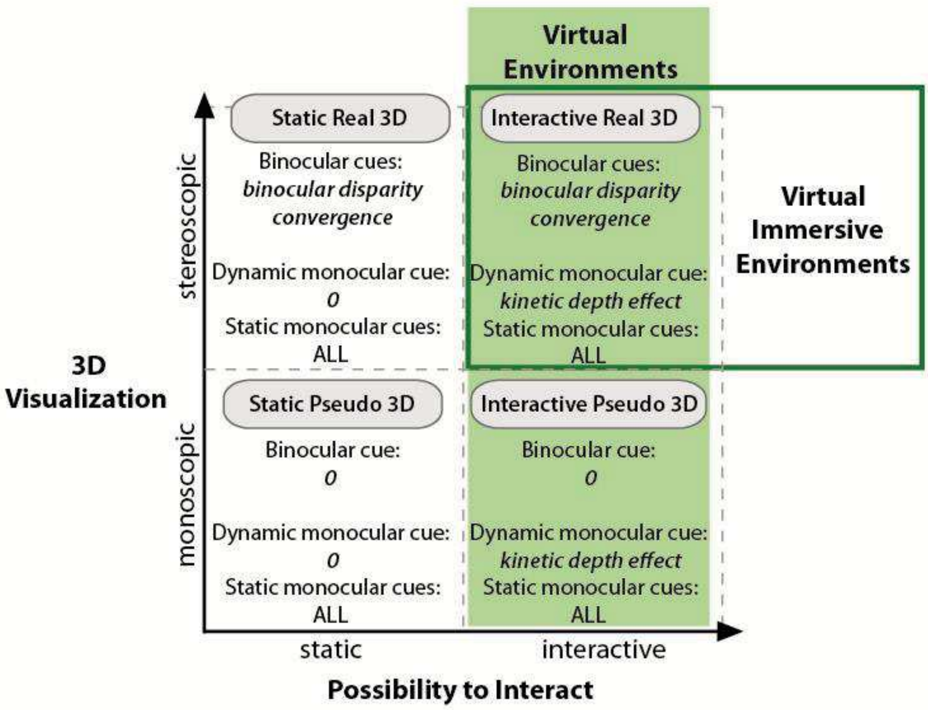

Figure 10: Definition of a Virtual Immersive Environment (Stachoň et al., 2020).

Maps / map-like visualizations

The term *map* has existed for centuries. However, its exact definition is continually evolving, and most of the variations of this definition are not able to capture the full scope of cartographic visualization and cartography as a scientific discipline. Most of the newly established terms are reactions to technological developments – see the image map by Vozenilek & Belka (2016) or 3D map by Herman (2018). We examined these definitions of maps and 3D maps as stimuli for the current research.

A variety of definitions and classifications of maps serve as the primary output and means of research in cartography. A comprehensive analysis by Andrews (1996) describes a continuum extending from traditional detailed definitions:

"*A map is a symbolized representation of geographical reality, representing selected features or characteristics and resulting from the creative effort of its author's execution of choices, and is designed for use when spatial relationships are of primary relevanc*e." (Rystedt et al., 2011)

to broader definitions:

"*map: a representation of spatial relationships*" (Griffin, 2021),

or

"*Maps are media designed to communicate generalized spatial information and relationships*" (Lapaine et al., 2021)

An interesting approach which considers real and virtual maps is presented by Moellering (2007). Montello (2009) describes maps from a cognitive perspective, "*maps and other representations of geographic information serve the purpose of communicating information about space, place and environment to people, or otherwise elicit ideas and thoughts".* Discussion about the various aspects of map definition was published by Fairbairn et al., (2021).

3D maps

The term 3D map is even more actively debated (Herman, 2018). A very promising definition was published by Bandrova & Yonov (2018): "*A 3D map is a digital, mathematically defined, three-dimensional virtual representation of the Earth and surfaces (e.g., luminous body), objects and phenomena occurring in nature and society"*.

This broad definition covers the majority of existing 3D models, and therefore, it has been modified to include spatial reference: "***A 3D map is a mathematically defined, three-dimensional representation of the surfaces, objects and phenomena occurring in nature and society and uses a spatial reference system****"*.

Symbolization

Symbolization in cartography is generally defined as the visual encoding of data in a map or diagram (Kraak et al., 2020a). Terms such as *symbolization* and *symbol* have been commonly used in cartography since cartographers started developing their interest in cartographic theory (see Robinson et al., 1995); these terms are linked to the semiological approach by Bertin (1983). A cognitive-semiotic explanation of how maps work was later elaborated by MacEachren (1995). In a classification designed by the scientist Charles Sanders Peirce, the term *symbol* represents a meaning according to a rule, law or convention; however, this is not true of most symbols in cartography. Keates (1982), MacEachren (1995) and other cartographers refer to and discuss this confusing matter. In addition, both the map symbol and map itself can be understood as signs.

General classifications use geometry to classify map symbols. For example, Morita (2011) distinguishes three types of sign (points, lines and zones). Pravda & Kusendová (2004) apply a different approach by classifying map signs as simple or complex according to the signified meaning in geometric figures, lines and areas. Contrary to the classification designed and used by Keates (1982), the categories of conventional signs and iconic signs appear to be universal for use in cartography.

In our research, we understand a map symbol as the definition of map sign according to Schlichtmann (2006) "*A (map) sign consists of a conceptual item – a (sign) content or meaning – and a perceivable item – an expression or sign".*

3.2 Methods

Cartography is considered a visual language (Kraak et al., 2020a), and therefore, visual perception is a fundamental component in most cartographic visualization methods. This is highly influenced by the physiological nature of the visual organ and its perceptual limitations (see chapter *How Maps are Seen* in MacEachren, 1995) and the cognitive processes which enable the comprehension of presented information (see chapter *How Maps are Understood* in MacEachren, 1995).

In the current research, limitations at the perceptual level are represented mainly by the ability to capture only the visible part of the spectrum limited to the observer's field of view, colour spectrum shifts, and the asymmetry of visual searching (Figure 11; Wolfe, 2001).

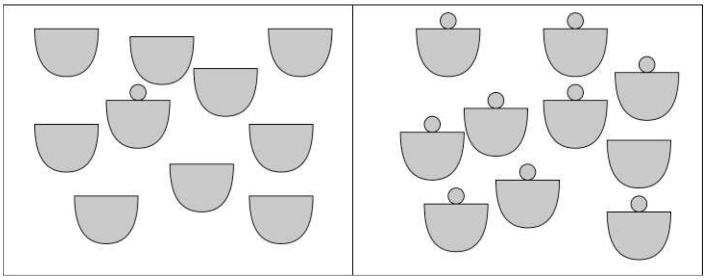

Figure 11: Example of one possible relevant difference at the perceptual level in cartographic visualization.

At the cognitive level, the user's performance is affected by their ability to comprehend abstraction, their mental rotation abilities and experience with the presented topic, and socio-cultural aspects.

The articles published for the first part of our research attempted to identify methods which are crucial to experimental cartographic research and related fields. Most of these methods were later incorporated into research tools (Paper 1, Paper 2, Paper 3).

An overview of methods for researching usability is found in the works by Nielsen (1993) and Štěrba et al. (2015). In these works, we encounter two mixed research design approaches:

- An eye-tracking system used in a pilot study to examine the quality of an experimental design, and application of the results to improve the design before incorporation into large-scale data collection.
- Software (e.g., Hypothesis – Paper 2) used with a large-scale quantitative approach and an eye-tracking method for subsequent analysis of results and adjustment or modification of tasks.

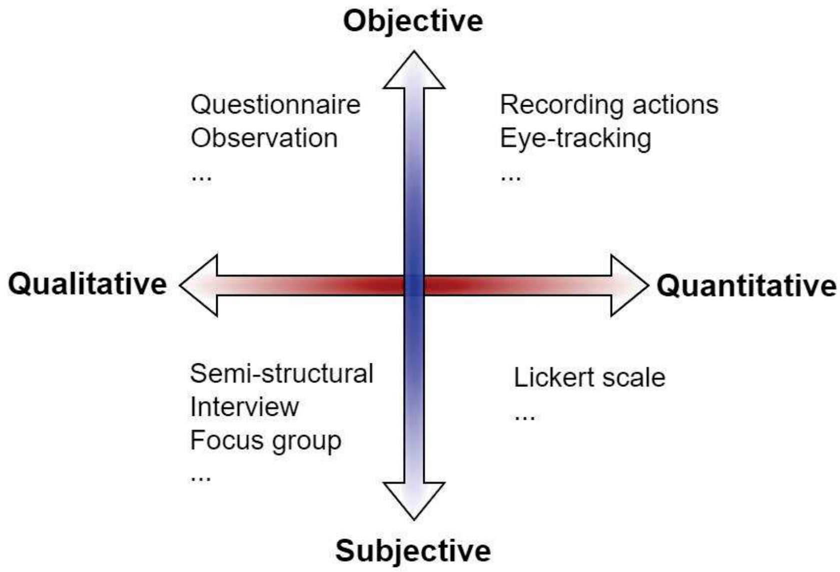

Figure 12: Methods and approaches applied in the current research (adapted from Šterba et al., 2014).

The experimental studies in the second part of our research investigated three essential aspects of usability in cartographic visualization: effectiveness, efficiency and satisfaction. Along with methods for measurement, these aspects are defined in ISO standards (Bevan et al., 2016).

Throughout our research, we have applied objective and subjective methods (Figure 12), mainly according to mixed research designs. The course of studies involved a combination of large-scale experiments aimed at generalizable findings and discovering the differences in a large sample of participants, and small-scale studies designed for more detailed investigation of specific topics. The small-scale studies worked with small participant samples but employed highly specific methods (e.g., eye-tracking) for detailed insight into observed phenomena and clarification of results.

Quantitative methods were defined (PART 1) and applied (PART 2) to measure effectiveness (error rate), efficiency (response time), and satisfaction (Likert scale) using the software Hypothesis (Paper 2) and CIVE (Paper 3). Eye-tracking was used to identify in greater detail the differences in cognitive processes (e.g., search strategies) involved in map-reading (Paper

1). Eye-tracking provides objective, detailed data on user eye-movements during exposure to specific cartographic stimuli (e.g., Popelka & Brychtová, 2013). Subjective evaluation was obtained from semi-structural interviews and focus groups with the participants of selected experiments.

The second part is divided into three subsections based according to task complexity. Kubíček (2012) indicates that cartographic literature offers multiple taxonomies of tasks involving maps, outlining the ideas of Wehrend & Lewis (1990), who offer one of the most extensive taxonomies of map tasks regarding number of items. Tasks which have much potential for use in research are mentioned in the list below, ranked according to degree of difficulty (Wehrend & Lewis, 1990):

- **Identify** – identify a general (visual) feature distinguished by individual objects.
- **Locate** – locate items of certain value and recognizing absolute or relative location. Where is it? Is it on the left or the right?
- **Distinguish** – recognize or distinguish two separate elements. This entails discriminating the map field’s individual elementary visual elements (between each other or from the underlying base), which should be easily distinguishable by the user.
- **Categorize** – create categories or classifications, for example, according to the colour, size, location and type (shape) of an object.
- **Cluster** – create of cluster groups according to the same, similar or related type of graphical quality.
- **Spatial distribution** – describe the entire spatial pattern. This task is closely related to cluster, also to locate and identify, but it is more complex in character. The aim of locating clusters is to detect individual cluster groups, whereas spatial distribution also requires a detailed description of overall cluster organization.
- **Rank** – requires that objects be ordered or positioned according to similar type (with respect to a pre-defined set of attributes).
- **Compare** – the process of finding similarities, differences or order.
- **Associate** – the process of linking graphical elements according to certain relationships.
- **Correlate** – finding a direct connection between elements.

The experimental research in Papers 4, 5 and 6 focused mainly on identify and locate tasks. The research in Papers 7, 8 and 9 added the distinguish task; Paper 10 added cluster; Paper 11 added compare; Paper 12 added associate.

3.3. Socio-Cultural Context

The importance of cultural background in cartography is mentioned by several authors, for example Wood (1984) and MacEachren (1995), and is linked with the long-term cartographic research goal of unifying cartographic visualization. Cartographic communication is considered potentially universal (Modley, 1970), but obstacles exist in the different languages, writing systems, and so on, used in cultures around the world.

Research into the socio-cultural differences of perception has a relatively long tradition in the field of psychology. Various published works highlight the differences in basic perception of visual materials (Deregowski, 1972) or the significant influence of language on segmentation of the user's world, which includes an understanding of terms to describe colour, categorization of existing objects and phenomena, and methods for determining the relative positions of objects in space (Imai, 2010). These differences are perhaps due to understanding information through verbalization (Imai, 2010). Depending on the individual user, the same graphic sign is possible to verbalize in various ways. This assumption is based on the hypothesis of linguistic relativity, otherwise known as the Sapir–Whorf hypothesis. From studies of different languages, American linguist Benjamin Lee Whorf concluded that thought cannot be separated from language and that the categories expressed in the mother tongue are synonymous with the concepts generated in thought (Imai, 2010), (Whorf, 1956). This approach was later criticized, however, and cannot be considered universal; it is rather a stimulus for investigating the effects of language on the use of maps by certain speakers, especially concerning the general validity of mechanisms associated with the perception of visual variables.

We assume that these principles and effects might also be widely applied or encountered during the process of cartographic communication, for example in designing coding systems and individual map symbols and in map use. Even cartographers are aware of this and argue that the meanings of signs differ in space and time (MacEachren, 1995, p. 329). This has also been documented and highlighted in comparative studies of cross-cultural topics in the context of mapping (Morita, 2009) and articles which have illustrated the differences in map characters used on German and Chinese maps (Angsüsser, 2014). Differing writing system structures should also be highlighted in connection with the perception of signs by people of different cultural backgrounds; the most striking example is Chinese script (the evolution of Chinese characters over is well documented, e.g., Wei, 2014).

Chinese script comprises a system of characters which each carry a meaning. In the case of Chinese maps, this often led to approaches where maps were created with no map legend, as the characters in the map field already clarified intended meanings (Figure 13).

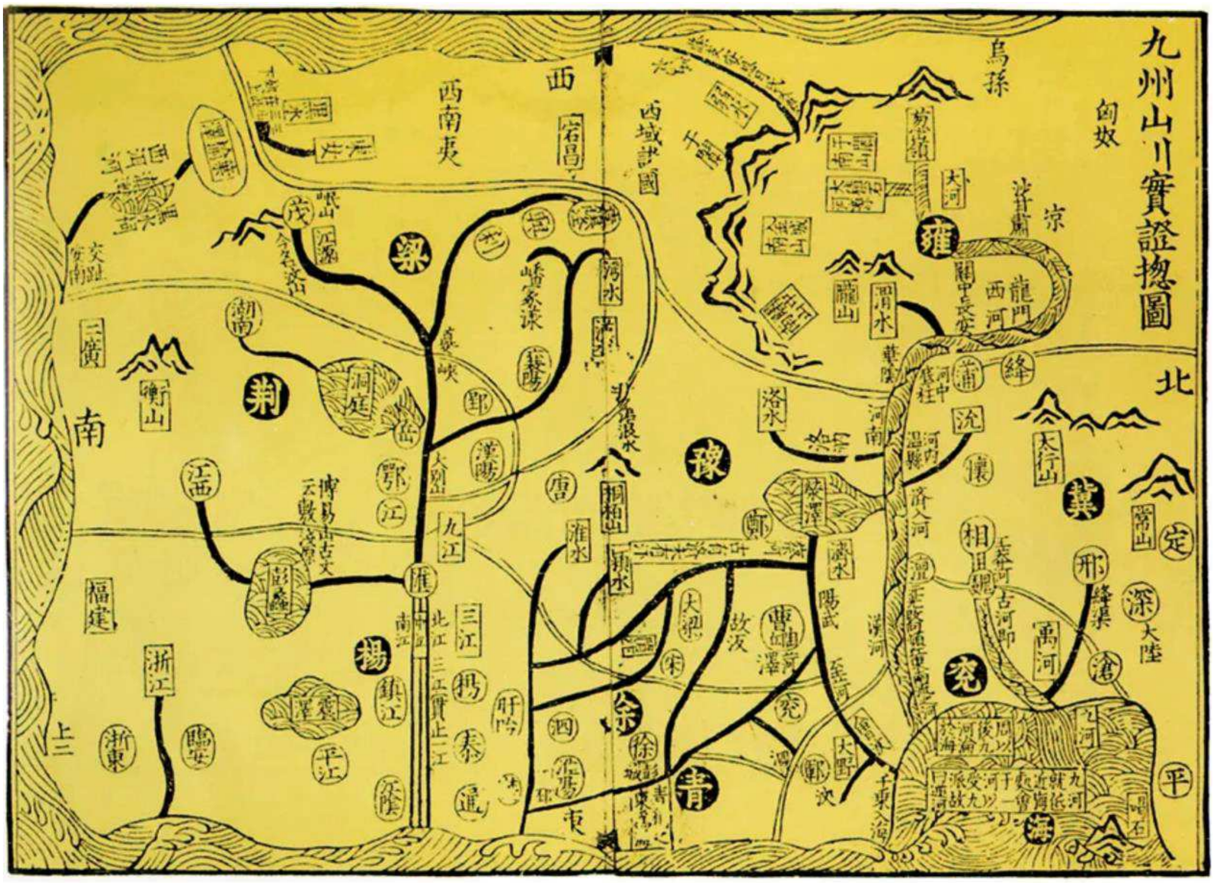

Figure 13: Example of a Chinese map – 12th century Song dynasty territorial map (retrieved from https://www.viewofchina.com/ancient-chinese-maps/)

The current Anglo-European approach to creating maps for China and other countries often leads, especially in descriptions, to a significant redundancy of information in the map field and thus may disadvantage Chinese and other map users. We therefore employed participants from European and Chinese populations in the research since we could expect that the differences between people of these population groups would be significant.

4. Results

The experimental research presented in this thesis is based on theoretical works in cartography (e.g., system of visual variables described by Bertin, 1983), studies in communication of cartographic information and utilitarian cartography (Koláčný, 1969; MacEachren, 1995; others), experimental studies which used cartographic visualizations (Flannery, 1971; Kimerling, 1975; Muller, 1979; Gilmartin, 1981; others), the research agendas of the above-mentioned ICA Commissions, and theories from the fields of cognitive psychology (Wagemans et al., 2012) and cross-cultural psychology (Nisbett, 2003; Imai, 2010).

The following points summarize the research activities:

- Cartographic visualizations are used as visual stimuli.
- Research progresses from atomized perceptual tasks to more complex cognitive operations.
- Experiments are analysed according to selected user characteristics, such as gender, age, domain knowledge, cultural background, etc.
- Tools and studies are designed for reproducibility.

The second part discusses and considers the primary research questions from a general and a socio-cultural level.

4.1 Part 1 – Aim 1 Research Tools

Cartographic visualizations are complex stimuli (Thorndyke & Stasz, 1979; Edler et al., 2014; others) which complicate the possibility to maintain an experiment (Worth, 1989). Specific research tools are therefore needed to not limit the research with various constraints. These constraints are found in the large variety of stimuli (static vs. interactive, 2D vs. 3D, etc.), methods and combinations of sensors available for research purposes. New challenges/opportunities in experimental cartographic research have been reported in various research papers and research agendas (Griffin, Robinson, et al., 2017; Roth, 2017; Griffin, White, et al., 2017). To explore a complex set of aims, suitable tools must be created for experimental research in cartography. Identifying these needs establishes a framework for researching and developing the software tools that enable a wide range of methodological approaches for use in experimental cartographic research and related fields. The necessity for a combination of research methods is indicated by several researchers (Štěrba et al., 2015). Roth et al. (2017) outline recommendations for expanding qualitative and mixed research methods are outlined in their paper *User Studies in Cartography: Opportunities for Empirical Research on Interactive Maps and Visualizations*.

The tools for research in cartography should support:

- Use of a range of stimuli with different characteristics relevant to specific tasks and contexts.
- Recording of data from a large variety of methods and inputs.
- Collection and storage of a relatively large volume of data suitable for subsequent statistical analysis. (Valid and reliable results can only be obtained with sufficient participant sample sizes and specific research methods).
- Application of procedures in a controlled environment to enable the replicability of experiments.

Eye-Tracking for research in Cartography (Paper 1)

Eye-tracking is a unique method for obtaining quantitative data which records the movements of the human eye, i.e., for use in the analysis of user performance with visual stimuli. The method is widely applicable, and the beginnings of its use date to the nineteenth century (Popelka, 2018). Its application in cartography begins around the second half of the twentieth century (e.g., Enoch, 1959; Morita, 1987), but greater use has occurred more recently in the twenty-first century through technological developments that have simplified devices and improved their availability. These observations inspired Paper 1, which focused on verifying the accuracy of the inexpensive EyeTribe eye-tracking system (vs. the professional SMI RED 250 system, Figure 14) and its suitability with the Hypothesis software (see below). The results demonstrated the usability of the EyeTribe system for experimental research in general and verified the possibility to link the data recorded by the EyeTribe with records stored in the Hypothesis system.

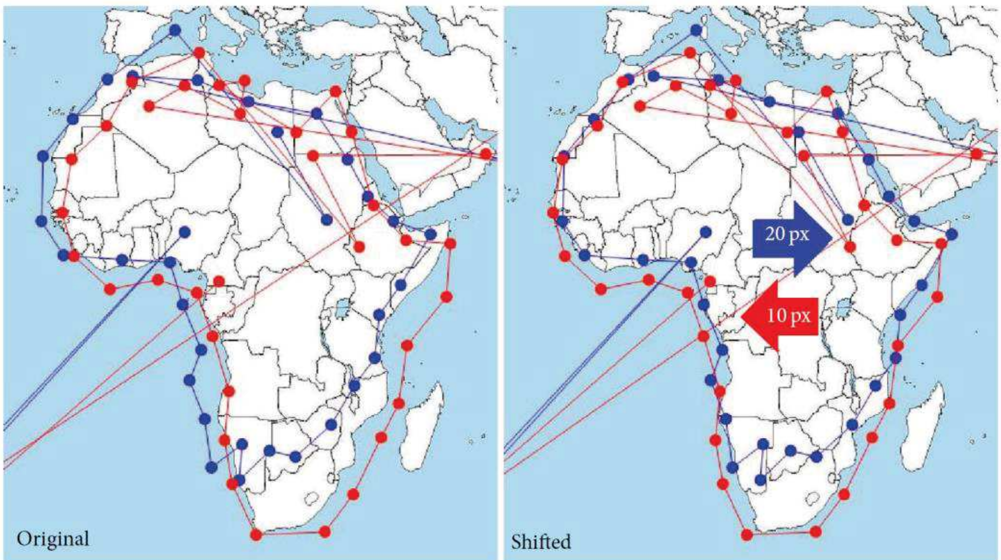

Figure 14: Comparison of recorded eye-movement data from EyeTribe (blue) and SMI RED (red) (Paper 1).

Hypothesis software for research in Cartography (Paper 2)

To overcome or minimize any constraints on experimental research, an experimental platform, called Hypothesis, was designed and developed at Masaryk University. Hypothesis was developed in close cooperation with cartographers and psychologists at Masaryk University and other partnered universities (details in Papers 1 and 2) to satisfy the demand for tools suitable for experimental cartographic research and related disciplines. The platform was designed as a universal and open environment which enables the use of stimuli with different characteristics, linking of various data inputs, and a combination of methodological approaches. The Hypothesis software allows researchers to conduct experiments at various scales with a variety of stimuli in a controlled environment. It also enables large-scale studies with small-scale approaches through specific methods such as eye-tracking or EEG to explore certain research questions.

The development of the platform started under the Research Plan Geokrima (MSM0021622418), which was developed provide geographic support for crisis management. From an analysis of the research plan's requirements, the use of proprietary tools was abandoned and the development of a universal solution more suitable for user studies in various fields commenced. The pilot MuTeP software was developed in the first phase (Šterba et al., 2014). The Hypothesis software functions on two fundamental principles of sharing and accumulation (Paper 2). The basic premise behind the software is the ability to store test batteries, functionalities and research design templates created by researchers and to share these with other research teams (Figure 15). Resources, tools and other created content are therefore highly distinguishable and can also be developed gradually while their availability is maintained.

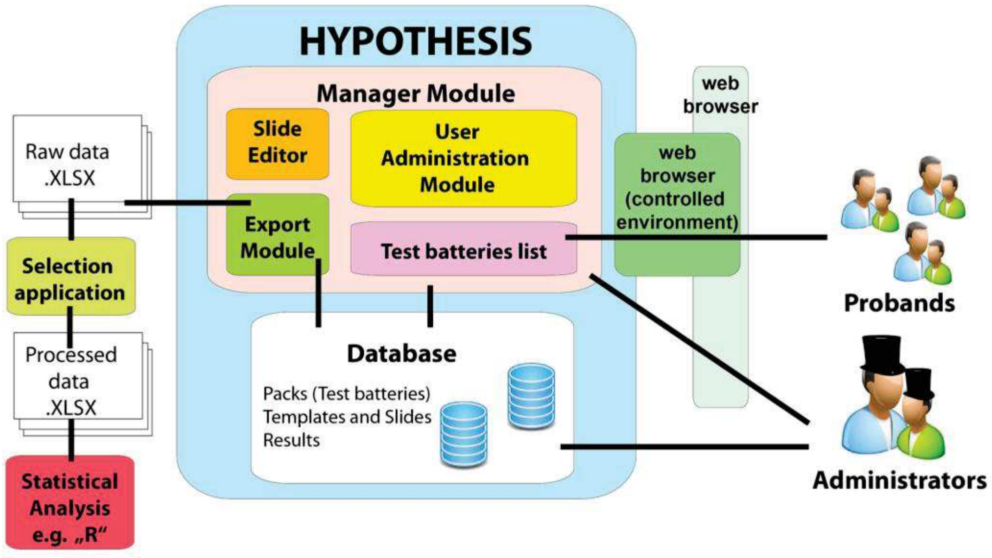

Figure 15: Basic functional components of the Hypothesis platform (Paper 2).

The system has significant potential for use in setting up experimental cartographic studies. It has been used several times for experimental studies conducted by local and international authors; research groups from Norwegian University of Science and Technology (Opach et al., 2017) and University of Zurich (Credé et al., 2019) have used the platform specifically for their cartographic studies.

Tool for Research on Immersive Environments (Paper 3)

To address the parallel matter of wider availability of systems for generating immersive virtual environments, an experimental testing environment was developed. The tools for experiments performed in this environment enable the use and handling of existing geographic data and the recording of user interaction within a virtual geographic environment. Virtual geographic environments provide a resource with significant added value in several research areas, for example crisis management, landscape planning and education, at both individual and multiple user levels; virtual geographic environments enable the presentation of complex topics in multiple dimensions and areas. To leverage these benefits, the Collaborative Immersive Virtual Environment – CIVE was created (PAPER 3), using the Unity programming environment (Figure 16). Users of the CIVE environment have reported many advantages in using the collaborative environment, one being the possibility to "enter" or immerse themselves in the presented topic. The advantages mentioned by users are partially limited by constraints resulting from cybersickness and few options for personalizing avatars in the environment, which led to some drawbacks in communication.

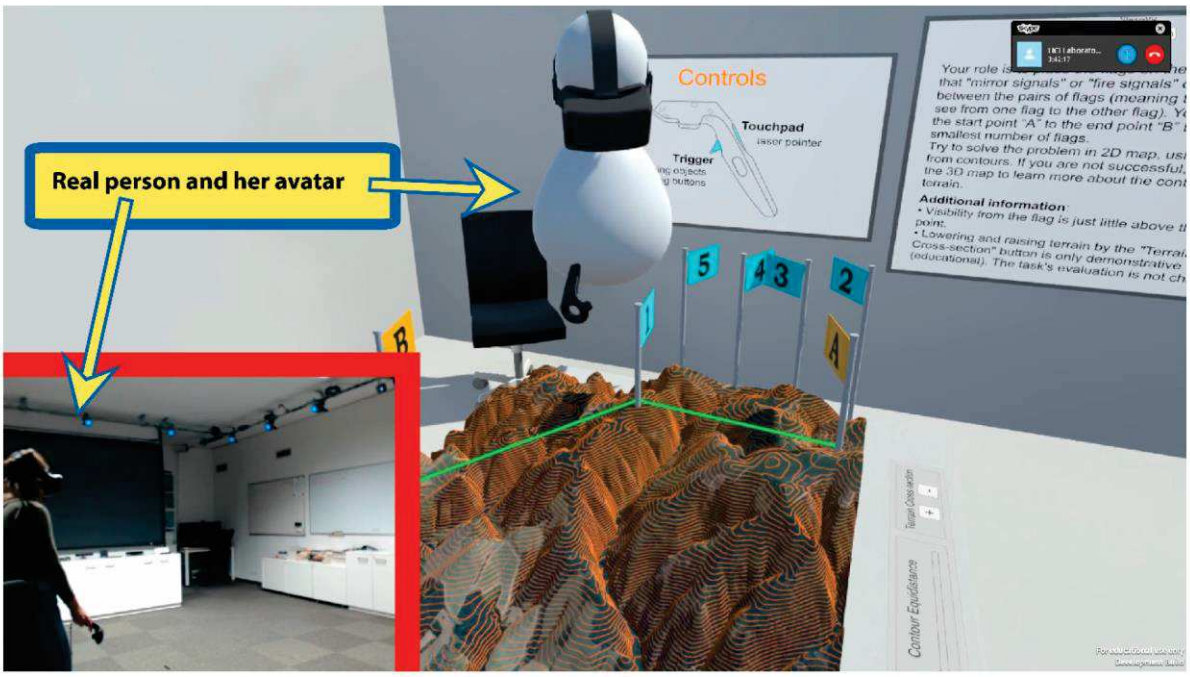

Figure 16: Comparison of person in objective reality (left corner) and an avatar in a virtual room (Paper 3).

An indisputable benefit of this environment is the transferability of conclusions drawn from the virtual environment to the real environment. This quality of transferability is especially beneficial in fields which carry inherent risk, such as crisis management, where few and limited options for simulation and exercises in a real environment are feasible, in addition to being expensive and demanding to organize. CIVE enables the recording of user activity and easy collection of user feedback.

4.2 Part 2 – Aim 1 Experimental Research on Visual Perception

The first stage of the research explored the visual search process with simple tasks and visual stimuli. We compared the different cartographic visualization methods for topographic backgrounds (figure and effects of the background – Paper 4) and map symbols (effect of the size and shape of the map symbol – Papers 5 and 6). The main research questions probed two levels:

General level:

- How does the map background's complexity affect the speed of performing various tasks with map stimuli? (Paper 4)
- What is the limiting size that significantly increases the speed of performing search tasks with map stimuli? (Paper 5)
- How does the shape of a point symbol affect the speed of performing search tasks with map stimuli? (Paper 6)

Cultural level:

- Do any differences exist at the cross-cultural level in the speed of performing various tasks with map stimuli? (Papers 5 and 6)

The effect of topographic backgrounds in the visual search process (Paper 4)

The study (Paper 4) was originally prepared for pilot verification of the tool created for the collection of user data. We used an orthophoto map and generalized topographic map as stimuli because we expected perceptual differences between visual material which contains generalized information (topographic map) and visual material which contains non-generalized information (aerial photograph). Although it was a pilot study, we observed significant differences between the stimulus material with a topographic map and the orthophoto as a topographic background (Figure 17); we also observed differences between participants who had different levels of map literacy.

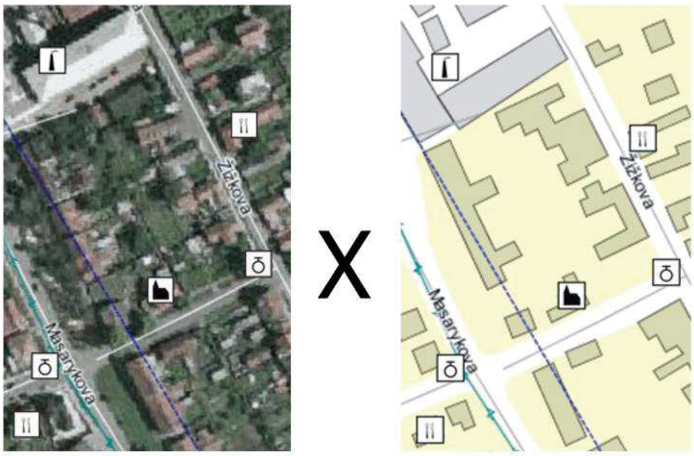

Figure 17: Different topographic backgrounds used in a study (Paper 4).

The results supported our hypothesis of the advantages of using generalized information versus the non-generalized information in an aerial photograph. The second major finding was that participants with greater map literacy performed better in the tasks.

The effect of the size and shape of map symbols on perception (Paper 5)

Bertin (1983) established a set of consistent expectations regarding visual variables (e.g., larger = more) in cartography. These expectations were discussed but still need verification. Paper 5 studied the two most prominent variables – size and shape. Generally, the most efficient searches are those where a single basic feature defines the target and the distractors are homogeneous (Wolfe, 2001). However, differences between certain visual variables are expected.

The research followed on from some studies in psychology and a cartographic study by Koláčný (1969), who established minimum sizes for map symbols at a given reading distance on a large participant sample and the dependence of the number of map symbols on search speed. The proposed experimental study measured the differences in perception of three basic shapes of different sizes in a sample of European and Chinese participants. The study contained two sub-parts, the first using no map background and the second using a map background as a distractor with more complex scene/stimulus material (Figure 18).

Figure 18: Differences in the stimuli with and without a map background (Paper 5).

The results identified differences in the perception of basic shapes within and between each studied population and with and without the use of a topographic background.

Experimental research on figure-ground perception in cartography (Paper 6)

The effect of figure and background is part of the system of visual hierarchy in each scene, even in cartographic visualizations. It plays a role in all maps, but it is critical in thematic maps, where themed information is prioritized over the topographic background. To experimentally verify this effect, we designed two sets of symbols (Figure 19) and arranged them on a unified map base with a location name in Greek to limit any effect of familiarity with a writing system. Participants in sample groups from the Czech Republic and China then completed visual search tasks focused on figures (symbols) and objects in the background (street crossings, etc.). Differences were observed at both at the level of the figure-background (participants were able to identify figures much more quickly) and the level of cultural background, being more obvious with objects in the background. The existence of these differences was verified with a cognitive style FLT (framed-line test) included in the experimental design. The results of the study verified that significant differences between participants from different cultural backgrounds exist.

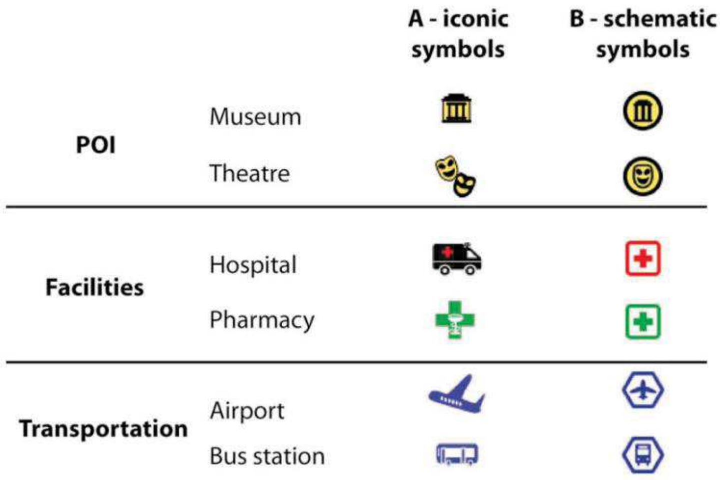

Figure 19: Examples of stimuli used in an experiment (Paper 6).

4.3 Part 2 – Aim 2 Experimental Research on Bivariate Mapping

Bivariate mapping is defined as "*a form of multivariate mapping specific to encoding two data variables into a single product, for the purposes of investigating a relationship*." (Nelson, 2020) and is the simplest and most used multivariate mapping method. Cartography has various approaches to bivariate mapping. We investigated bivariate mapping for linear features (Paper 7) and bivariate mapping for areal features (Papers 8 and 9).

The proposed research questions investigated two levels:

General level:

- Are the informational equivalent methods of bivariate cartographic visualization equivalent at the level of perception? (Paper 7)
- Do any differences exist between bivariate cartographic visualizations which use separable or integral encoding? (Paper 8, Paper 9)

Cultural level:

- Do any differences exist at the cross-cultural level in the speed of performing different tasks with bivariate map stimuli? (Paper 9)

Experimental research on bivariate visualization for linear features (Paper 7)

The study investigated the differences in cognitive load during tasks where bivariate variables were used to visualize line data. Spatial data was represented with a simplified geographical scenario simulating a map. Based on previous research, we compared the line element variables for qualitative information (hue and shape) and quantitative information (size and intensity). The final combinations were hue and size vs. shape and intensity (Figure 20). The results highlighted the differences between visual variables used to visualize data and thus indicated the importance of research into cognitive functions involved in performing map tasks. The results also showed that visualization A (combination of colour hue and size) compared to visualization B (colour value and symbol shape) was more effective in all tasks, but only partially significant.

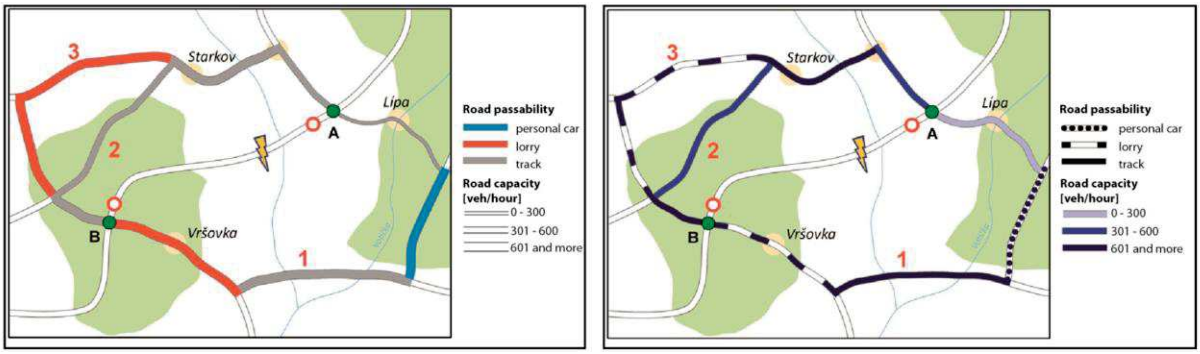

Figure 20: Examples of bivariate visualizations (Paper 7).

Experimental research on intrinsic and extrinsic bivariate visualization A (Paper 8)

Paper 8 presented a follow-up study to Paper 7 but instead focused on bivariate visualization methods used for the purpose of visualizing values and uncertainty in the presented phenomenon. We employed two bivariate cartographic visualization methods: extrinsic visualization (shape and hue) and visualization (hue and intensity) (Figure 21). The results indicated that participants performed worse with intrinsic bivariate visualizations at the beginning of the test battery. The differences then stabilized to a minimum. The results from eye-tracking revealed a higher cognitive load with the intrinsic legend, which the participants were able to access during the test. The use of intrinsic bivariate visualization therefore assumes an experienced target group of users and is limited to the visualization of a phenomenon and its uncertainty. In the case of a lay user group, the concept seems rather complicated. This effect would be removed in the follow-up study (Paper 9).

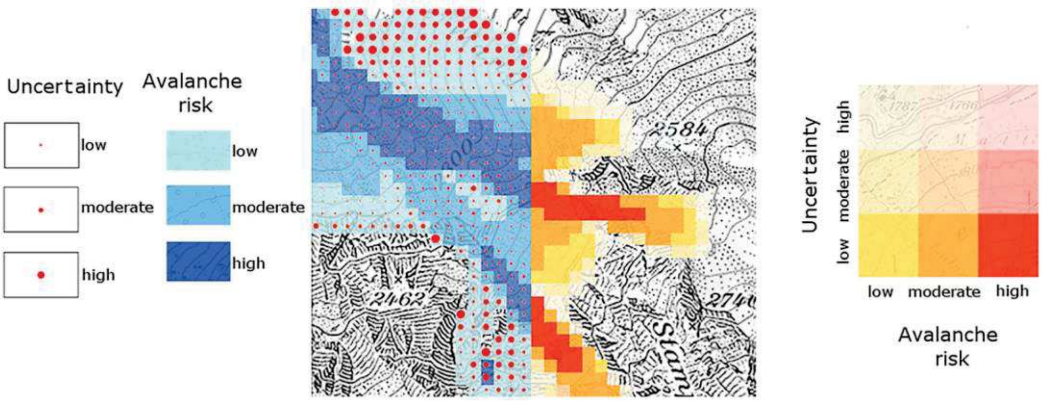

Figure 21: Bivariate visualizations used in a study (Paper 8).

Experimental research on intrinsic and extrinsic bivariate visualization B (Paper 9)

The follow-up study explored analogous methods of bivariate cartographic visualization (separable and integral, Figure 22) but with the difference of visualizing two correlated phenomena. Separable bivariate visualization proved faster and more accurate. A detailed analysis using eye-tracking showed that reading the legend is more cognitively demanding with intrinsic visualization. However, the observed differences were reduced significantly in tasks which focused on parallel processing of two variables. Our findings, however, were only verified on the target lay population. We could therefore assume that the results would be different in a professional population sample.

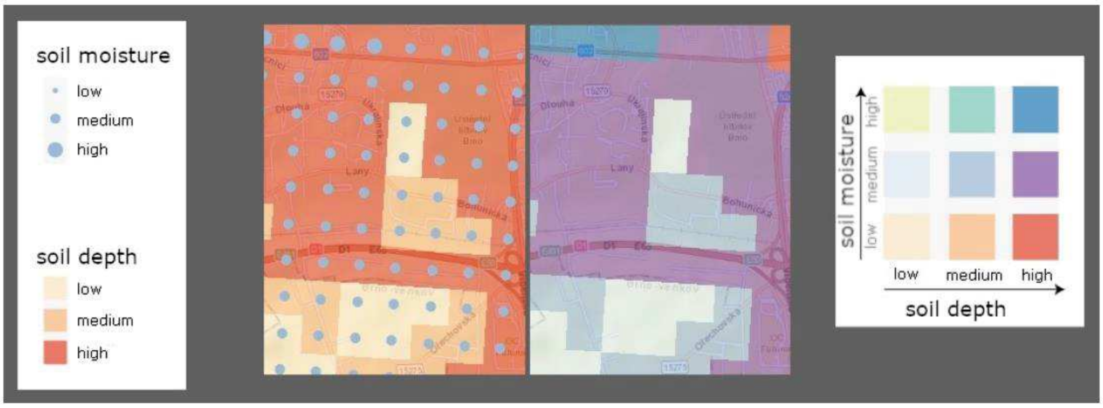

Figure 22: Bivariate visualizations used in a study (Paper 9).

4.4 Part 2 – Aim 3 Experimental Research on Complex Spatial Tasks

The final aim investigated more complex tasks linked to categorizing multivariate point symbols (Paper 10), comparing 3D profiles using real-3D and pseudo-3D cartographic visualizations (Paper 11), and associating landmark symbols for navigation purposes (Paper 12). The proposed research questions investigated two levels:

General level:

- Are there any differences in the perception of real-3D and pseudo-3D cartographic visualizations? (Paper 11)
- What is the role of interaction in the perception of 3D visualizations? (Paper 11)
- Are there any differences in association and preferences between imagery and iconic, pictorial and textual symbols? (Paper 12)

Cultural level:

- Are there any differences at the cross-cultural level in the preferred manner of categorizing point multivariate symbols? (Paper 10)

Effect of clustering on Cartographic Visualization (Paper 10)

For the experiment, figural multivariate map symbols were used to measure clustering, one of the components of categorization (McCleary, 1975). The maps were intentionally created to provoke categorization (Figure 23) in relation to the cognitive styles of participants from Europe and China and the differences expected as a consequence of dissimilarity in culture. Asian cultures tend to be more holistic, while Anglo-European cultures tend to be more analytic. The inherent differences of holistic and analytic approaches were expected to have an effect on clustering the map stimulus. The results highlighted the differences between the research sample groups in performing the categorization process.

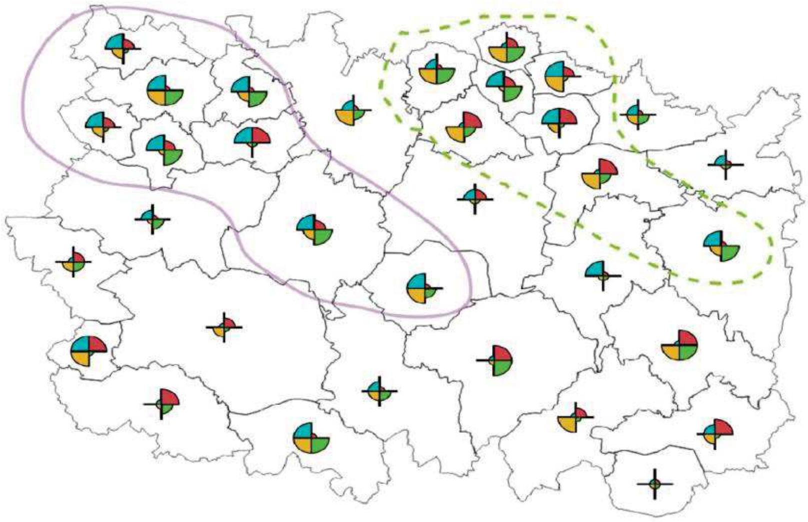

Figure 23: Example of regions (analytic – left, holistic – right) for different approaches to clustering (Paper 10).

Role of interaction in perception of 3D visualizations (Paper 11)

Paper 10 examined the role of interaction in the perception of real-3D and pseudo-3D cartographic visualizations. 3D terrain models (Figure 24) were presented as stimuli, supplemented by a mental rotation test (MRT). The task was involved comparing a 2D terrain profile with the 3D visualization.

The results indicated a minimal advantage of real-3D visualizations over pseudo-3D visualizations. The main benefit in correct comparison in the 3D profile was interactivity, suggesting that pseudo-3D visualization was sufficient for the given task.

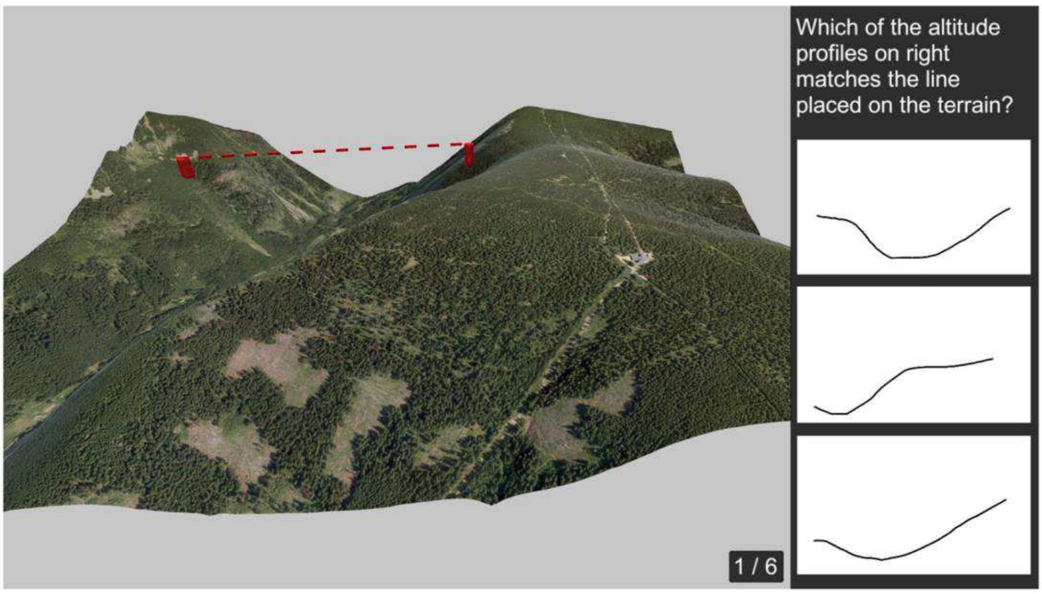

Figure 24: Example of 3D visualization used in the study (Paper 11).

Association and preference of landmark visualization during pedestrian navigation (Paper 12)

The paper studied the use of adaptive navigation landmark visualizations based on the user familiarity with the environment. Four types of landmark map symbols were investigated (Figure 25). The results provided strong evidence of preferences in users for associative image-based visualizations in the case of unfamiliar environments; in a familiar environment, users preferred text-based visualizations. The results could be applied, for example, in mobile map applications.

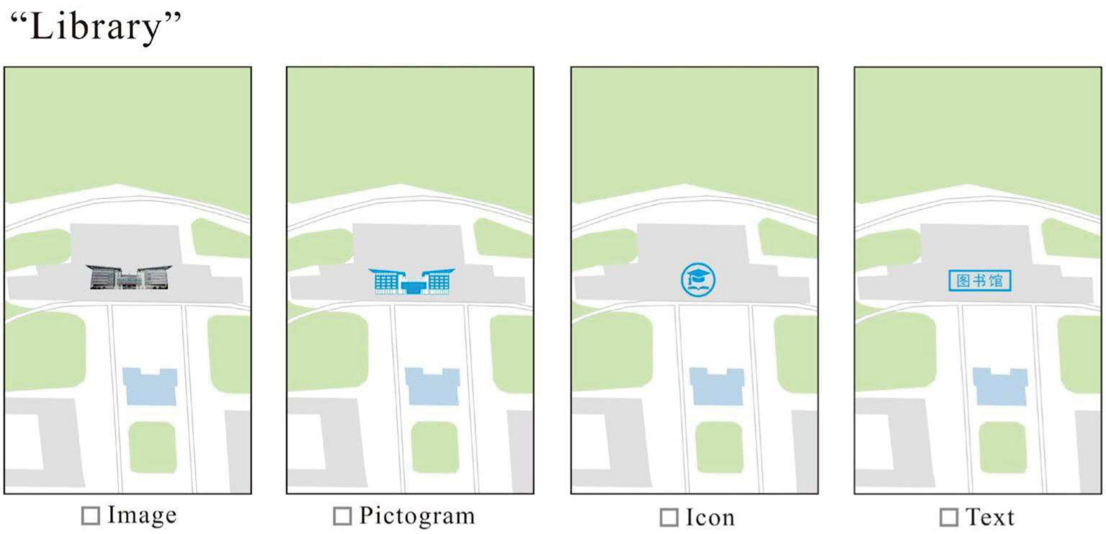

Figure 25: Example of the variation of landmark symbols used in the study (Paper 12).

5. Discussion, Conclusions and Future Work

The development of experimental research in cartography is an opportunity for an objective shift of theoretical knowledge in cartography and has significant application potential in cartographic practice.

The aims of both parts of the research were accomplished:

- PART 1 – Experimental tools were created and applied successfully in the research.
- PART 2 – The experimental studies of selected aspects of cartographic visualizations were accomplished and many differences at the perceptual and cultural levels were observed in the results.

Discussion

The results of the studies contribute to the creation of new ideas and redefinition of established concepts in cartography in direct response to dynamically changing technologies and cartographic communication environments. From the presented facts, the approach to the process of cartographic communication requires both minor modifications and significant changes as a consequence of developments in technology, greater understanding of differences in socio-cultural aspects, and the expansion of knowledge in the functioning of cognitive processes (Figure 26).

The results of the experimental studies indicate that understanding of the process of cartographic communication according to the concept of Koláčný and subsequently published works requires adjustments at several levels. Redefining the position of the cartographer as a map creator is therefore also a consideration, as map creation is widely transferred to the population beyond the geo-community and includes the means and options to interact with the mapping process. Furthermore, the influence of technology on most of the processes involved in the process of cartographic communication is significant and permits the incorporation of feedback from map users. Therefore, a modified user-centered cartographic communication schema was proposed.

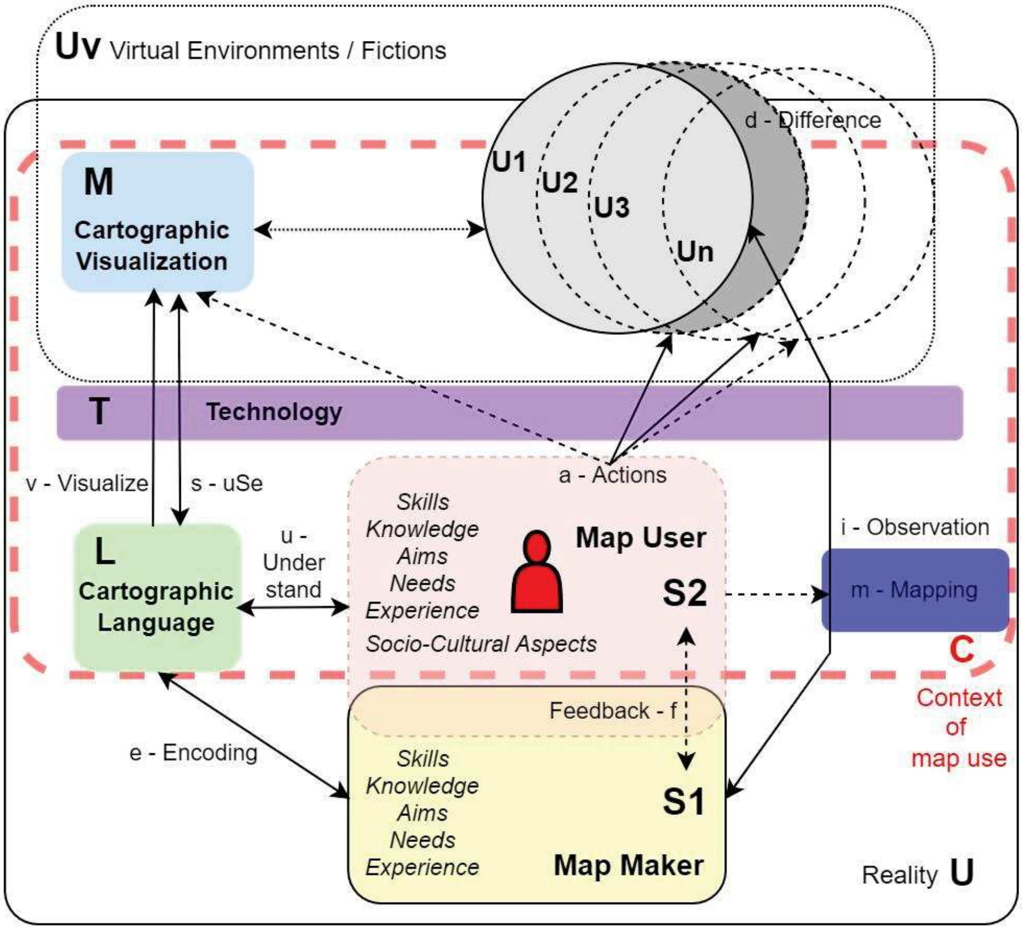

Figure 26: User-centered schema of cartographic communication.

In the diagram (Figure 26), the map maker (S1) is influenced by certain factors (overlap with map user S2 because through the availability of advanced tools, anyone today can create a map) as they observe (i) and map (m) a real or fictitious phenomenon (U1) from reality (U) or fiction (Uv). The technology (T) required to acquire the input data affects these observations. Information is encoded (e) with the map language (L), and a cartographic visualization (M) in real or virtual environment is created (v) using certain technology (T). The cartographic visualization represents a part of reality which exists independently of the displayed object/phenomenon and is ideally an image of its significant properties. The user (S2), who is influenced by certain factors and socio-cultural aspects while using and understand (u) the map language (L) and technology (T), studies and interprets (s) the visualization for distant phenomena. The user then acts (a) according to their perceptions and may create an alternative interpretation (U2, Un) of the visualized phenomenon. For the user, the difference (e.g., U1 - U2 = d) in the resulting representation of the phenomenon may represent a loss or distortion of information, but it might also create new information or add value. Actions can be also performed only on the cartographic visualization.

In this process, interaction or feedback (f) between the map maker and the user may or may not necessarily occur, and the user may participate in the map maker's mapping or creative process. The user can also use the map without understanding the map language, for example as a picture on a wall. In this case, however, the user is not acting according to their understanding. The context of map use (C) then includes the user, their characteristics and socio-cultural background, the map language, the technology used, and finally, the influences of the external environment and reality.

The scheme below (Figure 27) contains a classification and list of possible factors to demonstrate the complexity of variables which influence the process of cartographic communication. It was created based on application of the approach from *Visual Methodologies* authored by Rose (2001).

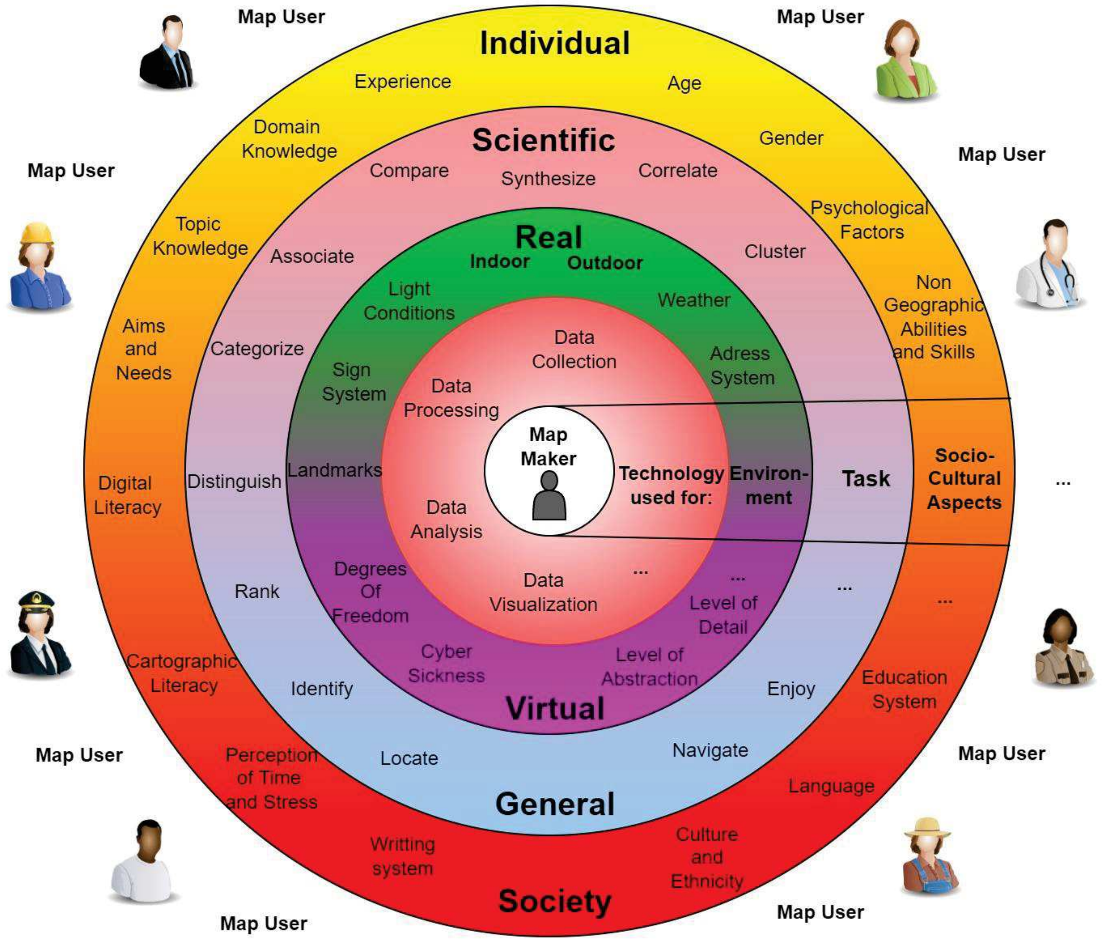

Figure 27: Factors of Cartographic Communication.

The above diagram (Figure 27) indicates four levels of factors influencing process of cartographic communication, i.e., technology, environment, performed activity (task), and socio-cultural aspects. This definition was produced from work by Morita (2009), who studied map use and mapping in the context of wayfinding, Konečný et al. (2006), who researched adaptive visualization in cartography, Hanus (2019), who explored the factors which influence map skills in education, and Wehrend & Lewis (1990), who authored one of the most extensive taxonomies of research tasks for maps and number of items contained in maps.

This list is certainly not exhaustive, but it demonstrates the complex process of creating and using cartographic visualizations and therefore the need for detailed comprehension of the processes involved.

Conclusions and Future Work

The results of the research can potentially contribute to advancing the theoretical knowledge of cartography at several levels:

1. New tools (Papers 1, 2 and 3) provide a catalyst for many empirical studies and aid the verification of theoretical concepts and application of these tools in practice.

2. Observations from the studies introduce a new perspective on how cartographic communication functions, especially in the differences during visual searches of map stimuli (Papers 4, 5 and 6), the differences between informationally equivalent methods of bivariate cartographic visualizations (Papers 7, 8 and 9), and the differences in complex processes involved in using maps (Papers 10, 11 and 12).

3. The differences observed in population samples with different cultural backgrounds (Papers 5, 6 and 10) support the significance of this factor in designing suitable maps keys and cartographic visualization methods. In addition to thorough knowledge of the mapped topic, map makers must also have thorough knowledge of the target user group; this is an integral part of the data acquisition methodology, data processing method, and choice of cartographic visualization method.

Both the theoretical research we performed and the results from our partial studies are immediately applicable in practice. The tools (Papers 1, 2 and 3) designed for the research are available for further study and development, and the experimental results can also be applied; for example, we investigated the principles of perception (Papers 4 and 8) and their possible effects in general map use and other areas, such as geographic support for crisis management. At the general level, personalized cartographic visualizations can be generated according to the user's map literacy (Paper 9), familiarity with the environment (Paper 12), cultural background (Papers 5, 6 and 10).

- A generalized map base is preferred over orthophotos in visual search tasks (Paper 4).
- In designing a map key, the differences in mean detection time of shapes (Paper 6) are a major consideration. Significant objects or events are often represented by diamond-shaped symbols (e.g., Dymon & Mbobi, 2005), which has an evident disadvantage during visual searches (Figure 28).

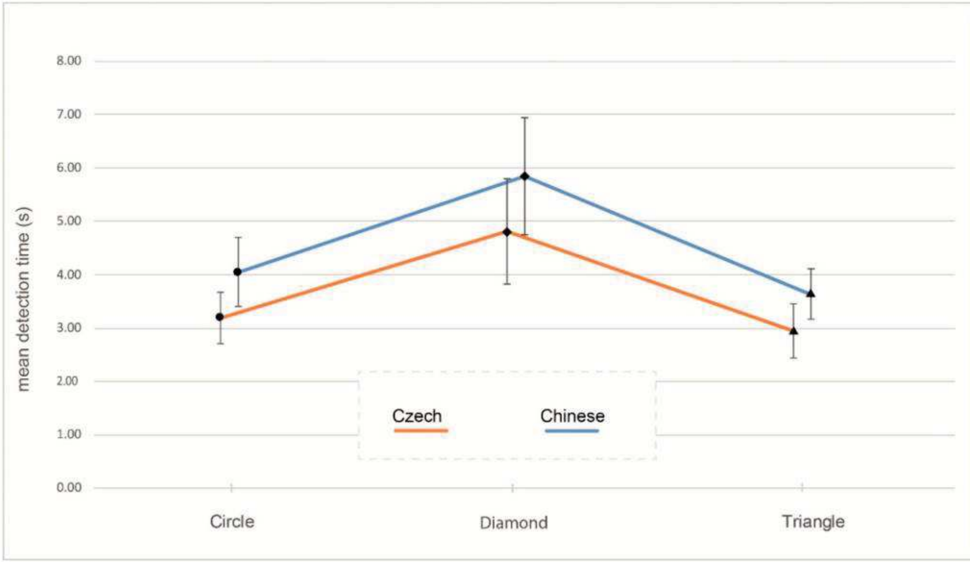

Figure 28: Mean detection time of shapes (Paper 5).

Six basic pillars emerge from this research on cartographic visualization:

1. Clear terminological anchoring of cartographic concepts in the existing terminological apparatus of related fields and modern technologies (e.g., virtual geographic environments).
2. The need to expand interdisciplinary cooperation, especially with experts in cognitive psychology, applied informatics and other related fields.
3. Research into the processes of effective perception of generalized information.
4. Research into the effective use of multivariate mapping methods.
5. Expansion of research into the basic mechanisms of 3D geovisualizations and immersive virtual geographic environments.
6. Research into geography education.

In conclusion, cartographic visualization remains a key output of cartography as a science. The results of the research demonstrate that different methods of cartographic visualization are suitable in a variety of ways for certain tasks and users with differences in experience, cultural background and other aspects. Cartographers should not therefore abandon experimental research or studies to verify the efficiency and effectiveness of maps and satisfaction with their use.

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List of related publications

Major publications which were published on the subject of cartographic visualization.

- Lang, M., Šašinka, Č., Stachoň, Z., & Chmelík, J., (2022). Brýle pro rozšířenou realitu: letová podpora pilotů ultralehkých letadel - funkční prototyp.
- Snopková, D., Ugwitz, P., Stachoň, Z., Hladík, J., Juřík, J., Kvarda, O., & Kubíček, P. (2022). Retracing evacuation strategy: A virtual reality game-based investigation into the influence of building's spatial configuration in an emergency. Spatial Cognition & Computation. Taylor & Francis, 22, 1-2, pp. 30-50. ISSN 1387-5868. doi:10.1080/13875868.2021.1913497.
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- Šašinka, Č., Chmelík, J., Šašinková, A., & Stachoň, Z. (2021). Metodika vzdělávání pomocí aplikace VR-Pilots pro potřeby základního kurzu a piloty začátečníky.
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- Ugwitz, P., Juřík, V., Herman, L., Stachoň, Z., Kubíček P., & Šašinka, Č. (2019). Spatial Analysis of Navigation in Virtual Geographic Environments. Applied Sciences. Basel, Switzerland: MDPI, 9, n. 9, pp. 1-22. ISSN 2076-3417. doi:10.3390/app9091873.
- Herman, L., Kvarda, O., Stachoň, Z. (2018). Cheap and Immersive Virtual Reality: Application in Cartography. In Zlatanova, S., Dragicevic, S., Sithole, G. ISPRS Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Vol. XLII-4. Gottingen: Copernicus GmbH, pp. 329-334. ISSN 1682-1750.

List of Figures

Supplements

The list of attached publications:

Paper 1

Popelka, S., **Stachoň, Z.,** Šašinka, Č., & Doležalová, J. (2016). Eyetribe Tracker Data Accuracy Evaluation and Its Interconnection with Hypothesis Software for Cartographic Purposes. Computational Intelligence and Neuroscience, Vol. 2016, Special Issue, February, Article ID 9172506. https://doi.org/10.1155/2016/9172506. (WoS JIF QUARTILE: Q2)

Abstract

The mixed research design is a progressive methodological discourse that combines the advantages of quantitative and qualitative methods. Its possibilities of application are, however, dependent on the efficiency with which the particular research techniques are used and combined. The aim of the paper is to introduce the possible combination of Hypothesis with EyeTribe tracker. The Hypothesis is intended for quantitative data acquisition and the EyeTribe is intended for qualitative (eye-tracking) data recording. In the first part of the paper, Hypothesis software is described. The Hypothesis platform provides an environment for web-based computerized experiment design and mass data collection. Then, evaluation of the accuracy of data recorded by EyeTribe tracker was performed with the use of concurrent recording together with the SMI RED 250 eye-tracker. Both qualitative and quantitative results showed that data accuracy is sufficient for cartographic research. In the third part of the paper, a system for connecting EyeTribe tracker and Hypothesis software is presented. The interconnection was performed with the help of developed web application HypOgama. The created system uses open-source software OGAMA for recording the eye-movements of participants together with quantitative data from Hypothesis. The final part of the paper describes the integrated research system combining Hypothesis and EyeTribe.

Paper 2

Šašinka, Č., Morong, K., & **Stachoň, Z.** (2017). The Hypothesis Platform : An Online Tool for Experimental Research into Work with Maps and Behavior in Electronic Environments. ISPRS International Journal of Geo-Information, 6(12). https://doi.org/10.3390/ijgi6120407. (WoS JIF QUARTILE: Q2)

Abstract

The article presents a testing platform named Hypothesis. The software was developed primarily for the purposes of experimental research in cartography and psychological diagnostics. Hypothesis is an event-logger application which can be used for the recording of events and their real-time processing, if needed. The platform allows for the application of Computerized Adaptive Testing. The modularity of the platform makes it possible to integrate various Processing.js-based applications for creation and presentation of rich graphic material, interactive animations, and tasks involving manipulation with 3D objects. The Manager Module allows not only the administration of user accounts and tests but also serves as a data export tool. Raw data is exported from the central database in text format and then converted in the selection module into a format suitable for statistical analysis. The platform has many functions e.g., the creation and administration of tasks with real-time interaction between several participants ("multi-player function") and those where a single user completes several tests simultaneously ("multi-task function"). The platform may be useful e.g., for research in experimental economics *or for studies involving collaborative tasks. In addition, connection of the platform to an eye-tracking system is also possible.*

Paper 3

Šašinka, Č., **Stachoň, Z. (corresponding author),** Sedlák, M., Chmelík, J., Herman, L., Kubíček, P., Strnadová, A., Doležal, M., Tejkl, H., Urbánek, T., Svatoňová, H., Ugwitz, P., & Juřík, V. (2019). Collaborative Immersive Virtual Environments for Education in Geography. ISPRS International Journal of Geo-Information, 8(1). https://doi.org/10.3390/ijgi8010003. (WoS JIF QUARTILE: Q2)

Abstract

Immersive virtual reality (iVR) devices are rapidly becoming an important part of our lives and forming a new way for people to interact with computers and each other. The impact and consequences of this innovative technology have not yet been satisfactory explored. This empirical study investigated the cognitive and social aspects of collaboration in a shared, immersive virtual reality. A unique application for implementing a collaborative immersive virtual environment (CIVE) was developed by our interdisciplinary team as a software solution for educational purposes, with two scenarios for learning about hypsography, i.e., explanations of contour line principles. Both scenarios allow switching between a usual 2D contour map and a 3D model of the corresponding terrain to increase the intelligibility and clarity of the educational content. Gamification principles were also applied to both scenarios to augment user engagement during the completion of tasks. A qualitative research approach was adopted to obtain a deep insight into the lived experience of users in a CIVE. It was thus possible to form a deep understanding of very new subject matter. Twelve pairs of participants were observed during their CIVE experience and then interviewed either in a semistructured interview or a focus group. Data from these three research techniques were analyzed using interpretative phenomenological analysis, which is research method for studying individual experience. Four superordinate themes—with detailed descriptions of experiences shared by numerous participants—emerged as results from the analysis; we called these (1) Appreciation for having a collaborator, (2) The Surprising "Fun with Maps", (3) Communication as a challenge, and (4) Cognition in two realities. The findings of the study indicate the importance of the social dimension during education in a virtual environment and the effectiveness of dynamic and interactive 3D visualization.

Paper 4

Konečný, M., Kubíček, P., **Stachoň, Z. (corresponding author),** & Šašinka Č. (2011). The usability of selected base maps for crises management: users' perspectives. SpringerLink, Applied Geomatics. Springer, 2011/3, pp. 189–198. ISSN 1866-9298. https://doi.org/10.1007/s12518-011-0053-1. (WoS JIF QUARTILE: Q3)

Abstract

Cartography has become an important tool for supporting decision-making processes in the field of crisis management. Maps (or GIS) can be used for solving various problems, e.g. the localization of accident site, the delimitation of endangered areas, the formulation of evacuation plans and others. People involved in decision making processes use various procedures to solve these problems. However, a suitable and efficient form of cartographic support for particular situations and crisis management cycle stages is still missing. The main goal of the experiment was twofold. First, we wanted to assess the interdisciplinary (cartography–psychology) web-based testing environment and achieve the first usability results. Second, the use of different cartographic base map representations was analysed in order to judge the efficiency for specific situations. Testing was focused on various types of tasks, e.g. simple sign selection, the possibility of memorizing important information from the map and the choice of the optimal evacuation route. The overall testing was performed within the interactive web environment, based on predefined templates, automatically recorded and calibrated against the evaluation

of the pretest users' abilities. Preliminary testing results provide valuable inputs concerning the usability of selected base maps for supporting decision-making processes during various crisis situations.

Paper 5

Stachoň, Z., Šašinka, Č., Čeněk, J., Angsüesser, S. Kubíček, P., Štěrba, Z., Bilíková, M. (2018). Effect of Size, Shape and Map Background in Cartographic Visualization: Experimental Study on Czech and Chinese Populations. ISPRS International Journal of Geo-Information, 7/427, pp. 1-15. ISSN 2220-9964. https://doi.org/10.3390/ijgi7110427. (WoS JIF QUARTILE: Q2)

Abstract

This paper deals with the issue of the perceptual aspects of selected graphic variables (specifically shape and size) and map background in cartographic visualization. The continued experimental study is based on previous findings and the presupposed cross-cultural universality of shape and size as a graphic variable. The results bring a new perspective on the usage of shape, size and presence/absence of background as graphic variables, as well as a comparison to previous studies. The results suggest that all examined variables influence the speed of processing. Respondents (Czech and Chinese, N = 69) identified target stimuli faster without a map background, with larger stimuli, and with triangular and circular shapes. Czech respondents were universally faster than Chinese respondents. The implications of our research were discussed, and further directions were outlined.

Paper 6

Stachoň, Z., Šašinka, Č., Čeněk, J., Štěrba, Z., Angsüesser, S., Fabrikant, S., I., Štampach, R., & Morong, K. (2019). Cross-cultural differences in figure–ground perception of cartographic stimuli. Cartography and Geographic Information Science, 46(1), 82-94. https://doi.org/10.1080/15230406.2018.1470575. (WoS JIF QUARTILE: Q3)

Abstract

This article reports on an empirical study investigating cultural differences in the visuospatial perception and cognition of qualitative point symbols shown on reference maps. We developed two informationally equivalent symbol sets depicted on identical reference maps that were shown to Czech and Chinese map readers. The symbols varied in visual contrast with respect to the base map. Our empirical results suggest the existence of cultural influences on map reading, but not in the predicted direction based on the previous cross-cultural studies. Our findings stress the importance of considering the cultural background of map readers, especially when designing reference maps aimed for global online use.

Paper 7

Kubíček, P., Šašinka, Č., **Stachoň, Z.,** Štěrba, Z., Apeltauer, J., & Urbánek, T. (2017). Cartographic Design and Usability of Visual Variables for Linear Features. Cartographic Journal, 54(1), 91-102. https://doi.org/10.1080/00087041.2016.1168141. (WoS JIF QUARTILE: Q4)

Abstract

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.*

Paper 8

Šašinka, Č., **Stachoň, Z.,** Kubíček, P., Tamm, S., Matas, A., & Kukaňová, M. (2018). The Impact of Global/Local Bias on Task-solving in Map-related Tasks Employing Extrinsic and Intrinsic Visualization of Risk Uncertainty Maps. The Cartographic Journal, ISSN 0008-7041. https://doi:10.1080/00087041.2017.1414018. (WoS JIF QUARTILE: Q4)

Abstract

The form of visual representation affects both the way in which the visual representation is processed and the effectiveness of this processing. Different forms of visual representation may require the employment of different cognitive strategies in order to solve a particular task; at the same time, the different representations vary as to the extent to which they correspond with an individual's preferred cognitive style. The present study employed a Navon-type task to learn about the occurrence of global/local bias. The research was based on close interdisciplinary cooperation between the domains of both psychology and cartography. Several different types of tasks were made involving avalanche hazard maps with intrinsic/extrinsic visual representations, each of them employing different types of graphic variables representing the level of avalanche hazard and avalanche hazard uncertainty. The research sample consisted of two groups of participants, each of which was provided with a different form of visual representation of identical geographical data, such that the representations could be regarded as 'informationally equivalent'. The first phase of the research consisted of two correlation studies, the first involving subjects with a high degree of map literacy (students of cartography) (intrinsic method: $N = 35$; extrinsic method: $N = 37$). The second study was performed after the results of the first study were analyzed. The second group of participants consisted of subjects with a low expected degree of map literacy (students of psychology; intrinsic method: $N = 35$; extrinsic method: $N = 27$).The first study revealed a statistically significant moderate correlation between the students' response times in extrinsic visualization tasks and their response times in a global subtest ($r = 0.384$, $p < 0.05$); likewise, a statistically significant moderate correlation was found between the students' response times in intrinsic visualization tasks and their response times in the local subtest ($r = 0.387$, $p < 0.05$). At the same time, no correlation was found between the students' performance in the local subtest and their performance in extrinsic visualization tasks, or between their scores in the global subtest and their performance in intrinsic visualization tasks. The second correlation study did not confirm the results of the first correlation study (intrinsic visualization/'small figures test': $r = 0.221$; extrinsic visualization/'large figures test': $r = 0.135$). The first phase of the research, where the data was subjected to statistical analysis, was followed by a comparative eye-tracking study, whose aim was to provide more detailed insight into the cognitive strategies employed when solving map-related tasks. More specifically, the eye-tracking study was expected to be able to detect possible differences between the cognitive patterns employed when solving extrinsic- as opposed to intrinsic visualization tasks. The results of an exploratory eye-tracking data analysis support the hypothesis of different strategies of visual information processing being used in reaction to different types of visualization.

Paper 9

Šašinka, Č., **Stachoň, Z. (corresponding author),** Čeněk, J., Šašinková, A., Popelka, S., Ugwitz, P., & Lacko, D. (2021). A Comparison of the Performance on Extrinsic and Intrinsic Cartographic Visualizations through Correctness, Response Time and Cognitive Processing. PLoS ONE, 16(4). https://doi.org/10.1371/journal.pone.0250164. (WoS JIF QUARTILE: Q2)

Abstract

The aim of this study was to compare the performance of two bivariate visualizations by measuring response correctness (error rate) and response time, and to identify the differences in cognitive processes involved in map-reading tasks by using eye-tracking methods. The present study is based on our previous research and the hypothesis that the use of different visualization methods may lead to significant cognitive-processing differences. We applied extrinsic and intrinsic visualizations in the study. Participants in the experiment were presented maps which depicted two variables (soil moisture and soil depth) and asked to identify the areas which displayed either a single condition (e.g., "find an area with low soil depth") or both conditions (e.g., "find an area with high soil moisture and low soil depth"). The research sample was composed of 31 social sciences and humanities university students. The experiment was performed under laboratory conditions, and Hypothesis software was used for data collection. Eye-tracking data were collected for 23 of the participants. An SMI RED-m eye-tracker was used to determine whether either of the two visualization methods was more efficient for solving the given map-reading tasks. Our results showed that with the intrinsic visualization method, the participants spent significantly more time with the map legend. This result suggests that extrinsic and intrinsic visualizations induce different cognitive processes. The intrinsic method was observed to generally require more time and led to higher error rates. In summary, the extrinsic method was found to be more efficient than the intrinsic method, although the difference was less pronounced in the tasks which contained two variables, which proved to be better suited to intrinsic visualization.

Paper 10

Lacko, D., Šašinka, Č., Čeněk, J., **Stachoň, Z.**, & Lu W.-L. (2020). Cross-Cultural Differences in Cognitive Style, Individualism/Collectivism and Map Reading between Central European and East Asian University Students. Studia Psychologica, 62(1), 23-42. http://dx.doi.org/10.31577/sp.2020.01.789. (WoS JIF QUARTILE: Q4)

Abstract

The article examines cross-cultural differences encountered in the cognitive processing of specific cartographic stimuli. We conducted a comparative experimental study on 98 participants from two different cultures, the first group comprising Czechs (N = 53) and the second group comprising Chinese (N = 22) and Taiwanese (N = 23). The findings suggested that the Central European participants were less collectivistic, used similar cognitive style and categorized multivariate point symbols on a map more analytically than the Asian participants. The findings indicated that culture indeed influenced human perception and cognition of spatial information. The entire research model was also verified at an individual level through structural equation modelling (SEM). Path analysis suggested that individualism and collectivism was a weak predictor of the analytic/holistic cognitive style. Path analysis also showed that cognitive style considerably predicted categorization in map point symbols.

Paper 11

Kubíček, P., Šašinka, Č., **Stachoň, Z.,** Herman, L., Juřík, V., Urbánek, T., & Chmelík, J. (2019). Identification of altitude profiles in 3D geovisualizations: the role of interaction and spatial abilities.

International Journal of Digital Earth, 12(2), 156-172. https://doi.org/10.1080/17538947.2017.1382581. (WoS JIF QUARTILE: Q1)

Abstract

Three-dimensional geovisualizations are currently pushed both by technological development and by the demands of experts in various applied areas. In the presented empirical study, we compared the features of real 3D (stereoscopic) versus pseudo 3D (monoscopic) geovisualizations in static and interactive digital elevation models. We tested 39 high-school students in their ability to identify the correct terrain profile from digital elevation models. Students' performance was recorded and further analysed with respect to their spatial abilities, which were measured by a psychological mental rotation test and think aloud protocol. The results of the study indicated that the influence of the type of 3D visualization (monoscopic/stereoscopic) on the performance of the users is not clear, the level of navigational interactivity has significant influence on the usability of a particular 3D visualization, and finally no influences of the spatial abilities on the performance of the user within the 3D environment were identified.

Paper 12

Zhu, L., Shen, J., Zhou, J., **Stachoň, Z.,** Hong, S., & Wang, X., (2022). Personalized landmark adaptive visualization method for pedestrian navigation maps: Considering user familiarity. Transactions in GIS. Wiley, 26/2, pp. 669-690. ISSN 1361-1682. https://doi.org/10.1111/tgis.12877. (WoS JIF QUARTILE: Q3)

Abstract

Landmark-based pedestrian navigation can assist pedestrians in navigating successfully. Previous studies have investigated the factors affecting the cognitive efficiency of landmark visualization in terms of both the visual salience of landmarks and the personal characteristics of users. However, empirical studies and applications that consider the influence of spatial familiarity on landmark representation are limited. In this article, we propose a personalized landmark adaptive visualization method for pedestrian navigation maps considering user familiarity. We first explore the influence of spatial familiarity on landmark salience and symbols using cognitive experiments. The results showed that unfamiliar people preferred strong visual salience landmarks and image-based symbols, while familiar people preferred strong semantic salience landmarks and text-based symbols. Based on these results, a mathematical model of landmark salience for selecting personalized landmarks is proposed, and association rules between landmark salience and symbols are mined. Finally, the framework of a landmark visualization method is proposed based on the rules. To verify the effectiveness of the proposed method, a prototype system is developed, and a comparative experiment is conducted with a Baidu map. Experimental results showed that the proposed method has direct practical implications for the development of pedestrian navigation systems, depending on different target users.

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Research Article

EyeTribe Tracker Data Accuracy Evaluation and Its Interconnection with Hypothesis Software for Cartographic Purposes

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The mixed research design is a progressive methodological discourse that combines the advantages of quantitative and qualitative methods. Its possibilities of application are, however, dependent on the efficiency with which the particular research techniques are used and combined. The aim of the paper is to introduce the possible combination of Hypothesis with EyeTribe tracker. The Hypothesis is intended for quantitative data acquisition and the EyeTribe is intended for qualitative (eye-tracking) data recording. In the first part of the paper, Hypothesis software is described. The Hypothesis platform provides an environment for web-based computerized experiment design and mass data collection. Then, evaluation of the accuracy of data recorded by EyeTribe tracker was performed with the use of concurrent recording together with the SMI RED 250 eye-tracker. Both qualitative and quantitative results showed that data accuracy is sufficient for cartographic research. In the third part of the paper, a system for connecting EyeTribe tracker and Hypothesis software is presented. The interconnection was performed with the help of developed web application HypOgama. The created system uses open-source software OGAMA for recording the eye-movements of participants together with quantitative data from Hypothesis. The final part of the paper describes the integrated research system combining Hypothesis and EyeTribe.

1. Introduction

The paper presents methodological-technical approach combining quantitative and qualitative methods which are based on specific technical tools. The aim of this paper is to introduce the newly developed technical research system and results of its validation: specifically, the creation and empirical verification of an interconnection of a web-based platform Hypothesis with an EyeTribe eye-tracking system connected to open-source software OGAMA. The interconnection was done by the creation of a new web application HypOgama.

The introduction of the paper discusses the methodology and mixed-research design (combination of quantitative and qualitative, resp., explorative methods) in the area of cognitive visualization and cartography. The paper consists of three parts which are ordered due the logic and procedure of the research system creation and verification. The first part is focused on the presentation of a tool for mass data collection: web-based platform Hypothesis. The second part of the paper presents the new low-cost eye-tracking system EyeTribe, which allows efficient realization of qualitative, respectively, explorative studies. In this part, close attention is paid to empirical study verifying the truthfulness of the low-cost EyeTribe tracker in comparison with SMI RED 250 system. The final part of the paper describes the research system which combines and integrates above-mentioned tools. Part of this last section is also an illustration of possible empirical study, where the interconnection of Hypothesis and EyeTribe for cartographic and psychology research is presented. However this case study is only an example of how the integrated research system and HypOgama application works, and it should only illustrate the procedure of conducting a mixed-research design.

A significant portion of experimental studies in the area of cognitive visualization can be sorted into two main categories. The studies in the first category monitor and record the behaviour of individuals or, rather, their conscious actions and general work methods when completing tasks with a use of a map. The most common aspects of studies are completion speed, accuracy, and correctness or frequency of a given solution (see [1–5]). The mentioned studies use a quantitative approach and subsequent statistical methods of data analysis. A second significant category is the use of eye-tracking systems. Eye-tracking studies are in many cases combined with the recording of conscious behaviour, that is, user actions (see the first category), but the crucial activities recorded are eye-movements, which offer continuous data about (even unconscious) behaviour of the participant while solving a task. In other words, the focus of the user's attention is foregrounded [6]. Due to the high processing requirements, these studies are often performed on a small sample of participants and methods other than statistical data analysis are being used, for example, explorative data analysis [7].

Eye-tracking was used for the evaluation of maps for the first time already in the late 1950s [8], but it has been increasingly used in the last ten to fifteen years. The main reasons are the declining prices of the equipment and the development of computer technology that allows faster and more efficient analysis of measured data. For usability research, eye-tracking data should be combined with additional qualitative data, since eye-movements cannot always be clearly interpreted without the participant providing context to the data [9].

An example of comprehensive research in the field of cognitive visualization by using eye-tracking is the work of Alaçam and Dalcı [10], who compared four map portals (Google Maps, Yahoo Maps, Live Search Maps, and MapQuest). The basic assumption of the study was that lower average fixation duration indicates more intuitive map portal environment. The shortest average fixation duration was found in the case of Google Maps. Fabrikant et al. [11] used eye-tracking for the evaluation of map series expressing the evolution of the phenomenon over time, or for evaluation of user cognition of weather maps [12]. Ooms et al. [13] dealt with the suitability of map label positions and differences in map reading between experts and novices. Popelka and Brychtova [14] investigated the role of 2D and 3D terrain visualization in maps.

Olson [15] compared cognitive visualization and cognitive psychology, arguing that cartographers can adapt ideas and experiments in methodology from cognitive psychologists. Equally, psychologists can use maps as stimuli in their studies. Both disciplines can examine the cognitive processes while reading and understanding maps. However, cognitive psychologists are interested in different types of cognitive processes such as attention, visual perception, memorizing, or decision-making. A map is only a tool in this context. For a cognitive cartographer, the map is far more important.

The approach mentioned above is based on close cooperation between cartographers and psychologists and shows

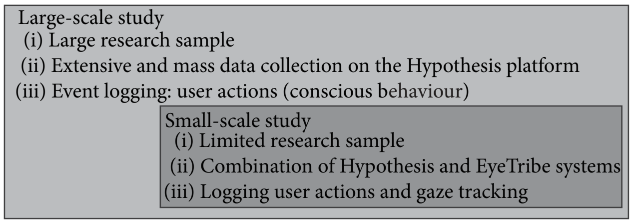


Figure 1: The combination of large-scale and small-scale study.

the possibility of a connection between large-scale studies and small-scale studies based on gathering and analysing eye-tracking data. Differences between large-scale and small-scale studies are described in Figure 1.

As it is discussed in Štěrba et al. [16], using only a qualitative (explorative) or quantitative type of evaluation method is not sufficient. Therefore, it is necessary to combine those methods, enabling their suitable completion, obtaining more valid results, and achieving better interpretation. A combination of quantitative and qualitative methods was established as mixed-research design [17]. The key idea and innovation of our method are the interconnection of two approaches in the area of cognitive visualization and also finding a technological solution.

The Hypothesis platform serves primarily for the creation of experimental test batteries, online administration, and extensive data gathering. After connecting with the eye-tracking system, more detailed data on the experimental task processing methods are gathered, which allow deeper insight into the postulated cognitive processes that underlie the behavioural reactions.

Štěrba et al. [18] propose two variants of mixed-research design:

(i) Using the eye-tracking system for a pilot study examining a quality of experiment design with results from this pilot study being used for improvement of experiment design before large-scale data collection.

(ii) Using Hypothesis for large-scale quantitative approach and secondary using of eye-tracking method for the subsequent specification of certain results with adjusted or changed types of tasks.

Both approaches and technical specification of Hypothesis platform are described in detail in [18] and are available online in English.

2. A Tool for Mass Data Collection: Web-Based Platform Hypothesis

For the purposes of large-scale experimental investigation, the creation of psychological tests, and evaluation of cartographic works, new research software concept was designed within the project "Dynamic Geovisualization in Crisis Management" [19]. Subsequently, this concept has been realized, and original software MuTeP was developed [20, 21]. MuTeP

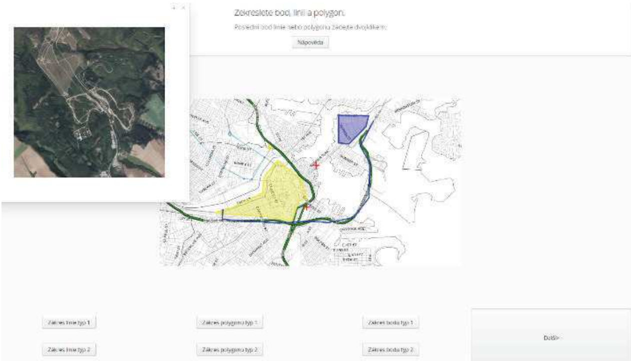


Figure 2: Example task on WMS interactive map. The user indicates the requested objects, draws lines, and marks out target areas by polygons. In the example shown, the user called up an orthophoto map in a dialogue-window. All the actions including the drawn point coordinates, lines, and polygons are saved in the database, and the correctness of the solution is automatically evaluated under preset conditions.

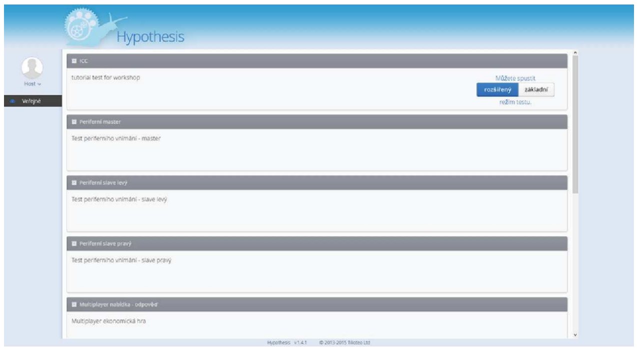


Figure 3: Management module in the Hypothesis platform. The user can launch the available tests in two modes: (a) legacy (launches in a normal browser) and (2) featured (launches in a controlled mode in SWT browser). The manager and the superuser have an extended access and can unlock the tests, create users, export results, and so forth.

was primarily created for the purposes of objective experimental exploration and evaluation of cartographic products in the perspective of user personality.

Although MuTeP was practically proven [22], it was clear that the conception used will soon reach its limits. Another impulse for the search for a more flexible solution was an effort to involve dynamic cartographic visualization as stimuli, randomization, nonlinear test batteries, connection with eye-tracking technology, and so forth, which were not possible to implement into MuTeP software.

Based on experience with MuTeP and in the context of current requirements, a new software concept was designed. This new software should have the potential for long-term growth and development [23]. Hypothesis has several important advantages in comparison with MuTeP. Above all, Hypothesis enables computer adaptive testing and offers a modular solution with plugin support (such as video or interactive animation plugins) and enables the work with interactive maps (such as web map services; see Figure 2).

The technology used for designing Hypothesis consists of the following: (1) the application core and user interface are built on framework Vaadin 7; work with the database is provided by ORM Hibernate; and (2) PostgreSQL in version 9.1 (and higher) is used as a primary database system [18].

The architecture of the system is three-layer: a client, server, and database. The client part is designed for communication and interaction with the user, and its operation is provided by standard web browsers (thin client) or a special browser distributed in the application package—special Hypothesis Browser. Hypothesis Browser is based on Standard Widget Toolkit (SWT) components and ensures more strict conditions and control over running tests [18, 24].

Hypothesis works as an event-logger application, which logs all user actions and events (coordinates and timestamps of clicks, key presses, start and end time of each presented slide, exposition time of every component such as a picture or dialogue-window, zoom of maps, rotation of 3D objects, etc.). Extensive logging of user actions and events is enabled through the structure of the final slides used for the test battery (package). The package comprises the hierarchical structure of branches which contain one or more tasks, and each task contains at least one slide. The slide consists of a template and content. Such structure enables nonlinear branching of the test slides or randomization of slides. All parts of the package are stored in structured XML format. After starting a test, a selected package is loaded from the database to the server application and a new test is created. Emphasis was placed on variability and range of software usability. Figure 2 shows an example of the slide using WMS. The slide consists of two layers. The underlaying image is created with a layer: ImageLayer. Above it, there is a transparent layer: FeatureLayer, which is designed to draw demanded points, polylines, or areas by mouse and store the events [18].

Hypothesis is also improved with two new key functionalities that are vital for the interconnection between eye-tracking systems (or other peripherals such as EEG) and enable the realization of experiments with high reliability. These functionalities involve the use of SWT browser that allows the client to monitor and control the testing process. In other words, when using the controlled mode (see Figure 3), the participant has no way to intentionally or unintentionally exit the test by, for example, pressing alt + F4. Other common functions of web browsers are also strictly disabled, such as page refreshing or opening menus by right-clicking the mouse. The second key functionality is the recording of two time sets in the database. To avoid the problem of slow internet connection, both server time and local PC time are recorded, which means that events on the client side can be accurately synchronized (e.g., synchronizing stimulus exposition with data from the eye-tracker).

Researchers can effectively create new test batteries thanks to a combination of a number of subfunctions and tools. Emphasis is also placed on the efficiency of the software. Researchers can effectively change the content of already finished test slides and create derivatives from sample

Table 1: Summary of calibration results for all participants.

Participant	SMI X	SMI Y	EyeTribe
P01	0,4	0,2	Good
P02	0,3	0,1	Poor
P03	0,4	0,6	Moderate
P04	0,4	0,4	Perfect
P05	0,9	0,5	Good
P06	0,3	0,5	Redo
P07	0,2	0,4	Moderate
P08	0,6	0,3	Moderate
P09	0,4	0,1	Perfect
P10	0,3	0,4	Poor
P11	0,6	0,3	Poor
P12	0,5	0,5	Moderate
P13	0,3	0,3	Moderate
P14	0,4	0,6	Poor

templates through the modules for user access administration and also export structured results.

Hypothesis software is freely available for collaboration on a various research topic in the Czech Republic and abroad. Access to the database and modules is provided after registration.

3. In-Depth Analysis of Cognitive Processes Using Eye-Tracking System

3.1. EyeTribe Tracker. Eye-tracking technology is becoming increasingly cheaper, both on the hardware and on the software front. Currently, the EyeTribe tracker is the most inexpensive commercial eye-tracker in the world, at a price of $99. More information about the device is available at the web page of the manufacturer (https://theeyetribe.com/). The low-cost makes it a potentially interesting resource for research, but no objective testing of its quality has been performed as of yet [25]. Dalmaijer in his study [25] with five participants compared the EyeTribe tracker with high-frequency EyeLink 1000. He states that concurrent tracking by both devices of the same eye-movements proved to be impossible, due to the mutually exclusive way in which both devices work. One of the reasons was that EyeLink uses only one eye for the recording. Delmaijer [25] also states that recording with both devices at the same time results in deterioration of results of both and often leads to a failure to calibrate at least one. Ooms et al. [26] compared EyeTribe with SMI RED 250 but also did not use the concurrent recording. In our study, we compared the EyeTribe tracker with SMI RED 250. In our case, we have not noticed any problems with calibration (see Table 1).

3.2. Methods of EyeTribe Accuracy Evaluation. For the comparison study, recording with SMI RED 250 and the EyeTribe tracker at the same time was performed. Laboratory setup is displayed in Figure 4. The EyeTribe tracker stands in front of the SMI device.

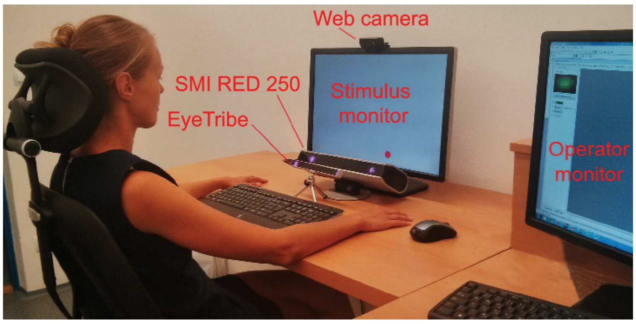


Figure 4: Laboratory setting for EyeTribe and SMI accuracy comparison.

EyeTribe tracker was connected with the OGAMA software [27], where the experiment with six static image stimuli was prepared. At the same time, screen recording experiment was created in SMI experiment center (sampling frequency was set up to 60 Hz, to be the same as EyeTribe). Both devices were calibrated separately (but the eye-trackers were at their positions and turned on).

After calibrations, recording with SMI started. After that, experiment with static images in OGAMA was performed. That means the SMI device recorded the experiment data as well (as a screen recording video). The whole experiment procedure was done with fourteen participants. The purpose of the study was to verify how trustworthy data from EyeTribe tracker are. Recorded fixations from both eye-trackers were compared qualitatively and quantitatively. A diagram of the whole recording procedure is displayed in Figure 5.

For the comparison of recorded data from both devices, the OGAMA environment was used. Data from EyeTribe were displayed in OGAMA directly; SMI data had to be converted. For this conversion, the tool smi2ogama developed by S. Popelka was used. The tool is available at http://eyetracking.upol.cz/smi2ogama/.

The recorded screen data were cropped according to the pertinence to individual stimuli. For that, recorded key presses (for a slide change) were used.

3.3. Participants. Total of 14 respondents participated in this part of the study (ten males and four females with an average age of 29.5). They were employees and postgraduate students of department of geoinformatics. 16-point calibration was used for both devices. Results of calibration are summarized in Table 1. With the EyeTribe, it was almost not possible to achieve perfect calibration result. Figure 6 shows the details of calibration results for participant P03. The results in OGAMA show calibration result for each of the 16 calibration points (with the use of colour); SMI shows only the average value in degrees of visual angle for axes X and Y.

For all recordings, I-DT fixation detection in OGAMA was used with the same settings. A value of 20 px was used as “maximum distance”; “minimum number of samples” was set up to 5. More information about fixation detection settings is available in [28, 29].

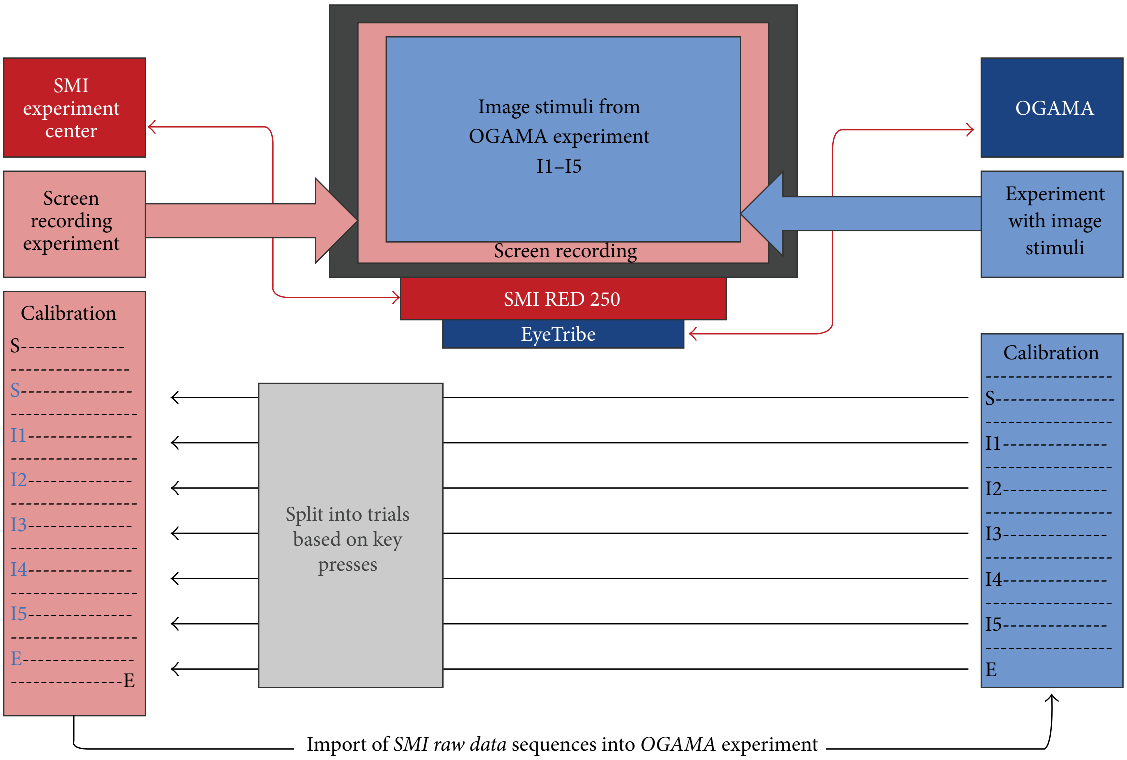
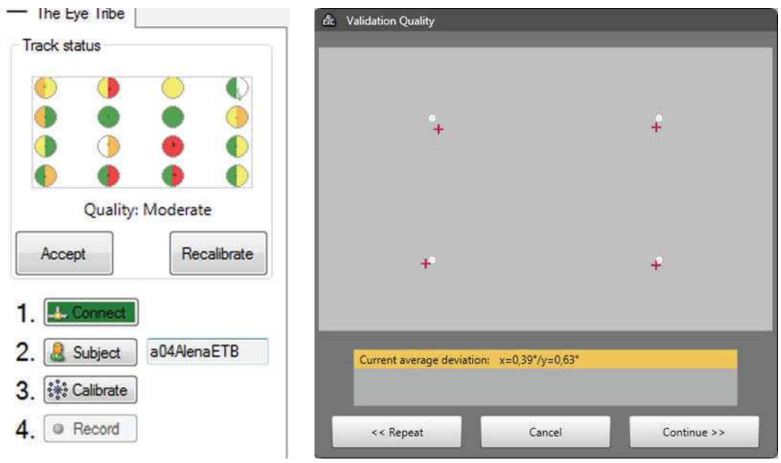


Figure 5: Diagram of concurrent eye-movements recording with SMI RED 250 and EyeTribe.



(a) (b)

Figure 6: Calibration results from EyeTribe (a) and SMI RED (b) for participant "P03."

3.4. Stimuli. The experiment contained six static images. The first one contained a grid with nine numbers; second one (Slide 2, Figure 7) contained sixteen numbers. The task of the participants was to read numbers in ascending order (from top to the bottom). Next three stimuli contained different types of maps, but the results of these stimuli are not described in this paper. The last stimulus (Slide 6, Figures 8 and 9) contained a map of the world and respondents' task was to move the eyes around Africa.

3.5. Results and Discussion of EyeTribe Evaluation. Eye-movement data recorded from participant P03 are displayed in Figure 7. Red points represent fixations from SMI, and blue points are fixations from EyeTribe. The task in this stimulus was only to read the numbers.

From Figure 7, it can be seen that both devices recorded around one or two fixations over each number. The accuracy of the recording is comparable. Accuracy reflects the eye-tracker's ability to measure the point of regard and is defined

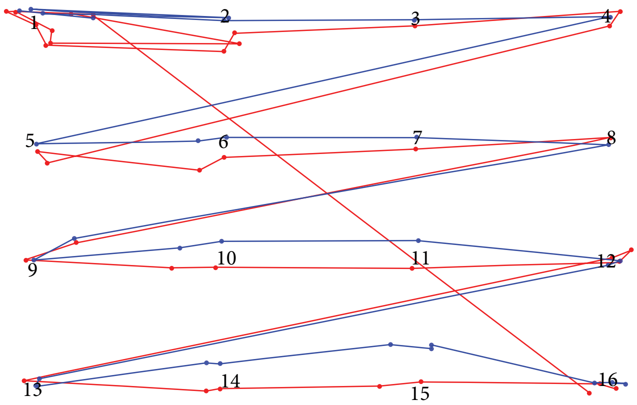


Figure 7: Comparison of recorded eye-movement data from participant P03 in Slide 2 from EyeTribe (blue) and SMI RED (red).

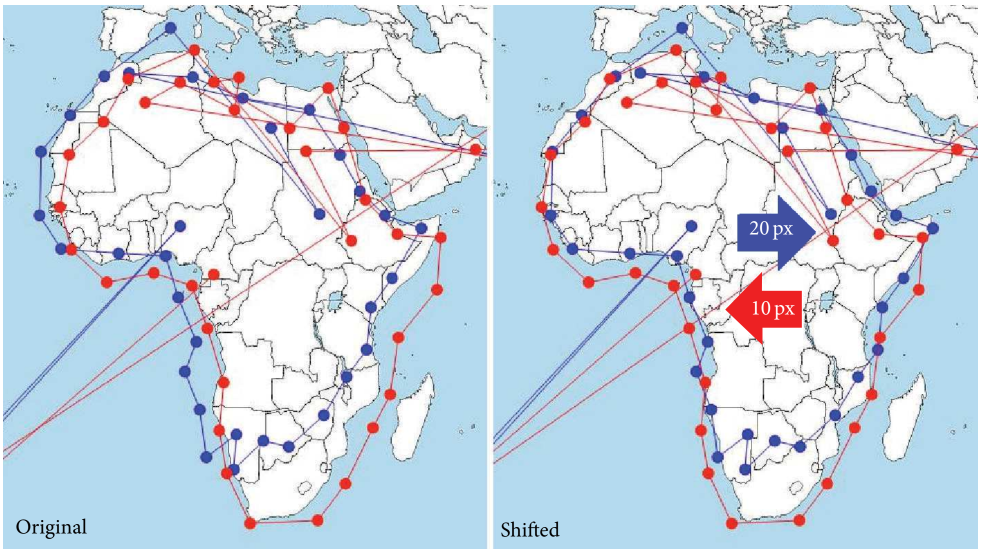


Figure 8: Comparison of recorded eye-movement data from participant P03 in Slide 6 from EyeTribe (blue) and SMI RED (red).

as the average difference between a test stimulus position and the measured gaze position [30]. The largest deviations of the EyeTribe tracker data were observed for two points in the middle of the bottom line. This situation was observed in almost all recorded data. The situation can be seen in Figure 7 in the case of points 14 and 15 (middle points in the lowest line of numbers). Gaze position recorded by EyeTribe is shifted upwards.

Another example is visible in Figure 8, which is the crop of Slide 6 stimuli. In this stimulus, the task was to move the eyes around the continent of Africa on the map. The data recorded by EyeTribe tracker were moved to the left by 20 px, but this systematic error can be corrected by a manual shift of fixations in OGAMA. This situation is depicted in Figure 8. On the left side, original data are displayed. On the right, data after horizontal shift (20 px to the right for EyeTribe and 10 px to the left for SMI) are depicted. Eye-movement data from EyeTribe for horizontally central fixations are shifted upwards, especially in the bottom part of the stimuli. See Figure 12 for more detailed analysis of fixation locations. The same issue was reported in all stimuli for most of the participants. Visualization of gaze trajectories of all participants is in Figure 9. The solution for dealing with this inaccuracy is to avoid placing important parts of the stimulus to the bottom of the screen. It will be possible to compare recorded raw data, but, in cartographic research, fixations are used for analysis, so it was more meaningful to compare fixations (identified with the same algorithm).

As an alternative for the comparison of raw data, comparison of data loss was performed. In the case of SMI recordings, average data loss (samples with coordinates 0, 0) was 0.57% of all recorded data. With the EyeTribe, the average data loss was 1.22%. Although the value is more than twice higher than in the case of SMI, it is still acceptable.

The graph in Figure 10 shows the percentage of data loss for Slide 2. It is evident that data loss is higher in the case of EyeTribe recordings, but, in most cases, less than 2% of data is missing. The highest values were observed for participants

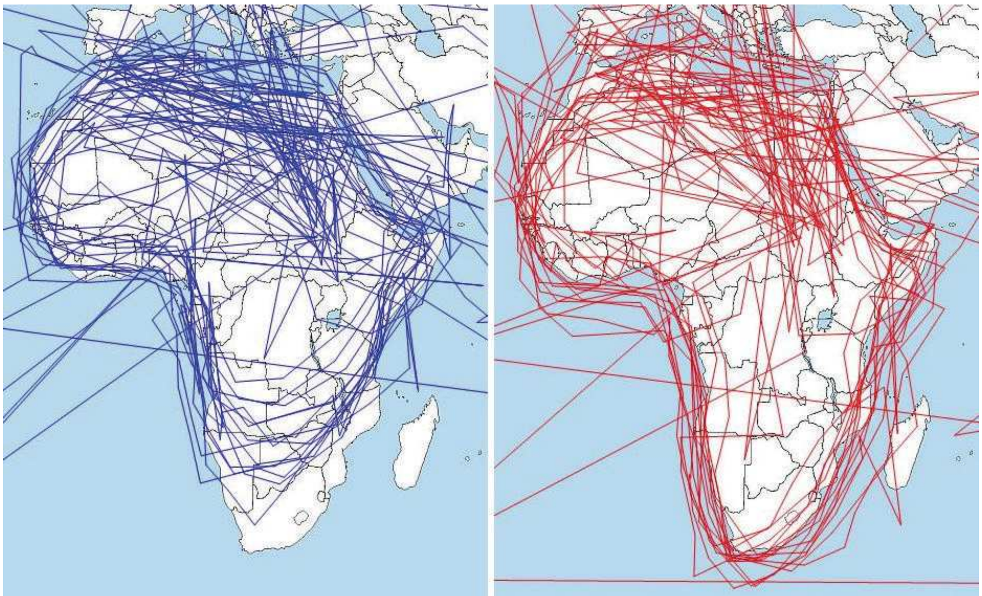


Figure 9: Problems with data recorded by EyeTribe (blue) at the bottom of the stimuli in comparison with SMI data (red).

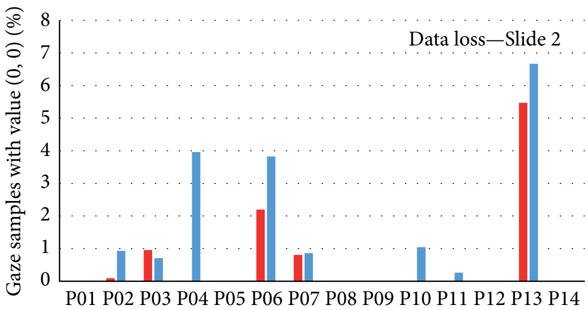


Figure 10: Comparison of data losses of fourteen participants during observation of Slide 2. Red bars represent SMI RED 250; blue ones represent EyeTribe tracker.

P06 and P13. Participant P06 had the worst calibration from all respondents. Participant P13 has worn glasses which can possibly cause the high data loss.

In the next step of accuracy evaluation, values of eye-tracking metric fixation count recorded by SMI RED 250 and the EyeTribe tracker were compared for all six stimuli in the experiment. A summary of the results is shown in Figure 11. The correlation between numbers of detected fixations was between 0.949 and 0.989 with the exception of participant P13 with the correlation of 0.808. The ratio between a number of recorded fixations with SMI device and EyeTribe was also investigated. On average, EyeTribe recorded 88.2% of fixations that were recorded by SMI device. The correlation and ratio values for each participant are presented as part of Figure 11.

Beside the number of fixations, their location was compared. For this evaluation, Slide 2 with a grid of 16 numbers was chosen (Figure 7). For each participant, the deviations between coordinates of the target (number) and closest fixation were calculated. The graphs in Figure 12 show the median size and direction of the deviation for each of the 16 targets in the stimuli. It is evident that the largest deviations (heading upwards) for EyeTribe were observed for the points in the bottom part of the image (numbers 14 and 15). Each graph contains the value of the Euclidean distance of median deviations from the origin. Average deviation was 26 px for EyeTribe and 22 px for SMI.

The evaluation of truthfulness was performed on fourteen participants. According to Nielsen [31], this number should be sufficient. The evaluation of qualitative (Figures 7, 8, and 9) and quantitative (Figures 10, 11, and 12) data indicates that accuracy of low-cost EyeTribe tracker is sufficient for the use in cartographic research. Similar results were found by Ooms et al. [26], who measured the accuracy by the distance between recorded fixation locations and the actual location.

The limitation of the low-cost device is the sampling frequency, which is only 60 Hz (compare with 250 Hz of SMI RED eye-tracker). Another problem is shift of fixation locations in the bottom part of the screen. Taking into account described limits of the device, the EyeTribe may be an appropriate tool for cartographic research.

4. Integrated Research System: Interconnection of Hypothesis Software and EyeTribe

As one of the practical applications of the mixed-research experiment design, the Hypothesis software interconnected with the EyeTribe tracker was chosen. For the recording of eye-tracking data, the OGAMA software was used because the EyeTribe tracker is intended for developers and contains no software for data recording and analysis. OGAMA has an inbuilt slide show viewer, but the range of functionality of this viewer in comparison with SW Hypothesis is quite

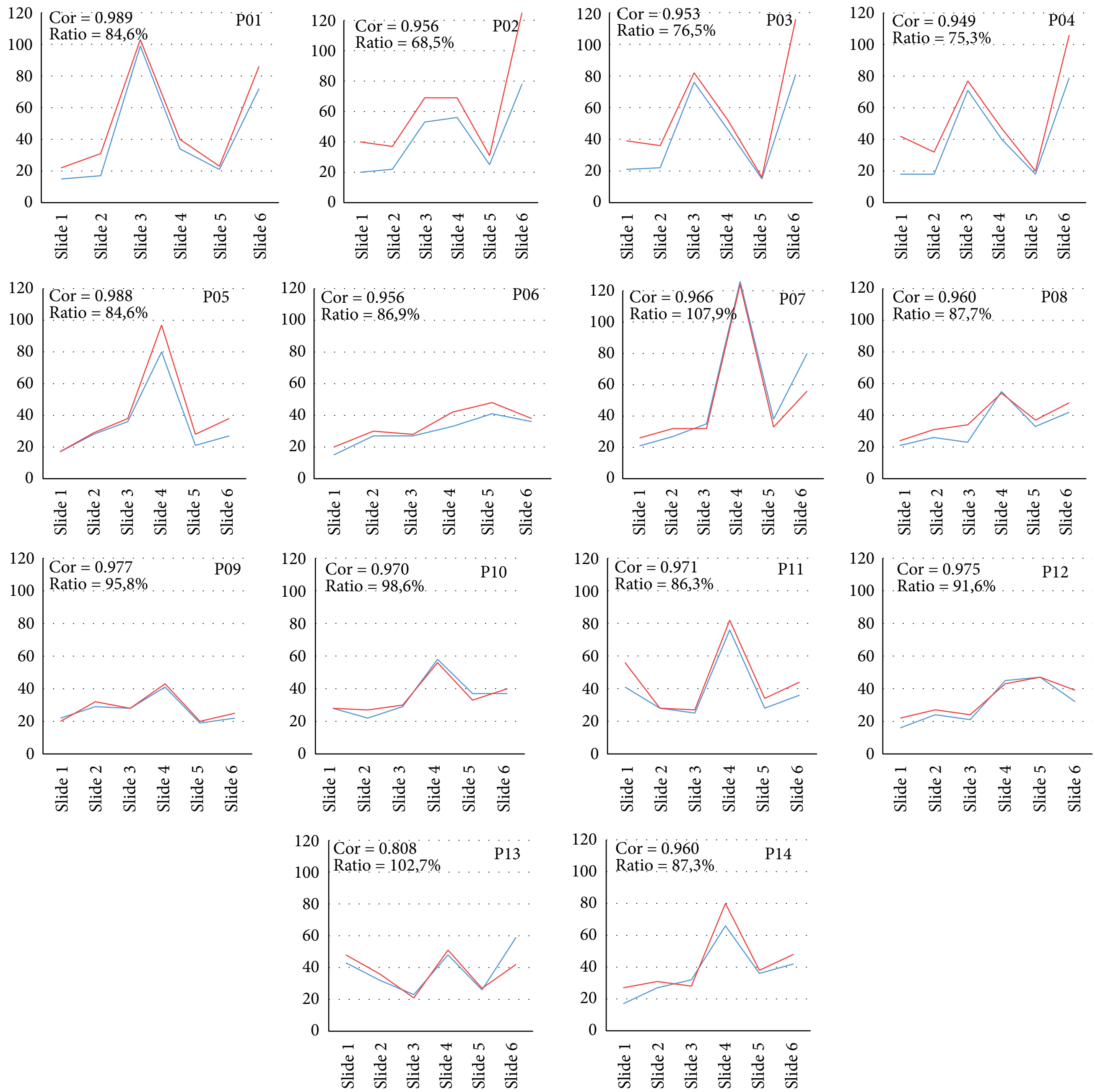


Figure 11: Comparison of fixation count eye-tracking metric for fourteen participants. EyeTribe data are displayed as blue line; SMI data are displayed as red line.

limited. Desktop application OGAMA principally does not allow working with web-based interactive maps and mouse clicks are recorded but not shown. Oppositely, Hypothesis visualizes clicks and allows drawing of lines and polygons. This functionality is crucial in the context of working with maps. Because of this functionality, Hypothesis connected to OGAMA via HypOgama was used.

4.1. Methods of Hypothesis and EyeTribe Interconnection. For the study, a simple Hypothesis experiment containing five stimuli (intro, three pairs of maps, and last slide) was used. Participants' task was to identify the differences between the maps. Coordinates of the clicks representing differences were also recorded.

OGAMA experiment was designed with only one screen recording stimulus. OGAMA in version 5.0 can record dynamic web stimuli, but it is not possible to use slides from Hypothesis as separate stimuli.

Recorded data were split according to their belonging to particular slides in the Hypothesis experiment. For the split, timestamps from Hypothesis indicating the slide change were used. The splitting and conversion of recorded data

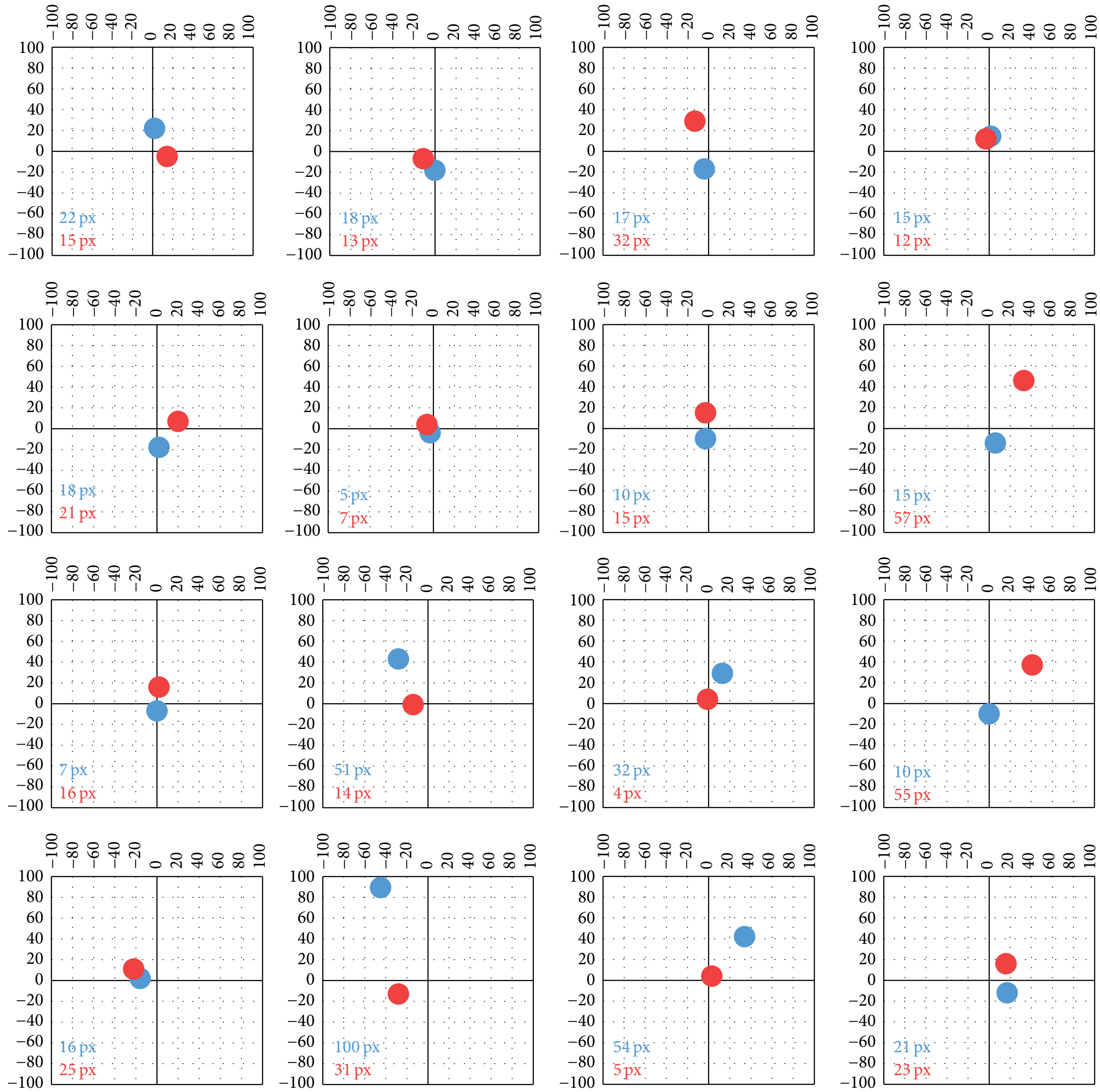


FIGURE 12: Comparison of fixation positions in Slide 2 for fourteen participants. Distance from the center of the image shows fixation deviation in pixels. EyeTribe data are displayed as blue dots; SMI data are displayed as red dots.

manually were time-consuming and not user-friendly. Thus, a web application called HypOgama was written in PHP for the automation of the process. The functionality of HypOgama application is illustrated in Figure 13.

The HypOgama application (Figure 14) is freely available at http://eyetracking.upol.cz/hypogama/.

The application synchronizes the Hypothesis time with the timestamp from the eye-tracking recording in OGAMA. The synchronization is processed by the key press that was used to start the Hypothesis experiment and which was recorded in both systems—in Hypothesis and OGAMA.

In the next step, the application scans the Hypothesis file and finds the timestamps of slide changes. These timestamps are then used for splitting raw eye-tracking data into blocks belonging to particular slides. The name of the relevant stimuli is added to all records from each block. In the final step, the data structure is modified for the direct import into a new OGAMA project.

The application contains six input fields:

(1) Exported file from Hypothesis manager containing data for one participant.

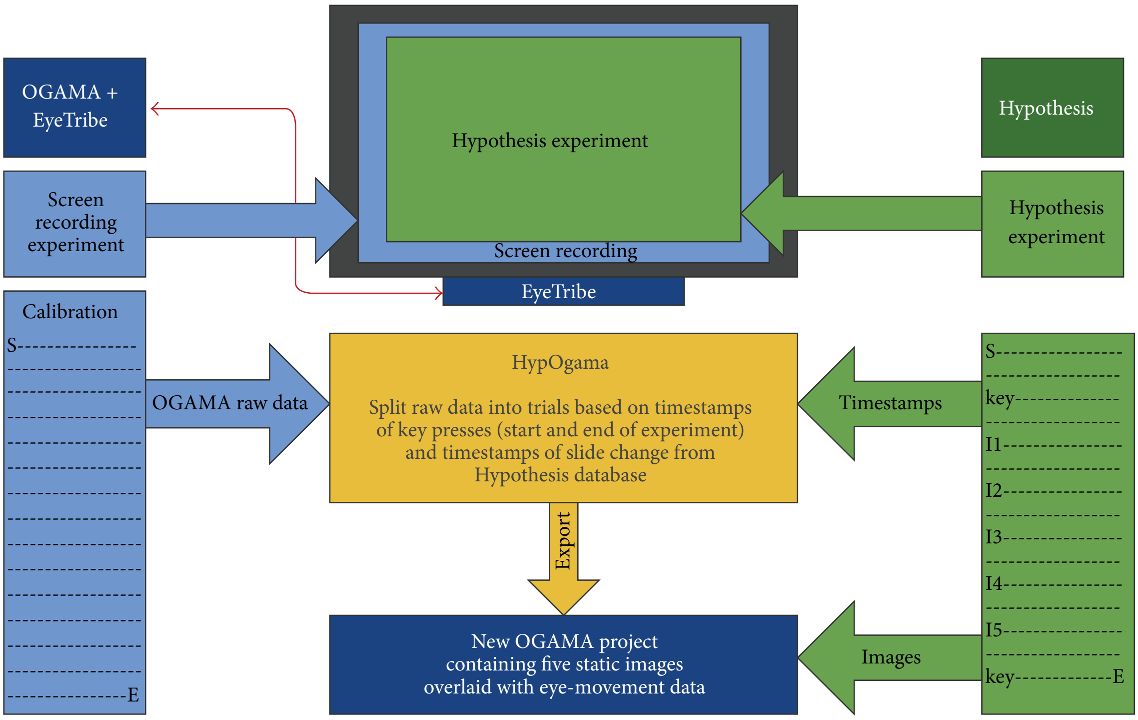


Figure 13: Process of splitting recorded data (screen recording) into trials with the use of HypOgama web application.

Figure 14: Environment of HypOgama web application.

(2) Exported raw data from the OGAMA application for one participant.

(3) Name of the output file.

(4) Subject name (if blank, the ID from Hypothesis will be used).

(5) Frequency of an eye-tracker (30 or 60 Hz).

(6) Synchronization variables: these values indicate which key was used for the synchronization of Hypothesis and OGAMA (default value is "Key: Down" in OGAMA format and "Down" in the format of Hypothesis application).

In the Hypothesis file (ad 1), HypOgama finds the row with the key press (default Key: Down) and the corresponding time, which corresponds to the beginning of the experiment. In the next step, the column containing the slide names is scanned and the time of the first occurrence of each slide is also stored. According to this time, OGAMA recording is split. The last information obtained from the Hypothesis file is the name of the subject, overwriting the subject name in the OGAMA file.

In OGAMA file, all records prior to the synchronization key press are erased. Stimuli names are replaced by those from Hypothesis file.

Outputs of the created script are raw eye-movement data for each slide that could be directly imported into the OGAMA project. The only one necessary thing is to put image files (stimuli) into OGAMA project folder. If it is the same filename as the one contained in the Hypothesis file, images will be automatically assigned to proper data. After the whole process, a user has OGAMA project containing static image stimuli with all corresponding eye and mouse movement data. The proposed concept was applied and verified through a selected case study described below. The purpose of this short study was to illustrate the functionality of interconnection of EyeTribe and OGAMA.

For the verification of the designed process of Hypothesis and EyeTribe combination, simple test battery was designed. For chosen procedure, Hypothesis was used for large-scale quantitative approach and eye-tracking method for the subsequent specification of certain results.

The test battery was established in the Hypothesis software and was focused on verification of Gestalt principles,

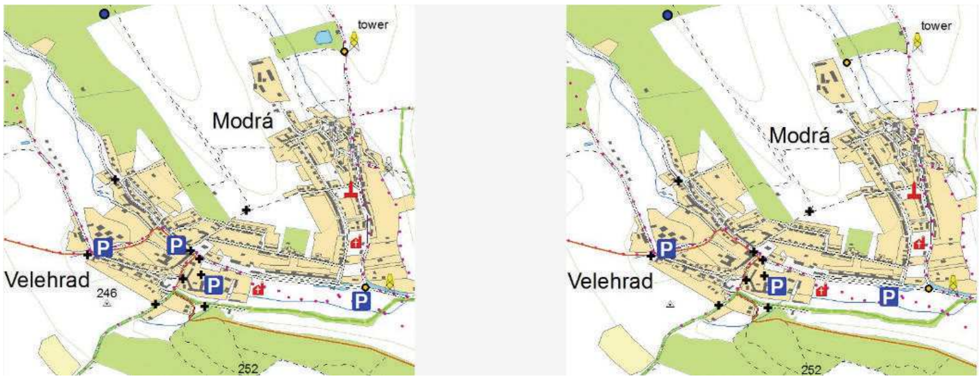


Figure 15: Example of stimuli—the first pair of topographic maps.

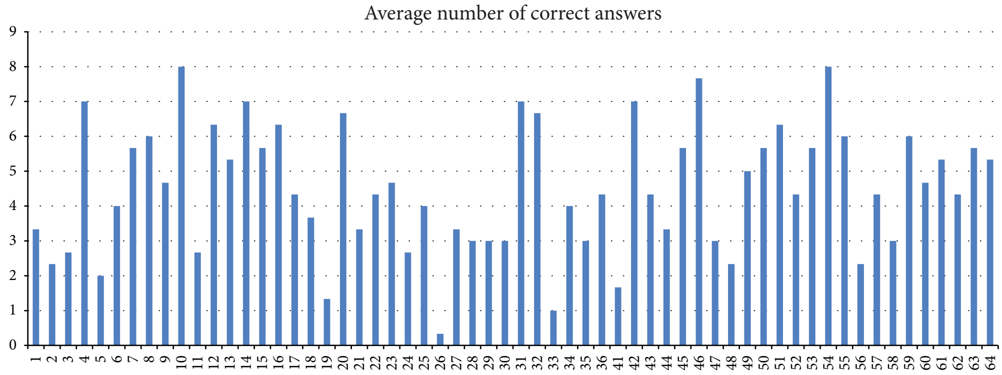


Figure 16: An example of results from Hypothesis. An average number of correct answers for each of the participants.

respectively, figure-ground organization, and on the cross-cultural comparison in the context of visual perception of cartographic stimuli [22, 32–35] on the example of specific cartographic products. The cartographic tasks were part of these more complex research batteries. The main purpose of this short cartographic study was the verification of HypOgama application and whole integrated research system for further research studies.

4.2. Participants. Participants of this illustrative case study were 64 students from the Masaryk University, Czech Republic, and 64 students from Wuhan University, China. In the first phase, participants were tested only on the web-based platform Hypothesis. Only a half of the dataset (Czech population) was further used in context of this particular study where the topographic and thematic maps were compared. In the second phase, the experiment was conducted with the use of eye-tracking system and the research sample is still continually extended.

4.3. Stimuli. The stimuli were represented by three pairs of maps that differed in 10 variables, for example, different colours of map signs, different position of the signs, and missing map signs. First two pairs of stimuli contained topographic maps. The third pair of the maps contained a thematic map.

The test was structured in three main parts. In the first part, participants filled out a personal questionnaire; in the second part, a representative example of the stimuli was presented to familiarize the participants with the environment of Hypothesis. In the third part, three tasks containing pairs of stimuli described above were presented. Participants were asked to mark the differences between presented maps. The time limit for each task was 45 seconds. An example of a topographic map (Slide 1) is displayed in Figure 15. On Slide 2, similar topographic map in different scale was shown. The last slide contained thematic map (see Figure 17).

4.4. Results and Discussion of Hypothesis and EyeTribe Interconnection. The performed study verified stability of proposed system on long distances and, at the same time, part of the test battery was used as a pilot study to verify the functionality of an integrated research system. Stimuli comparing the effectiveness of visual search between topographic and thematic maps were selected.

In the first phase, the test was performed in the Hypothesis application only. A number of differences identified between pairs of maps on Czech population were analysed (see Figure 16).

In the case of two pairs of topographic maps, the average number of correct answers was four. In the case of the stimuli

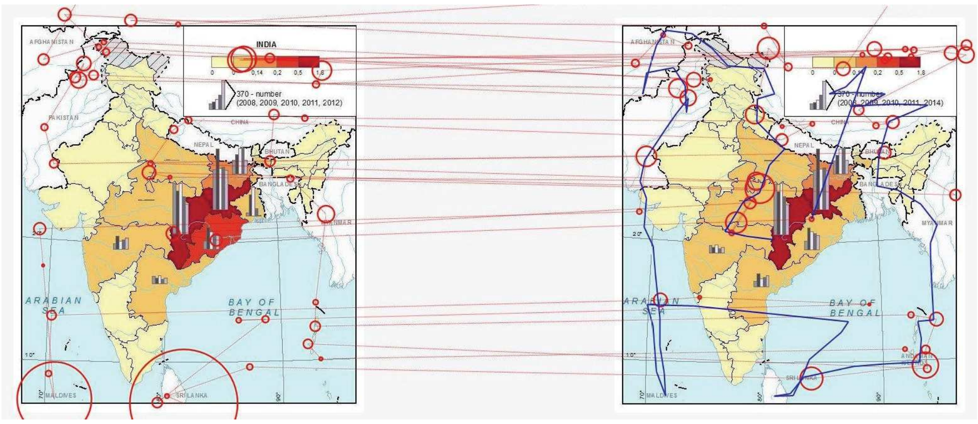


Figure 17: Example of eye-movement data recorded during the Hypothesis experiment. Circles represent fixations; blue line on the right is a mouse trajectory.

with a thematic map, the average number of correct answers was five.

To generalize the findings, an increase of the number of maps per condition would be necessary. However, this difference was the first clue to establish working hypotheses. Based on the data from the first phase of testing, hypotheses were established only at the level of stimulus-reaction. The way of task processing by users and their solving strategies were still a black-box; thus there was a need for more detailed procedural data, especially for information about distinct search strategies.

To explore differences in the visual search, eye-tracking can be used due to the ability to provide more detailed information (e.g., which kind of object was omitted, which kind of object could be found at first glance, and which areas attracts main attention).

Therefore, in the second phase, the already used experimental battery created in Hypothesis was interconnected with OGAMA through HypOgama application and the experiment was launched with the EyeTribe system. Cartographic stimuli and the eye-tracking data were linked together and further analysed with OGAMA.

The example in Figure 17 shows outputs from OGAMA-scan path and mouse trajectory of one participant over the stimulus with thematic maps. In this case, fixations are distributed mainly over the text labels in the map. Participant did not find the difference in the colour of the Odisha state (on the east coast of India) under the relatively large graph. At the same time, eye-tracking metrics (e.g., fixation count, dwell time for each map, and a number of saccades between these maps) can be statistically analysed. Based on findings from both types of analyses, the hypotheses for subsequent study can be established.

The functionality of the integrated research system has been fully verified in the above-mentioned pilot study. The experiment created on the Hypothesis platform was connected with OGAMA and EyeTribe via HypOgama. Data capture including eye-tracking recording continued and exploratory analyses of these data were performed.

5. Conclusion

The aim of the paper was to prove the concept of the mixed-research design through the interconnection of Hypothesis (software for experiment creation, experiment execution, and data collection) and the EyeTribe tracker (the most inexpensive commercial eye-tracker). This system could prove to be a valuable tool for cognitive cartography experiments and evaluation of user behaviour during map reading process.

The first necessary step was to evaluate the accuracy of the EyeTribe tracker with the use of concurrent recording together with the SMI RED 250 eye-tracker. The results of the comparison show that the EyeTribe tracker can be a valuable resource for cartographical research.

The next part of the study was focused on the interconnection of the EyeTribe with the Hypothesis platform, developed at Masaryk University in Brno. The connection was made through a newly created web application that modifies eye-movement data recorded during screen recording experiment in the OGAMA open-source application. The application is publicly available for the community of cartographers and psychologists at web page http://eyetracking.upol.cz/hypogama.

The interconnection advantages were illustrated on an example of simple case study containing three pairs of maps. The performed case study demonstrated the ability of the combined system of the Hypothesis platform and the EyeTribe tracker to support each other and to serve as an effective tool for cognitive studies in cartography.

Competing Interests

The authors declare that they have no competing interests.

Acknowledgments

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Article

The Hypothesis Platform: An Online Tool for Experimental Research into Work with Maps and Behavior in Electronic Environments

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Abstract: The article presents a testing platform named Hypothesis. The software was developed primarily for the purposes of experimental research in cartography and psychological diagnostics. Hypothesis is an event-logger application which can be used for the recording of events and their real-time processing, if needed. The platform allows for the application of Computerized Adaptive Testing. The modularity of the platform makes it possible to integrate various Processing.js-based applications for creation and presentation of rich graphic material, interactive animations, and tasks involving manipulation with 3D objects. The Manager Module allows not only the administration of user accounts and tests but also serves as a data export tool. Raw data is exported from the central database in text format and then converted in the selection module into a format suitable for statistical analysis. The platform has many functions e.g., the creation and administration of tasks with real-time interaction between several participants ("multi-player function") and those where a single user completes several tests simultaneously ("multi-task function"). The platform may be useful e.g., for research in experimental economics or for studies involving collaborative tasks. In addition, connection of the platform to an eye-tracking system is also possible.

Keywords: experimental testing; cognitive cartography; web-based software; behavior research method; psychological diagnostic; eye tracking

1. Introduction

Research on user aspects of cartographic visualization can be traced back to the middle of the twentieth century. Contemporary technological developments enabled the extension of existing methods of spatial data presentation, such as contextual visualization [1], interactive (stereoscopic) 3D visualization [2–4], audiovisual communication [5], augmented reality [6] etc. Thus, there arises a need for the establishment of new research tools. The need for a distributed web-based approach is mentioned e.g., by Robinson [7]. There are several strategies on how to handle the issue. Most of the studies use an environment designed for a particular study. Robinson [7] demonstrated the usage of the e-Delphi platform and the e-Symbology Portal. This approach brings increased demands on software development for each performed study. Other studies usually use general software tools such as WebEx, Microsoft PowerPoint, Microsoft NetMeeting, etc. The advantage of the aforementioned general software is the general availability without the need for further application development. The main disadvantage consists of the limited possibility to customize the tools for a particular study. As there was no tool specifically designed for the large variety of usability testing issues in cartography, we decided to start development in this area. As many authors proved validity and profitability of remote usability testing [8], we began development in this direction.

The character of the newly designed platform was determined by cooperation between psychologists and cartographers. In the course of a research project entitled "Dynamic Geovisualization in Crisis Management" [9], a need arose to develop a research tool which would record the behavior of research subjects when working with cartographic materials (including interactive ones) while making it possible to create and administer psychological tests. Interactive electronic maps usually involve web browsing [10,11], so the new platform was to be designed as a web-based application. Based on a set of specifications, a client-server Multivariate Testing Programme (MuTeP) was developed which made it possible to perform varying map reading-related operations, including clicking on objects, route plotting, and others [12–17]. The same functionality was used to create psychological performance tests and tasks (e.g., adaptation of the framed-line test [18] and Embedded Figures Test [19]. However, the MuTeP application showed principal limitations in several aspects, one being the absence of adaptive testing principles. Based on the experience with the MuTeP application, a completely new platform, Hypothesis, was developed to overcome the limitations of the previous software [20]. In defining the architecture of the new platform, emphasis was placed on the range and variability of its functionality, and its flexibility when creating test tasks and batteries.

1.1. Application in the Field of Cognitive Cartography

Cartographic visualizations can be viewed as complex visual stimuli [21,22], where content and form interact. When creating test batteries, every task of the same tape is related to a different territory, and so different "correct answers" need to be defined. In Hypothesis, the necessary level of flexibility was achieved by the unique connection of slide templates with related slide contents (see Section 2.1), which makes it possible to perform all the necessary modifications of stimuli and correct answers. The varying activities and operations [23,24] performed by research subjects may range from simple visual searches, clicking on target objects [25], and sorting of objects of a single category [26] to more elaborate operations which include optimal route planning, terrain passability investigation [27,28], and even highly complex operations, such as those involving crisis management [29–31], agriculture-related decision-making [32], and crime analysis [33]. The unique design of Hypothesis makes it possible to conduct not only "molecular-level" experiments, but also studies focusing on "molar behavior" [34]. The aim of the former is to study low-level cognitive processes; they include visual search or memory tasks, where the speed, accuracy, and precision of the participant's solution are analyzed. Molar-behavior studies, on the other hand, focus on high-level cognitive processes, investigating the strategies employed in the process of task solving. The analyzed behavior then includes a sequence of map-related operations (e.g., frequency of legend consulting, zooming, map shifting, switching between the varying map layers, selection of target areas, and their interconnection with optimal routes.

1.2. Application in the Field of Psychodiagnostics

Its wide functionality, central database, and well worked-out management module, along with the possibility to present rich and interactive visual stimulus, makes the Hypothesis platform suitable for psychological diagnostics as well. The platform allows for the creation (or adaptation) of a range of psychological performance tests which used to be available only in the paper-and-pencil version [35,36]. The platform contains expression evaluators so that the operations performed by participants can be evaluated in real time (while the participants are completing the tests). The table of results then contains not only raw data, but also the calculated scores and indices. The Hypothesis platform has already been used for the creation or adaptation of several psychological tests, including the D2 Test of Attention [37], Trail-making Test [38], and Grammatical Transformation Test [39], Perspective Taking Test or Mental Rotation Test [40,41].

2. Hypothesis: Characteristics and Architecture

The Hypothesis platform consists of a Module Manager and a Database. The Database, which contains whole Packs (Test Batteries) as well as the participants' results, is located on the central server. The participants and database administrators access the Management Module (Figure 1) through a web browser. After log-in, the Management Module interface offers several functional modes. The participants can access only the Pack Menu (list of test batteries). Depending on the setting, the tests can be run in either the "Basic" mode (full screen window of a standard web browser) or in the "Controlled" mode (SWT browser). Administrators (managers or super-users) can, in addition to the list of tests, access the Administrator Account which makes it possible to control and manage all the user accounts. Also, the Module Manager contains an Export Module for the export of raw data (from the table of results) in .xlsx format. For the purpose of raw-data post-processing, a Selection Application was developed. When creating new tests, administrators also make use of the Slide Editor, where the individual slides can be displayed and edited. The slides can be edited using a web browser, while tests as such, are created in the Database.

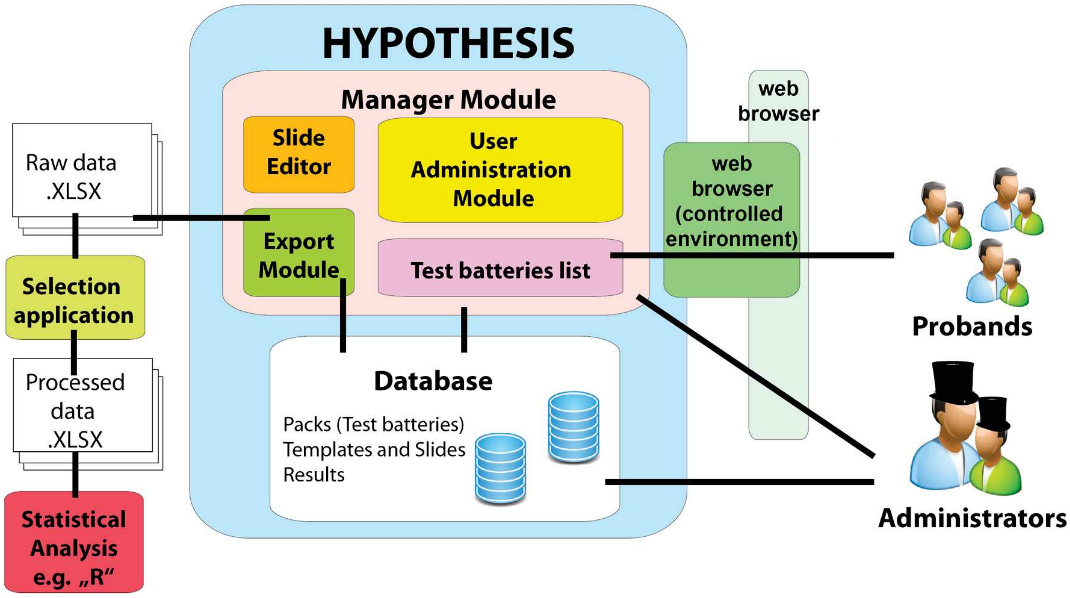

Figure 1. Basic functional components of the Hypothesis platform (modified and extended from Štěrba et al. [42]): The first part, Database (see Section 4); the second part, Module Manager (see Section 2.4) and Export Module (see Section 2.4.4), Administration Account (see Section 2.4.1) with the Pack Menu available (see Section 2.4.3) and a Slide Editor (see Section 2.4.2); the third part, user interface of the web browser, allowing for data collection using a special SWT browser (see Section 2.4.3); and the fourth part, Selection Application (see Section 2.4.5).

The use and development of the Hypothesis platform are expected to be based on two principles: sharing and accumulation. Effective accumulation requires that the database is located in a centrally accessible server. "Sharing" involves not only utilization of already created Packs or their parts, but also the possibility to take part in their creation. The web-based design of the platform allows the publication of research studies along with the original stimulus (i.e., the tests used in the experiments) and experiment design. In addition, raw data can be made available for the research community. The process of "accumulation" can be done in two ways. First, varying tests and/or individual tasks can be created and then made accessible for future use (for instance, psychodiagnostic tests), whether in their original or partially modified form. The second method of "accumulation" consists of gradual implementation of new functionalities necessary for the creation of new tests. The newly created functionalities are then made available in the form of Slide Templates. Gradual accumulation of slide templates broadens the usability potential of the platform.

2.1. Hierarchical Structure of Packs

The highest-level unit of the hierarchy is a Pack (basically, a test) which is further divided into lower-level units. Each Pack consists of a set of slides, usually linearly arranged, meaning that they are presented to the participant in a fixed order. The option of random, tree or cyclic ordering of slides is also available (see Section 2.2). The slides are arbitrarily clustered into Tasks (usually based on the thematic link). Typically, the administrator includes several Tasks in a Pack, for instance: Task 1. Introduction and personal information; Task 2. Instructions; Task 3. Training task; Task 4. Test tasks; Task 5. Feedback and Conclusion. The clustering of slides into sections allows for simple and effective utilization of the thematic clusters in later tests. The individual levels of the Pack hierarchy are defined in the Database (Figure 2).

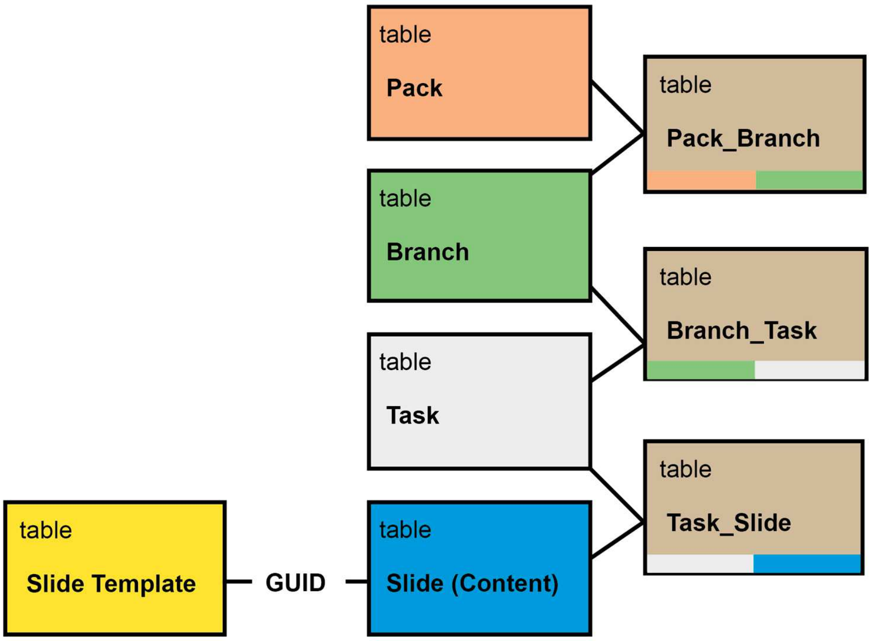

Figure 2. The content of Slide, Task and Branch Tables is associated with a higher level in the hierarchy through the following intermediary tables: Task_Slide, Branch_Task and Pack_Branch.

The basic unit of each Pack is the Slide. There are two components in each Slide: Slide Template and Slide Content (Figure 3). Each Slide Template should contain all the details concerning the structure of the relevant Slide; most importantly, it should include information on the visual arrangement of components, dialog windows, and functional logic of the Slide. Slide Templates (and Slides) are stored in the Database and are available to be used (whether in their original or customized form) by other research groups and in different experiments. The "functional logic" of a Slide concerns the response by the system to the operations performed by participants. The response is ensured by various control tools (for example, zoom, map shifting, point (polygon, broken line etc.) plotting, dialog window, timer), means of control (e.g., clicking, pressing of a button), definitions of actions related to the above events, definitions of variables used in each slide, definitions of any counters and, finally, definitions of slide-related output values saved into the Database. Each Slide Content is linked to the relevant Slide Template and determines the content that is to be presented in each Slide. For instance, if a Slide Template contains information about buttons (including their format), a picture and a text field, the Slide Content defines what buttons and picture are to be shown, what text is to be presented in the text field, and so on.

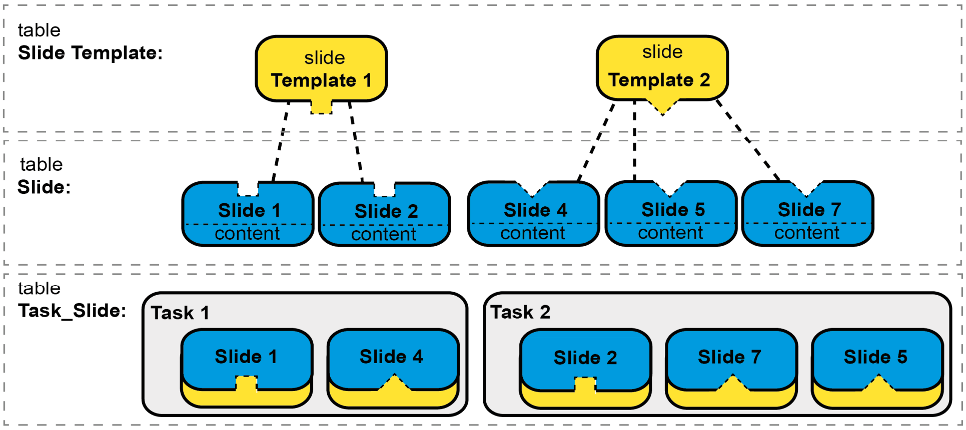

Figure 3. Database tables with hierarchical relations between Slide Templates, Slide Contents and Task slides. The slide template table contains Slide Templates defining the character of Slides. Linking of Slide Templates to Slide Contents is ensured by GUIDs. Typically, several Slide Contents are linked to a single Slide Template.

Tasks are linked to Packs indirectly, through Branches; they are linearly arranged within these Branches and presented to the participants in a fixed order. The purpose of a Branch is to allow for the effective creation of Packs for Computerized Adaptive Testing. In its simplest, linear form, a Test comprises a single Branch with a given number of Tasks (Figure 4a). More complex Packs have a tree structure, with participants going through the branches based on their current performance. Each Branch can be cyclically repeated until the participant achieves the required level of performance (e.g., percentage of correct answers in the training task; Figure 4b).

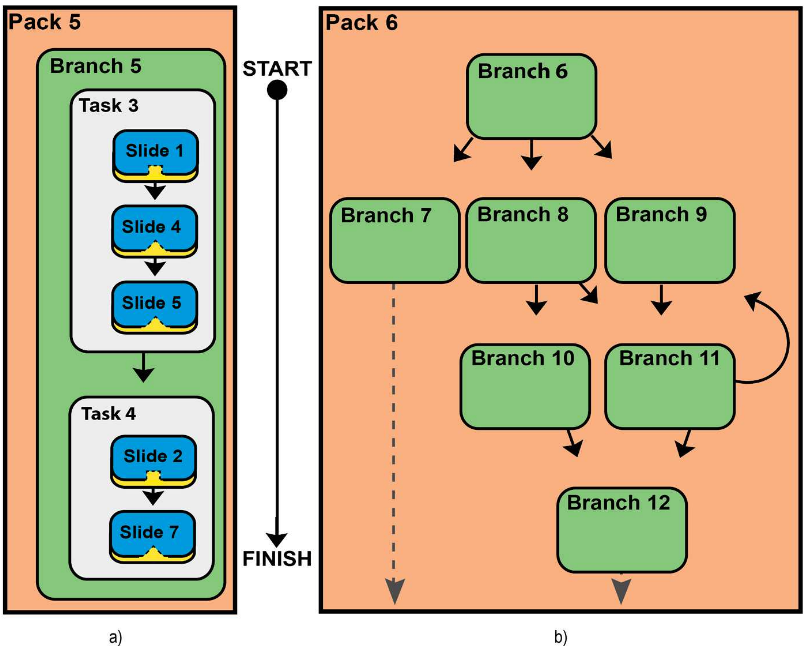

Figure 4. (**a**) Structure of Pack No. 5 with only one branch (5). The branch contains two Sections (Tasks) (3 and 4) with several linearly arranged Slides; (**b**) Pack No. 6 with multiple branches.

2.2. Computerized Adaptive Testing

The Hypothesis platform makes it possible to conduct Computerized Adaptive Testing (CAT) [43,44] at several levels of the hierarchy: slide level, task level, and branch level. At the slide level, events (e.g., mouse clicking) are paired with particular actions, with variables being assigned specific values which are subject to arithmetic and logic operations. Available algorithms include branching algorithms (IF-THEN-ELSE, SWITCH) and loops (WHILE), which are used to control slide-related actions. For the purposes of slide-level CAT optimization, a specialized slide was created (Image-sequence Layer; see Section 3.8). At the task level, each slide in a sequence of slides can be chosen based on the output related to the previous slide as well as on a set of pre-defined rules. The rules determining the course of each Task are a part of the Task table in the Database. A special way of ordering slides is randomization. In other words, there are three possible ways of slide ordering: linear, randomized, and adaptive. Adaptive ordering is available for the branch level as well, where each branch is chosen at the end of the previous branch.

2.3. Multi-Player/Task Tests

A significant aspect of the platform is the multi-player/task mode. It allows for real-time participation of two or more users in solving a single task (asynchronous testing); alternatively, one user may work on two different but interconnected tasks (synchronous testing).

2.3.1. Multi-Task Mode (Synchronous Testing)

Synchronous testing involves master and slave Packs. The Multi-task mode was developed for experiments requiring the participant to complete several tasks simultaneously, or to attend to several screens at the same time. The Multi-task mode was tested using an adaptation of the Peripheral Perception Test (PP-R Periphere Wahrnehmung-R) developed by Schuhfried [45]. The test is a part of the Vienna Test System (Germ. das Wiener Testsystem) and requires specialized hardware [46]. In the pilot experiment, whose purpose was to verify the synchronous testing functionality, the participants were asked to simultaneously complete a primary task (by clicking on target objects on the screen) and secondary tasks on peripheral screens using keyboard keys (Figure 5).

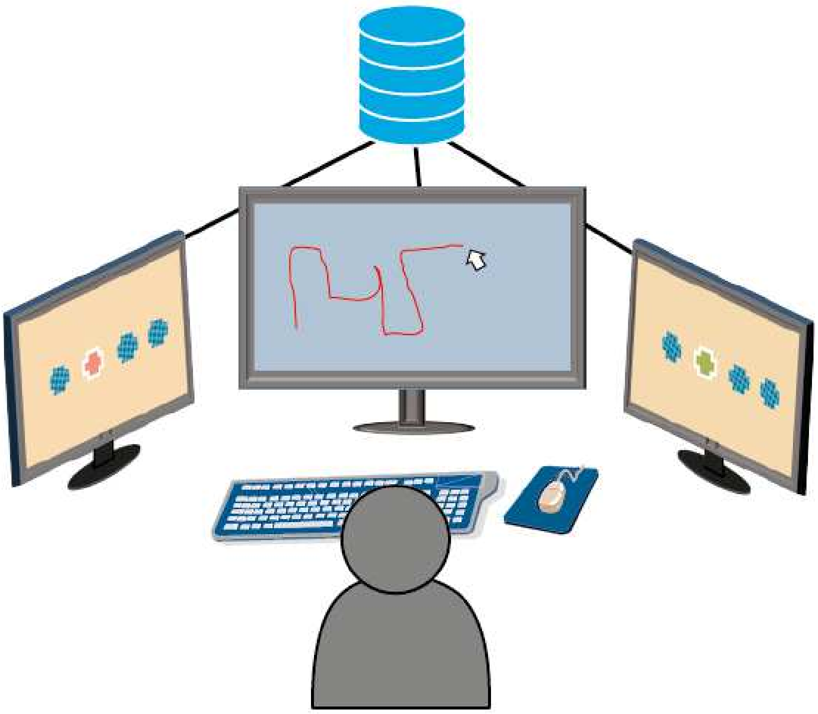

Figure 5. Multi-task mode scheme: while completing a primary task displayed on the central, mouse-operated screen (Master Pack), the participant uses keyboard to react to target stimuli presented on peripheral screens (Slave Packs).

2.3.2. Multi-Player Mode (Asynchronous Testing)

The Multi-player Mode was originally intended for research in the field of geography, online collaboration respectively [47,48]. The mode makes it possible for several users to participate in solving a particular task. All the tests involved are controlled independently by the respective users; however, pauses in synchronicity may occur where an event requires a particular operation to be performed. While all participants are working on the same task, it is the administrator's choice to define the conditions determining the course of testing, including, for instance, which participant has the first turn, in what order a picture is shown to the participants and so on. The Multi-player Mode has already been utilized in a series of adaptations of experiments related to social psychology (Figure 6) and behavioral economics [49,50].

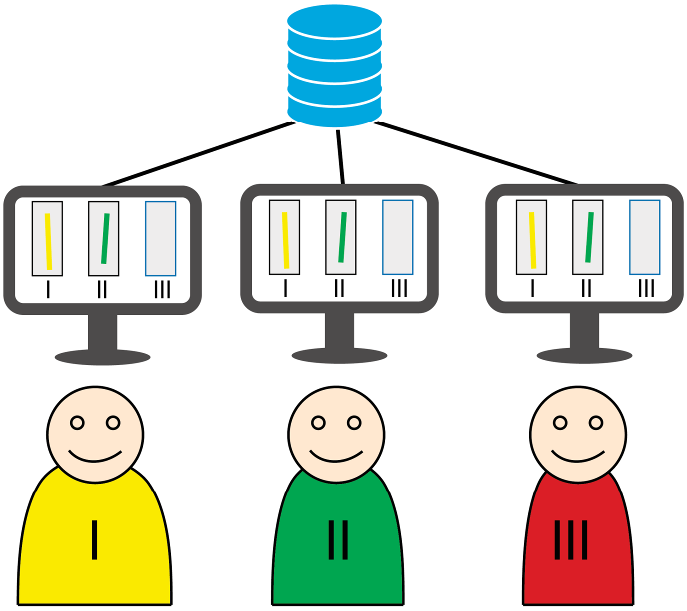

Figure 6. Use of the Multi-player Mode in a computerized adaptation of Asch conformity experiments. First, all three participants were simultaneously shown an identical object; then, they were asked to estimate its size by drawing a corresponding line. The line was then displayed to all the participants.

2.4. Module Manager

The Manager Module represents an interface through which the software is accessed. Three user roles are defined: User, Manager and Superuser. "User" is at the lowest access level and can only select and start the tests made available by higher-level users. Superuser and Manager can access the Administrator Account, Export Module, and Slide Editor. Login is done via entering a user name and password. Unlogged users can enter the Module Manager as Guests, in which case only the free Packs are available.

2.4.1. Administrator Account

In the Administrator Account, each user can be provided with a name, password and access level (user role). The Superuser (highest-level user role) has unlimited administration rights with respect to all the other users, tests, and results. A Manager has administration rights over his/her group, within which s/he can create user accounts, allot Packs, and access all the results obtained by members of his/her group. S/he can also use the Slide Editor. The User role is to be assigned to research participants, whose rights are limited to starting a test Pack. Expiration date and manner of starting each Pack are specified by the Manager or Superuser (Figure 7). The Administrator Account allows for mass creation and editing of multiple user accounts; also, it makes it possible to export lists of user accounts (along with all the necessary details, including e.g., automatically generated passwords) in .xlsx format.

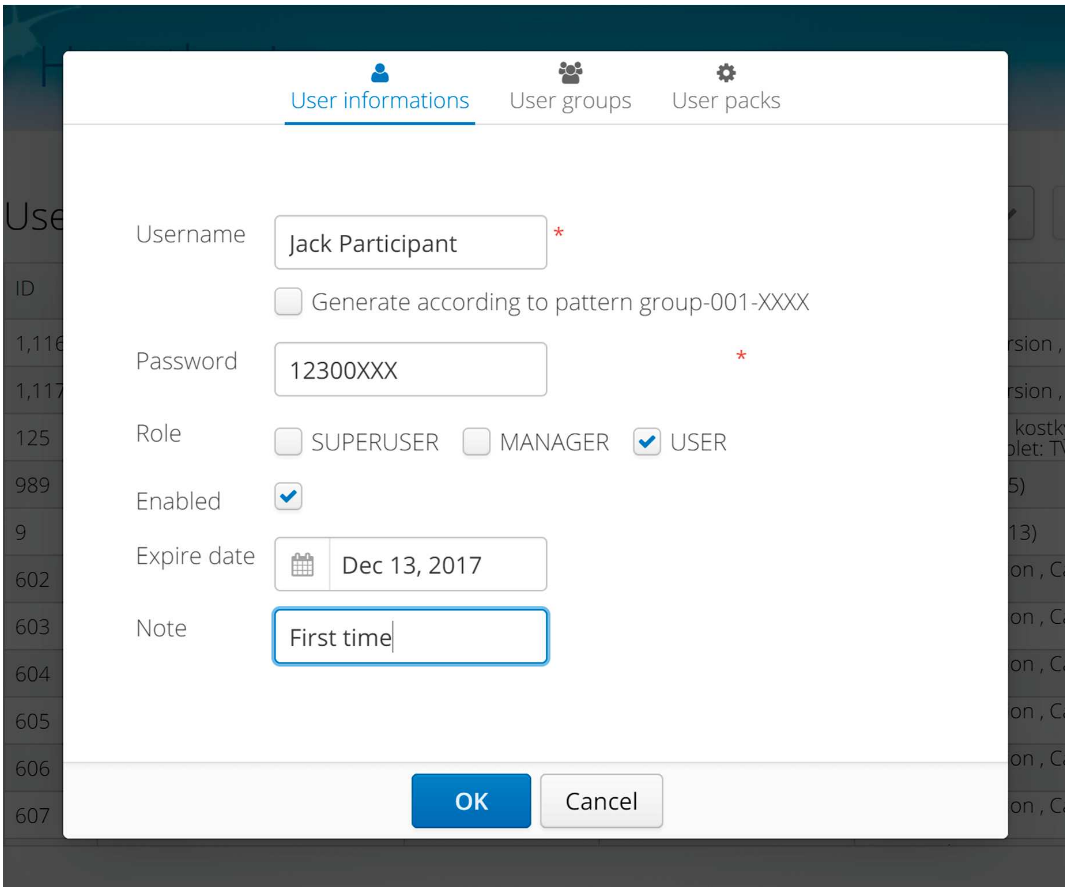

Figure 7. Sample Administrator Account. Editing of a new user account.

2.4.2. Slide Editor

Slide Editor is a part of the Module Manager functionality at the Superuser and Manager levels. In order to edit a slide using the editor, the user needs to copy its XML code (related to Content and Template) into corresponding windows of the Module Manager. The given slide then can be opened and edited. Verified XML codes are recorded into the Database.

2.4.3. Testing Modes and Pack Menu

In Hypothesis, there are several options for starting and running a test; of these, the most suitable one is chosen by the administrator. For the purpose of data collection where no control over experimental conditions is required (e.g., collection of data through online questionnaires), the test can be run using a standard web browser. The test opens in a pop-up, full-screen window; alternatively, a new browser window can be opened by clicking on a HASH link. The administrator can choose whether a user will be allowed to open a particular test in the controlled (featured) mode, in the standard (legacy) mode, or whether they will be allowed to choose (Figure 8). The controlled mode is realized through a browser based on SWT components. When opened, the SWT browser [51] requires installation of Java Runtime Environment. In the controlled mode, nearly all standard browser functions are disabled that could disrupt the highly controlled environment of the experiment. The SWT browser will open the test in a full-screen mode and will prevent the user from closing the application using standard means (Alt + F4 or Esc key); page refreshing and context menu are disabled as well. As Java gradually ceases to be supported in web browsers, an alternative way of running a controlled mode is currently being tested (see Section 6).

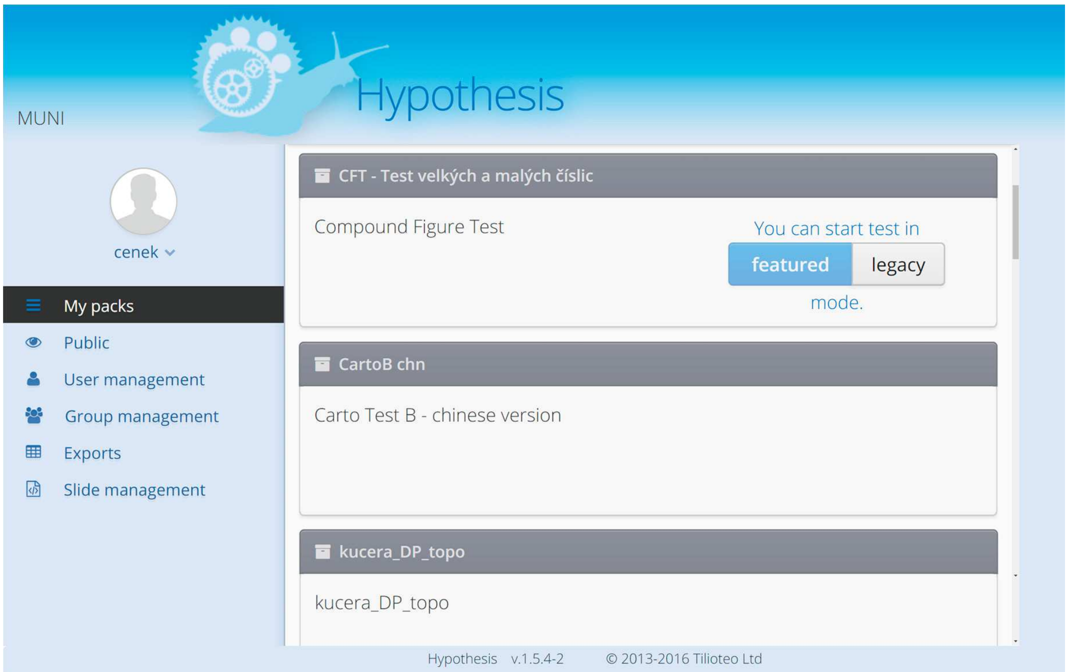

Figure 8. Opening of a Pack in a controlled (featured) or standard (legacy) mode.

2.4.4. Export Module

In the Hypothesis platform, operations and events related to the course of testing are saved in the Database (table of Results). Key target variables are defined by the author (maker) of the test, who can also define the rules for their clustering and evaluation. The pre-defined values are then saved as special variables called Slide Outputs. The Export Module (Figure 9) is a part of the Module Manager; here, test Packs to be exported are selected (based on, for instance, the time of administration). The exported file is in .xslx format and contains raw data for further processing.

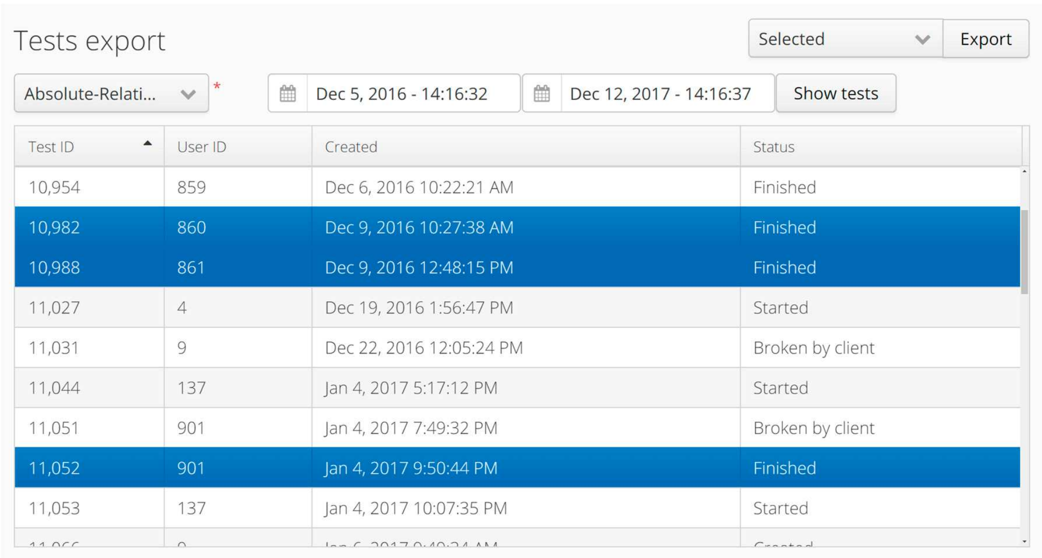

Figure 9. Export Module with finished tests (marked).

2.4.5. Selection Application

Effective selection (filtration) of variables from the raw data file is done in the selection application created in Visual Basic. The application searches through the data file, selecting values or chain parts in accordance with pre-defined rules. It always contains the following triplet:

1. List of raw data;
2. List of pre-defined variables, whose values are to be selected;
3. List of target values.

3. Slide Functionality

An important characteristic of the Hypothesis platform is modularity, which allows for continual development and broadening of the functionality of the software. The platform can be viewed as a high-performance core consisting of a content manager, processor for slide creation, and event logger with data store. An Open API makes it possible to create external modules and/or functions. The default configuration contains a set of basic components, including screen segmentation (vertical and horizontal), form features (e.g., TextField, ComboBox, SelectPanel), and also Button, Image, Panel, Label, and components for Audio and Video. Specific functionality is represented by a Dialog Window and Timer. Other components are a part of two separately supplied modules: Maps (for interactive maps) and Processing (for interactive animations created in the Processing language). See Supplementary Materials for examples of functionality.

3.1. Questionnaires

Questionnaires are commonly included in psychological research experiments. They may range from simple, personal information forms to Likert-type questionnaires. For the purpose of questionnaire creation, the software offers text fields, dropdown lists, scales, and others, with the possibility of intermediate validation of input values, which can be used to check whether obligatory information has been entered.

3.2. Visual Stimuli

Typically, visual stimuli are in the form of images. All standard raster graphics formats are supported (PNG, JPEG, GIF and similar ones). It is recommended to choose the format based on the type of content and with a view to minimum size of the file. For instance, GIF and PNG are suitable for schematic images with few colors, while JPEG should be used for photographs. The BMP file format is not recommended because it uses no data compression which results in enormously large files. When creating a slide with an image, longer loading time is to be expected, depending primarily on the file size and internet connection speed. Web browsers usually load images from cache, which makes loading of previously displayed images (identical image url) much faster. Different loading times can be compensated for by temporary masking of the images while they are loading. The Image component ensures recording of mouse clicks, which are provided with pixel coordinates.

3.3. Slide Control

Interaction with slide content can be realized through buttons or a button panel, e.g., for choosing between several options; alternatively, keyboard keys can be used (alphanumeric, arrow, or functional). The course of the test can also be controlled externally by Timer, with an optional display of time left. The timer can be stopped at any time and/or repeatedly activated. The most frequently used timer-related event is a timer end; however, timer start can be utilized as well. Timer can also be used to indicate that a pre-defined time interval has passed (event update). Button clicking, key pressing, and timer events are usually linked to slide-level actions.

3.4. Control of User Actions

At the slide level, various user actions can be defined which represent independent subroutines with specific names. Actions consist of evaluable expressions; these may be logical, mathematical, object-variable related, or branching expression-dependent (IF-THEN-ELSE, SWITCH-CASE). They are used to manage events, including, for instance, timer stop, key pressing, and clicking on a button/picture. Importantly, actions can call other actions, which is especially useful when branching is used, or when a more complex action is compiled and called by the individual parts. The advantage of actions is that they prevent the need to use an identical code several times; instead, a single action is called. Also, each action triggering is saved in the table of events. It follows from the above that using actions leads to higher transparency and comprehensibility of the expression of a functional algorithm related to a particular slide.

3.5. Dialog Window

The Dialog Window function may be used in order to repeatedly display Help while solving a task. The window appears after the calling of an appropriate function, which can be done e.g., by button clicking or any other pre-defined action. Closing is done by clicking on the cross button. Both the start and end of an action are saved into the Database. Dialog Window can either be non-modal (while it is active you can still work with the slide) or modal, meaning that the main window is disabled. Modal windows can be used to distinguish between currently running activities of the participant. The participant can only continue with his/her work after closing the modal window.

3.6. Maps

The map-related component is a part of the external plug-in module. The main purpose of the component consists of the implementation of maps into experiments. We distinguish between two main map layers: Base Layer and Feature Layer (with vector graphics). Examples of base layers include interactive Web Map Service (WMS) maps provided by servers offering WMS. The WMS layer requires specification of a coordinate reference system (CRS) and a bounding box. Depending on the data provided by the server, the WMS layer can contain either a single type of information or a complete set of cartographic details. Interactive features include zooming and shifting of the bounding box. Each change sends a request for data update to the server.

The Feature Layer contains vector objects; these can either be part of the default setting or they can be created by the participant using one of the special vector graphics tools. Various parameters of vector objects can be set including: stroke line color/style and fill style and color. Transparent vector objects are suitable to be used as Areas of Interest and may be utilized to assess a participant's actions. Another important map layer is one with a static image, called Image Layer. This type of layer can be used instead of the "Image" basic component because it contains both the options offered by the Vector Layer and tools for vector object creation. The map component makes it possible to gather data about clicking on an object and/or using tools for the creation of lines, sections, broken lines, polygons and other geometric shapes/objects. If a coordinate reference system is specified (especially in connection with the WMS layer), the collected data may contain not only pixel coordinates, but also real geographical coordinates.

3.7. Audio and Video

The Hypothesis platform has two basic multimedia components: Audio (typically for MP3 audio format) and Video, which is usually used for MP4 files. An advantage of the Video component involves the possibility to record mouse clicking in a way similar to a static image. In addition to coordinates, the current time of audio-visual elements is recorded as well.

3.8. Image-Sequence Layer

The Image-Sequence Layer component significantly broadens the applicability of the Hypothesis platform. A test typically consists of a sequence of slides, which requires some loading time to be allowed. Therefore, no fast sequences of visual stimuli (at the order of tens of millisecond) would be possible. The speed of presentation of visual stimuli is normally limited by the speed and reliability of client-server communication. In order to overcome the above problem, a special component was designed which allows pre-loading of the stimulus material into the cache of the browser so that tachistoscopic tests can be performed [52]. Here, a presented slide is inactive (masked) until all the content has been loaded. Another key characteristic of the component is slide programmability. An algorithm defining the course of a slide can be written which also allows for slide-level adaptive testing (see above).

3.9. Processing.js Component

Another external module which broadens the applicability of the software is called Processing. Its purpose consists of the utilization of applications created in the Processing language (i.e., its web implementation, Processing.js), a visual programming language featuring a user-friendly developmental interface suitable for those with only basic knowledge of programming. The language is intended for data visualization, interactive animation, videogames, and other graphic material [53,54]. Processing.js is the sister project of the Processing programming language; it has been designed for online environments. The Processing code is based on JavaScript and can be run by any HTML5-compatible browser [55]. The interface between the Hypothesis platform and Processing.js makes it possible to create and administer a range of highly interactive tasks with visually rich and complex environments. Due to two-way communication between the Processing application and the core of the Hypothesis platform, the course of a task running in Processing.js can be controlled; at the same time, key events are being saved (in a pre-defined form) into the Database of the Hypothesis platform. Using the so called "call-back method", each event/action occurring in Processing.js can call an action defined within a slide, which will affect the course of the slide. Similarly, a slide can call the processing code and thus influence the running of the Processing application.

4. Technical Design

The platform has been developed using the modern technology of the dynamic web page. The core and user interface are built on the Vaadin 7 framework [56]; database operations are ensured by ORM Hibernate, and PostgreSQL version 9.1 (or higher) is used as the primary database system. The application architecture is three-layer; a client, server, and database (Figure 10). The client part is responsible for user interaction and its operation is provided by a standard web browser (thin client) or a special browser distributed in the application package—Hypothesis Browser. This browser is built on Standard Widget Toolkit components and ensures more strict conditions for running tests. The client layer communicates in the background with the server through the technology Ajax RPC (remote procedure call). The server layer is implemented as a servlet of the application server (e.g., Apache Tomcat) which is responsible for the client's request handling and updating the user interface. The servlet then communicates with the database layer by methods of object mapping of entities through the Hibernate library. This library provides a unified interface for the connection to all commonly used database systems (PostgreSQL, MySQL, MS SQL, Oracle, etc.). Individual Packs (test batteries) are structurally stored in the database. After starting a test, a selected package is loaded from the database to the server application and a new test entity is created. For more details see [42].

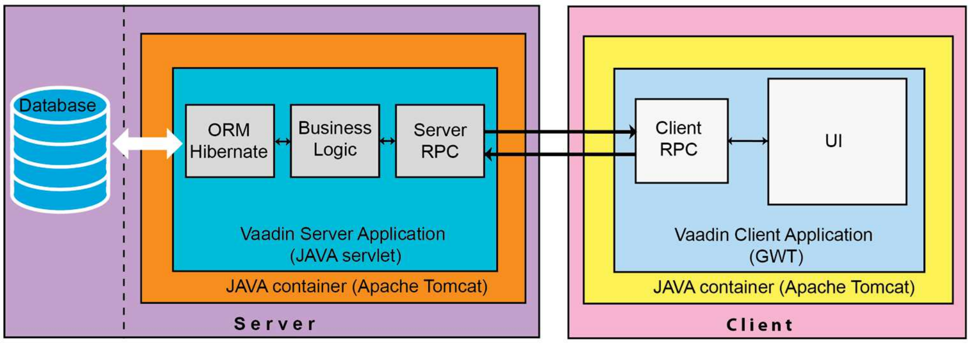

Figure 10. Scheme of the technical structure (adapted from Šašinka et al. [20]).

Time Measurement Accuracy

In the development of the software, great attention was paid to time measurement precision. The disadvantage of a client-server solution (as opposed to desktop applications), especially if the system responses are controlled by the server (which is the case of Hypothesis), which can lead to time delays during client-server communication. Delays in the server-to-client direction may occur e.g., as a result of the loading of images from a distant store. Client-to-server communication leads to a delayed response of the system to user actions. For instance, when a mouse click is sent from client to server, a delay occurs both in saving the event of clicking and sending back the system response. Negligible as they may seem (they are typically in the order of milliseconds), the delays are not invariable. The variability in client-server communication thus represents "noise" resulting in measurement inaccuracies. In order to compensate for this noise, several solutions have been implemented. First, the time of event occurrence at the client is recorded in addition to the time the event was accepted by the server, with the difference between these two representing the immediate time delay. When the system is located in a local network the delay tends to be negligible; with an online system it is dependent on external factors. Time delays can also be eliminated by the use of specialized "Image-Sequence Layer" slides (see Section 3.8) which prevent the delays related to the loading of content of the slide. Slides using the Processing.js plug-in relegate most of the event control to the client; therefore, the whole task is controlled locally, with only key events being sent to the server (for more details see the Supplement). Implementation of Processing.js fully eliminates the limits of the client-server solution and makes it possible to create tasks with high time accuracy (e.g., when an eye-tracking system is used).

5. Combination with Eye-Tracking

Although primarily intended for extensive research, the Hypothesis platform has, from the very beginning, been designed to support a relatively new intensive research method: eye-tracking. The use of Ogama, an already existing open-source application [57–59], and subsequent development of an online version called HypOgama made it possible to perform experiments involving a remote eye-tracking system SMI RED250 mobile or The Eyetribe. The existing solution is based on ex-post synchronization of an eye-tracker with the Hypothesis [60]. The above solution is a part of a wider concept which includes a ScanGraph tool for explorative data analysis [61]. At present, another version is being developed which will allow unified connection and real-time interaction between the Hypothesis platform and an eye-tracker. The solution is based on WebSocket communication elements of the Vaadin framework and its functionality has been verified in practice.

6. Comparison to Similar Tools

Nowadays, a range of tools are available which can be used to conduct computer-based experimental research. The development of the Hypothesis platform was motivated by the fact that there are currently no tools that would make it possible to collect a real-time record of an individual's work with interactive maps and of collaboration between multiple users. The software's architecture is highly universal and offers a unique combination of functions, one which is not provided by any other tool currently available. The software obviously has its limitations, too, and some types of experiments may want more specialized tools. Some applications, such as Presentation [62] and Psychtoolbox [63,64] were designed for experiments where high levels of precision are required; they are used for instance in neurocognitive research. Another example is E-prime [65], a software application with a large user base, which makes it possible to gather data using Tobii and SMI eye-tracking systems. There are numerous other applications available which offer eye-tracking-based data collection, including, for instance, the Paradigm software application [66], which allows for experiments to be conducted using both desktop and mobile devices. Free software applications from the above category include OpenSesame [67] and PsychoPy [68]; the latter is available online. In implementing eye-tracking into research experiments, some applications go a step further than the above-mentioned ones, combining inventive data collection using an eye-tracker with effective data analysis. Examples include the "Experiment Builder" and "Data Viewer" [69], Experiment Center and BeGaze [70] and Ogama [57]; all of these are applications provided by eye-tracker manufacturers. The limitations of these applications are related to basic functions in test creation. For instance, the Experiment Center and Ogama do not allow for several Likert scales to be used within a single slide; also, they do not make it possible to collect data online. Examples of free psychology software applications for online data collection include PEBL [71], Tatool [72], Social Lab [73] and jsPsych [74]. The latter two web-based tools in particular are conceptually similar to the Hypothesis platform, which, however, offers significantly broader functionality, with an emphasis on the controlled nature of the experiment. Among the areas which can benefit from the advantages of the Hypothesis platform is the field of cartography, which has a long tradition of employing usability tests; the importance of usability studies for cartography was emphasized in the International Cartographic Association Research Agenda published in 2009 [75]. Yet, the field has long been lacking a suitable tool for conducting usability tests. The lack of tools for usability studies in cartography is mentioned in Nivala et al. [76]. Even recently published papers still use domain-unspecific software and tools [77] and self-developed tools created ad hoc [78]. To our knowledge, cartography at present has no universal experimental tool for usability tests; thus, researchers have to use the software and tools mentioned above. Unlike these, the Hypothesis platform makes it possible to collect data online and in a controlled environment, offering high temporal precision of measurements. It is also suitable for multitask/multiplayer experiments and for investigating a user's behavior when they are working with interactive maps.

7. Test of Resources

During its development, the Hypothesis application was tested several times; also, feedback was requested from the researchers who used the platform when carrying out their experiments. In 2015, Z. Štěrba and J. Čeněk (both Masaryk University) performed an intercultural study consisting of a series of experiments in which 106 university students participated. The experiments were conducted at universities in the Czech Republic, China and Switzerland. The study used a set of tests involving different functionalities (including clicking, line drawing and Likert scales). When administering the tests, two relatively marginal problems were encountered. One of them consisted in different load times of the stimulus material, which was caused by varying quality of internet connection in different places; the application runs on a server located at Masaryk University in Brno, Czech Republic. A more substantial problem was related to the instability of the system during mass testing, when administering 10 to 15 (and more) tests simultaneously. There were several cases of the application "freezing" in mid-test during the first load test. A similar situation was encountered by Svatoňová and Kolejka [79] or Knedlová [80] and Helísková [81] while they were conducting research towards their theses. When a high number of tests were run simultaneously, the test shut down prematurely, leading to a loss of data. The tests were administered to 52 participants at the premises of Masaryk University. The functionalities used in the tests included multi-clicking (with feedback), line and area drawing with automatic evaluation, text fields, scroll-down windows, an image-sequence layer slide with a button bar and feedback, and keyboard control. Apart from the limitation in the number of tests that could be run simultaneously, no other significant problem was encountered during the testing. The cause of the problem was revealed to be related to "sessions", which are automatically created upon starting a test but did not always close as expected. After the error was resolved, the application was used by other research groups, for instance by Kubíček et al. [82], who conducted a study concerning mental rotations where a maximum of 5 participants were tested simultaneously; Opach et al. [83] (individual testing of 25 participants). No problem related to the Hypothesis platform was reported by any of the above research groups. After the implementation of the newest version of the platform, another load test was carried out. The test consisted of logging into the Manager Module of the platform 16 times (8× in Firefox and 8× in Chrome) and launching 82 identical tests simultaneously. Each test contained 2 slides of the image-sequence-layer type. As was expected, no complications occurred during the second load test, with all the data collected being saved into the database (see Supplementary Materials).

8. An Experiment Illustrating the Usability of the Hypothesis Platform

8.1. Introduction

We are presenting a conducted experiment in order to document the wide range of functionality, usability and stability of the Hypothesis platform. Our colleague, Markéta Kukaňová, conducted a complex study which explored the effectiveness and efficiency of contextual cartographic visualizations [84]. She compared work with usual topographic map and work with a combination of topographic and transport maps. She conducted a simulation using contextual visualization techniques in the transport planning and also measured the cognitive abilities of users which may have positively influenced performance during the map reading process. Because of the above-mentioned reasons, she used the Hypothesis platform, which made the creation and administration of all the necessary tasks and tests possible.

8.2. Methods

The main goal of the empirical study was to compare two variants of spatial data representation. Throughout the entire experiment, the control group only worked with standard military topographic maps. Alternately, the experimental group worked with standard military topographic maps and with adapted visualization focused on the tasks connected with transportation. Both visualizations were informationally equivalent. The whole battery consisted of two cartographic tests and four psychological tests (identical for both groups; Figure 11).

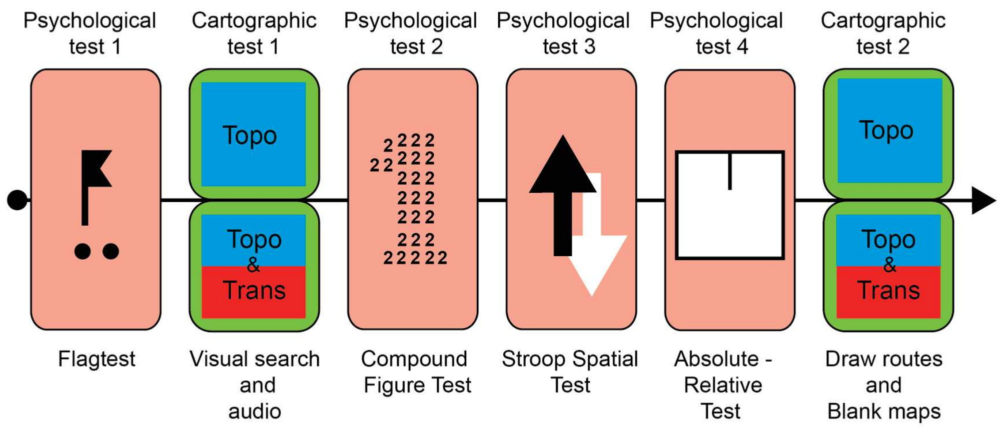

Figure 11. Scheme of the whole experimental design (adapted from Kukaňová [84]).

The main principle of the contextual maps is that the visualization adapts to the specific activity of the user. During free map exploration or a visual search for target objects, the basic topographic map is used. When the type of activity is changes e.g., to transportation planning, visualization is switched to a specific transport map, where the transport infrastructure is highlighted and unnecessary information is suppressed (Figure 12).

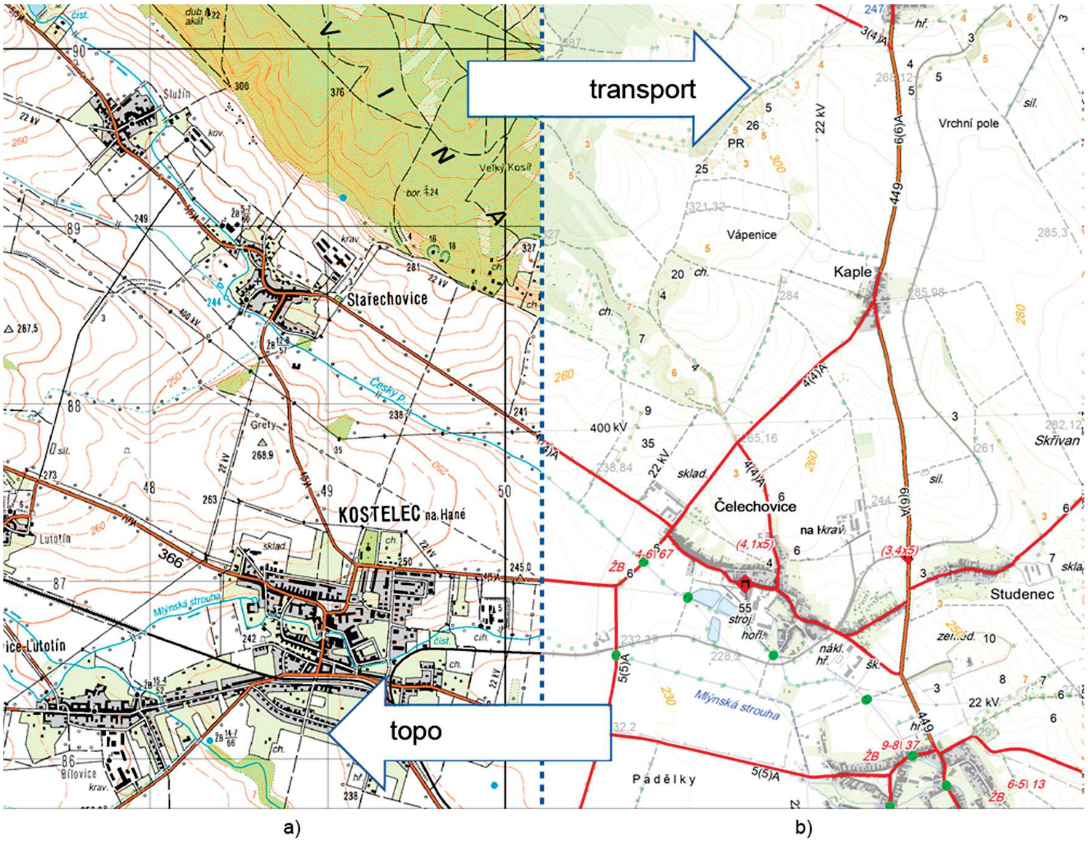

Figure 12. Topographic map (**a**) and contextual transport map (**b**).

Cartographic test 1 consisted of two subtests. The participants should search for target objects in the first subtest. The second subtest was similar to the first one but the participants were listening to an audio recording simultaneously, and were expected to react with a key press according to word cues. The correctness, visual search time, and reaction time to target words were measured. Alternately, the experimental group worked with topographic and transport maps. The level of cognitive load was explored in these types of tasks.

Cartographic test 2 consisted of four subsequent stages. Participants explored a map with multi-click marked target objects in the first stage. The reaction time and correctness was measured. In the second stage, participants localized a fire based on the instructions; afterwards they located the position of the fire truck. In the third stage, participants drew the optimal route between the fire and the fire truck. The control group always worked with a topographic map while the experimental group worked with a transport map during the third stage. The routes drawn were recorded to a database as were their reaction times. In the final and fourth stage, a blank map was presented. Participants were required to estimate the position of the objects which were previously presented in the first three stages. Accuracy of the marked objects was measured in pixels.

Every single test from psychological portion used different functionality. The Flagtest (measurement of selective attention) involved, among others, following functionality: multi-click, timer or feature layer. The Compound Figure Test (measurement of global/local precedence) used image sequence layer, real-time feedback, automatic evaluation of the assessment, button bar. In the Absolute Relative Test (measurement of holistic/analytic cognitive style) users estimated the size of previously seen objects with the help of drawn horizontal lines. Hypothesis calculated deviation (accuracy) in pixels. And finally, the Stroop Spatial Test (measurement of cognitive control) was based on image sequence layer, participants used a keyboard to react to the stimuli.

Totally 43 individuals (age was between 18 and 44; m = 26.6; men = 24, women = 19) participated in the study. There were 20 participant in control group and 23 in experimental group. A part of the research sample (*n* = 27) was tracked simultaneously with the eye-tracking system (The Eyetribe eyetracker and software OGAMA).

8.3. Results

After the data collection was finished, all data were exported to .xlsx files from the database of Hypothesis with the help of the export module. Afterwards, the selection application was used and the required variables were filtered and stored in a format enabling subsequent analysis. Data were analyzed in the IBM SPSS program and some analysis were also provided and visualized with the help of ArcGIS 10.2.2. No problems occurred during data collection that could be linked to the Hypothesis platform. However, some participants did not finish all the tests included in the test battery because of problems with the administrator's PC and internet connectivity issues. Also, there was some data loss with those participants who were measured with the eye-tracking system. The OGAMA software showed instability during longer tests. Figure 13 shows an analysis of the routes drawn in cartographic experiment 1. Green digits refer to the experimental group (context transport visualization), blue refer to the control group (topographic map). Routes drawn by 36 participants were analyzed.

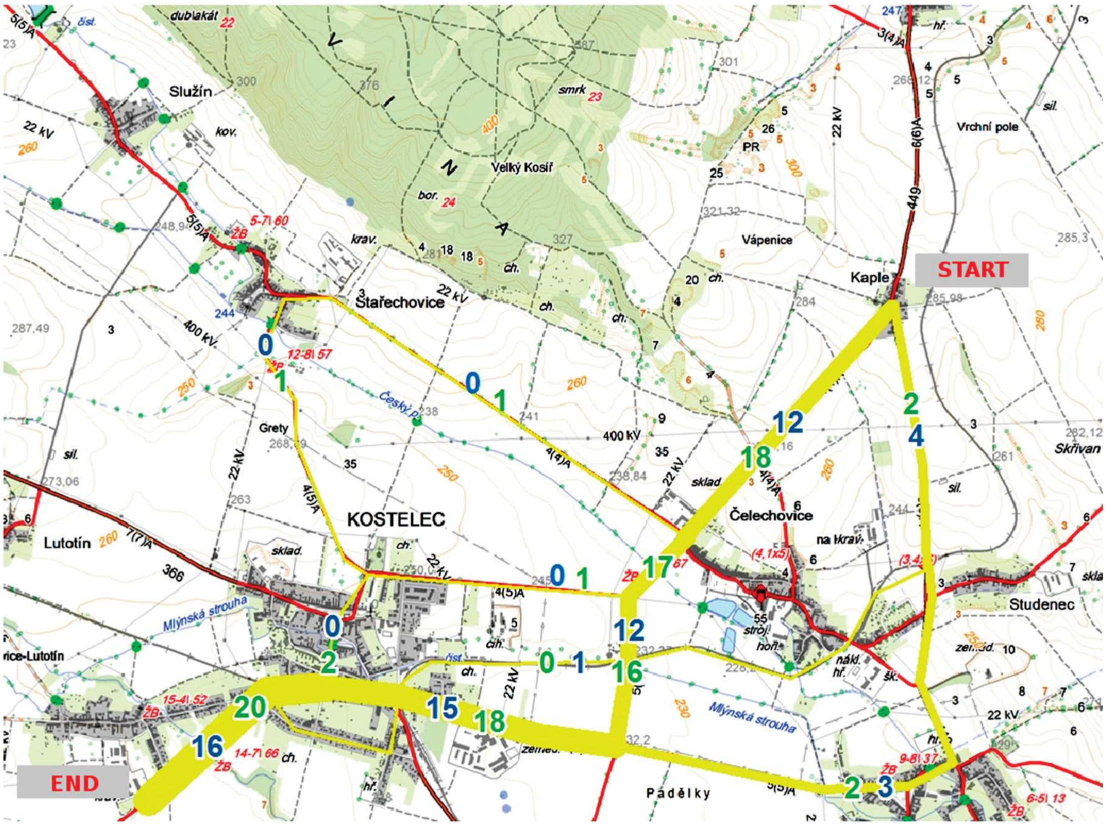

Figure 13. Yellow lines (**thickness**) express frequency of the routes chosen by the experimental group (**green digits**) and control group (**blue digits**) together. Data from both groups are presented at once in the transport map.

8.4. Discussion

The experiment conducted by Markéta Kukaňová clearly showed that the Hypothesis platform provides a range scale of functionality which enables the creation and administration of very different types of tasks. We are not aware of another research tool which would be able to provide all the necessary functionality for the realization of the above-described study. Without Hypothesis, a research study of this nature would have to use two or more different tools, and this of course would increase the costs of the research and make it more complicated. The Hypothesis platform also enabled the exportation and filtering of all the necessary variables in order to conduct the intended analysis. Figure 13 showed that even a research variable which has many degrees of freedom could be properly analyzed. These features offer a strong advantage over other research tools which are mostly able to present only very simple stimuli and collect simple responses such as a mouse click or a keypress. The most important thing should always be the robustness of the research tools. Hypothesis worked without a single problem, however, the general limitations of the web-based tools were detected. The stability of the internet connections played a crucial role in this case, too. An internet connection lost in even one single test may devalue the data from the affected participant for the entire study. For these reasons, it should be recommended that data be collected only under the highest quality conditions.

9. Conclusions

An original research tool, the Hypothesis platform, was described and its usability was presented in detail in the context of cognitive cartography and psychological testing. Its comparison to other research tools was presented, as was the testing and evaluation of the Hypothesis platform. One conducted experiment was chosen and described in more detail in order to make visible the range of functionality which was involved in one particular study. Other experiments were also referred to, some which were conducted by students for their diploma thesis, some by researchers who published their work in well-established journals. The usability of the current version of the Hypothesis platform was proven for research purposes and for educational purposes. However, the software is still being developed and new functionality is constantly incorporated in order to react to the development in the area of cognitive cartography. Current developmental efforts focus on 3D technology implementation (pilot experimental testing of 3D visualization using web technologies has already been made [85,86]), optimization for tablets or other devices with touch screens [87], interconnection with an eye-tracking system, and further development of a Firefox-based browser. The new application using Firefox was able to replace the original SWT-browser based solution in controlled data collection. Also, an entire graphical user interface is being developed which can be utilized in test battery creation, and which will allow access (and editing) through a standard web browser. The Hypothesis platform is now available for academic and other non-commercial purposes (under Masaryk University). However, special agreements may be negotiated with respect to commercial use or other specific purposes.

Supplementary Materials: The test data are available at: https://doi.org/10.6084/m9.figshare.4697674.v1; Installation of Hypothesis with examples of functionality for demonstrative purposes is available at (user name: isprs password: isprs): http://demo-hypothesis.phil.muni.cz; Tutorial "how to modify slides and work with the Slide Management".

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Author Contributions: Kamil Morong and Čeněk Šašinka designed the architecture of the software. Kamil Morong wrote the code of the software. Čeněk Šašinka and Zdeněk Stachoň designed and performed all empirical testing and analyzed the data. Čeněk Šašinka, Zdeněk Stachoň and Kamil Morong wrote the paper.

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Collaborative Immersive Virtual Environments for Education in Geography

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Abstract: Immersive virtual reality (iVR) devices are rapidly becoming an important part of our lives and forming a new way for people to interact with computers and each other. The impact and consequences of this innovative technology have not yet been satisfactory explored. This empirical study investigated the cognitive and social aspects of collaboration in a shared, immersive virtual reality. A unique application for implementing a collaborative immersive virtual environment (CIVE) was developed by our interdisciplinary team as a software solution for educational purposes, with two scenarios for learning about hypsography, i.e., explanations of contour line principles. Both scenarios allow switching between a usual 2D contour map and a 3D model of the corresponding terrain to increase the intelligibility and clarity of the educational content. Gamification principles were also applied to both scenarios to augment user engagement during the completion of tasks. A qualitative research approach was adopted to obtain a deep insight into the lived experience of users in a CIVE. It was thus possible to form a deep understanding of very new subject matter. Twelve pairs of participants were observed during their CIVE experience and then interviewed either in a semistructured interview or a focus group. Data from these three research techniques were analyzed using interpretative phenomenological analysis, which is research method for studying individual experience. Four superordinate themes—with detailed descriptions of experiences shared by numerous participants—emerged as results from the analysis; we called these (1) Appreciation for having a collaborator, (2) The Surprising "Fun with Maps", (3) Communication as a challenge, and (4) Cognition in two realities. The findings of the study indicate the importance of the social dimension during education in a virtual environment and the effectiveness of dynamic and interactive 3D visualization.

Keywords: immersive virtual reality; collaborative immersive virtual environment; immersion; sense of presence; telepresence; Head-mounted display; cyberpsychology; human–computer interaction; collaborative learning; hypsography; contour lines; map literacy

1. Introduction

Recent rapid and continuous development of immersive VR technology has opened the possibility for a wide range of applications. Decreasing prices and easy accessibility are factors helping to distribute these devices to different institutions as well as regular households. Immersive VR finds a purpose in many fields, for example, in psychotherapy and diagnostics [1–4], cognitive training [5,6], relaxation [7,8], rehabilitation [9,10], medicine [11,12], training in the industry [13–15], tourism and cultural heritage [16–18], journalism [19], and sport [20,21]. The rich potential of immersive virtual reality is also utilized in areas that use geographical data, for example, evacuation planning [22,23], geospatial data exploration and analysis [24–27], navigation in urban areas [28,29], visualization of spatial data quality [30], and urban planning [31].

Immersive virtual reality is also significantly employed as an educational tool in many areas. We can find its educational application in domains such as engineering [32,33], biology [34,35], foreign languages [36], geometry [37], emergency management [38], physics [39], design [40], geography and earth sciences in general [41–45], and in other more singular domains such as martial arts [46] and communication skills training for individuals with autism [47]. Virtual environments including VR have a long tradition in geographical research and education [48–51], but until recently, user experiences have only been rarely reported. Several recent studies analyzed the potential benefits of immersive technologies for education in geography and task solving. Philips et al. [52] examined the usage of immersive 3D geovisualization and its usefulness in a research-based learning module (flood risk assessment). The findings of a qualitative student survey showed a range of benefits (improved orientation in the study area, higher interactivity with the data, and enhanced motivation through immersive 3D geovisualization) and suggested that an immersive 3D visualization can increase learning effectiveness in higher education. Focusing specifically on hypsography education using modern technology, Carrera et al. [53] studied the possibilities of Augmented Reality technology (AR). They experimented with 63 students and tested the usability of AR to interpret relief (maximum slope, visibility between points, contour interval, and altitude interpretation). Usability was further assessed in terms of efficiency (time to accomplish the task), effectiveness (number of mistakes) and motivation (subjective satisfaction). The results of the study confirmed the enhanced usability of an AR environment for specific tasks dealing with questions of interpreting relief. None of the aforementioned studies combined both VR and a collaborative environment.

Merchant et al. [54] distinguish three types of instruction based on virtual reality technology: simulation, games, and virtual worlds. They conducted a meta-analysis of available empirical studies using desktop-based virtual reality of all three mentioned types of educational approaches. They found that games provided the highest learning outcome gain. They defined the important attributes of educational games, also called serious games [55]. Such games should provide players with sense of autonomy, identity, and interactivity [56] and enable them to test hypotheses, strategize their moves, and solve problems [57].

Collaborative learning is a trend in modern pedagogy for improving the quality of educational outcomes and processes [58–60]. It allows two or more users to interact and solve tasks together—with a critical approach towards the overly ambiguous definitions often used— and may be defined as a situation which Dillenbourg [61] (p. 7) described as “particular forms of interaction among people are expected to occur, which would trigger learning mechanisms.” Dillenbourg himself noted that the main concern of learning process designers was to find ways of raising the likelihood that certain types of interaction would occur. What we expected when designing our collaborative immersive virtual environment (CIVE) application was that students would use conversation to continually build, monitor, and repair a joint problem solution, as depicted by Dillenbourg [61]. Collaborative learning principles in college education of technical disciplines were introduced for example by Gokhale [62]. He evaluated the advantages of collaboration in a team of college students and confirmed a positive feedback of collaboration for analysis and synthesis compering to the traditional individual training. Another interesting aspect of collaboration within the VR is a distant cooperation of specialists from different disciplines solving complex problems like geohazards (tsunamis, landslides, and floods) [63,64]. Collaborative learning principles applied in college education for technical disciplines were introduced, for example, by Gokhale [62]. He evaluated the advantages of collaboration in a team of college students and confirmed the positive feedback of collaboration for analysis and synthesis compared to traditional individual training. Another interesting aspect of collaboration in VR is the remote cooperation of specialists from other disciplines engaged in solving complex problems such as geohazards (tsunamis, landslides, and floods) [63,64].

Computer-supported collaborative learning was introduced in the early 1980s as an overarching framework for various attempts to design a "technologically sophisticated collaborative learning environment designed according to cognitive principles" that "could provide advanced support for a distributed process of inquiry, facilitate advancement of a learning community's knowledge as well as transform participants' epistemic states through a socially distributed process of inquiry" [65] (p. 4). Jackson and Fagan [66] conducted a qualitative study where learning processes were explored by comparing individual users, two peer users, and student-expert modes. They used an immersive virtual environment called Global Change World, which is used to educate about concepts concerning global climate change. Other instances of collaborative learning using immersive virtual reality can be found in, for example, the domain of martial arts [67], geometry education [68], and training power system operators [69]. Innovative technologies for collaborative immersive virtual reality may be able to create a shift in the educational paradigm. Siemens [70] has challenged the traditional learning theories through his "connectivism" conception and emphasized that people in the digital age are no longer isolated individuals but located in a network where they continuously interact with human and nonhuman systems. Learning should be considered a lifelong net-building activity. Horvath [71] presents a technological solution in the form of a learning environment enabling collaboration in 3D virtual reality to teach the concept of the memristor.

The main advantage of using immersive virtual reality for educational purposes is overcoming the boundaries of a specific place and time and having a virtual experimental space [72]. This offers possibilities which are barely achievable or not possible to build in a classic classroom. Our geography learning CIVE application offers a high level of interactivity for the user, which was achieved through iterative testing and development. We also intentionally used gamification principles when creating instructional tasks in order to facilitate the learning process. Our solution incorporates immersive virtual reality, real-time social collaboration, and gamification principles. We chose hypsography as an educational topic, as it is one of the most insufficiently understood areas by our university students (according to the results of the Faculty of Science entrance exams: error rate was 86% in 2016 and 73% in 2017). The objective of this study was to describe the cognitive and social tendencies of participants during collaboration on geography learning tasks by applying the interpretative phenomenological analysis methodology.

2. Methods

2.1. Materials and Technology

This study utilized a geography education CIVE application developed by our interdisciplinary team. It makes use of the Unity cross-platform game engine version 2017.3, which facilitates data loading, real-time rendering, and communication with VR equipment. The CIVE application was built in a virtual environment described by Doležal, Chmelík & Liarokapis [73]. It is used in combination with SteamVR for the proper functionality of VR equipment. Authentic geospatial data were implemented as stimuli in the application. Digital terrain models (DTMs) were used as the main input data. A fifth-generation digital terrain model (DTM 5G) created by airborne laser scanning was acquired from the Czech Office for Surveying, Mapping and Cadastre. DTMs in the application represent various parts of the Czech Republic with a similar relief. Data were transformed by doubling the vertical values to accentuate the relatively small variation in landscape altitude. DTMs were supplemented by contour lines also generated from the DTM data as well as orthophoto images provided from a WMS (Web Map Service).

The application creates a shared virtual room for multiple users. Even though users are physically located in separate objective reality rooms, the VR headset lets them share a virtual room to collaborate on a given task. Physical movements in the objective reality room are tracked and transferred to the virtual room, which means users can walk around the room and examine geospatial material from all sides, angles and distances. In the virtual room, each participant is displayed as an avatar with virtual representations of controllers he or she is holding in objective reality (Figure 1). Controllers are used to manipulate the virtual environment and provide a laser pointer for communication. Users can also talk to each other via standard audio recording and reproduction devices. Objects added to the scene, such as houses and dams, are visualized abstractly and simply. It is considered a suitable method for highlighting task relevant objects [74].

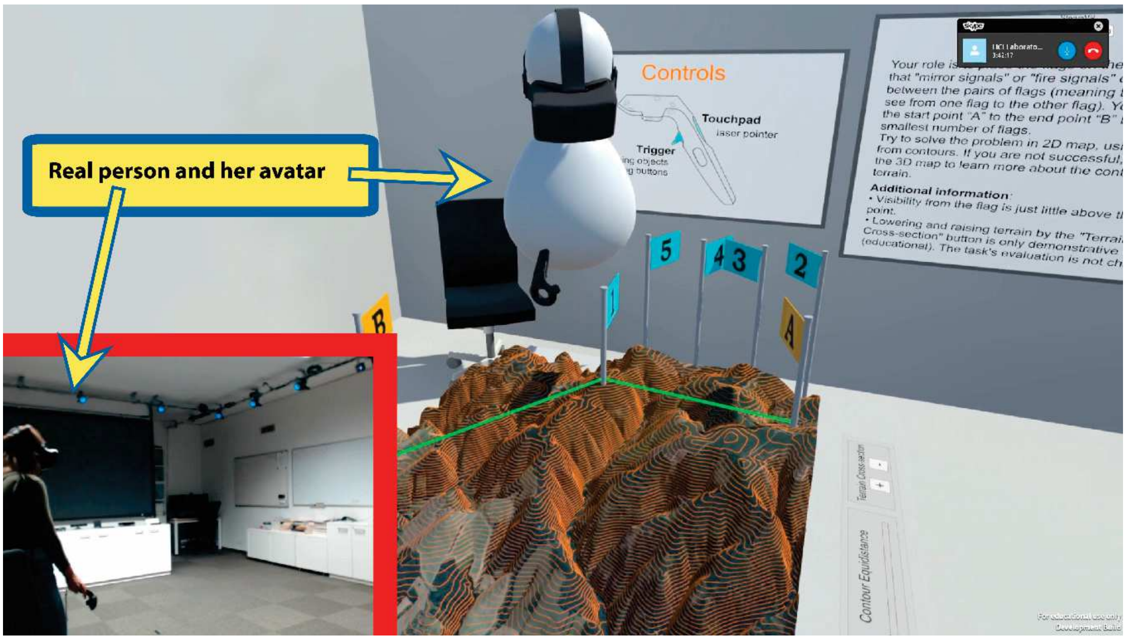

Figure 1. Objective reality (left corner) and virtual room.

The application includes two geospatial tasks. For each task, a different workplace in the room is offered. The room has a table with a map for the first task and a large map on the floor for the second task. Both geospatial tasks in the application require the user to examine contour lines on a 2D map to determine the shape of the terrain in order to find the correct solution.

The default visualization in both tasks is a 2D map. If the user cannot solve the task correctly on a 2D map, they can use various educational tools to help examine and manipulate the map. The application provides a virtual control panel (Figure 2) next to the map in the CIVE. One of the main advantages is the possibility to switch the map from 2D to 3D at any time. The map can also be switched between a white contour map and an orthophoto contour map. Contour line equidistance can be customized using a slider. Finally, when the user wants to verify their solution, they can use the Evaluate button.

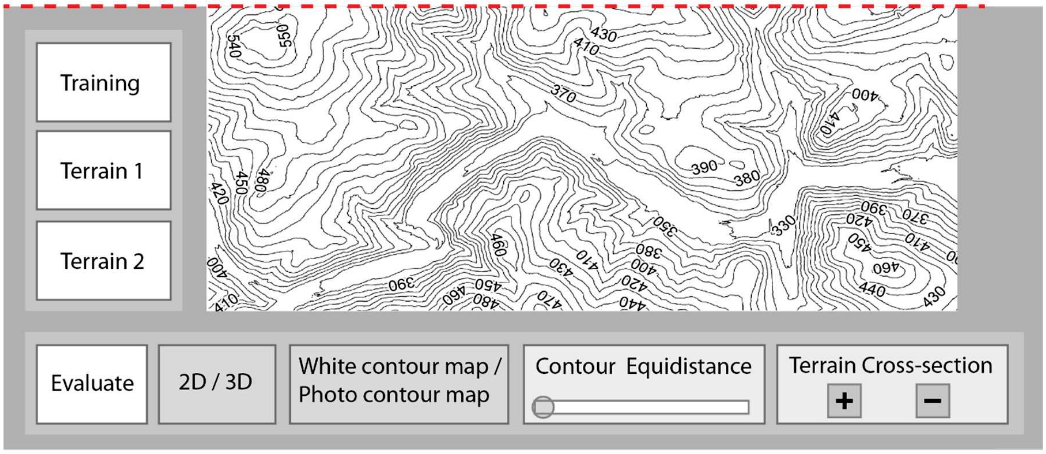

Figure 2. Virtual control panel for model manipulation.

2.2. Instructional Tasks in a CIVE Environment

For purposes of this research, two tasks were designed: Task 1—Mirror Signals and Task 2—Flooded Valley. In case of the Mirror Signals task, a map was presented to participants, with two fixed flags marking the start point (flag A) and the end point (flag B). Next to the map were five more available flags numbered 1, 2, 3, 4, and 5, which could be picked up and placed onto the map (see Figure 3). The task was to connect start point A with end point B using these additional flags in a way that mirror signals (or fire signals) could be transmitted between neighboring flags only with direct visibility. This means that the view to flag 1 from flag A, flag 2 from flag 1, and so on had to be unobstructed until an unobstructed view to flag B was obtained. The goal was to use the least number of flags possible to link the start point with the end point (see Supplement for Video S1). In the first task, the 3D model of the terrain can be dissected into individual layers and a cross-section of the terrain can be viewed.

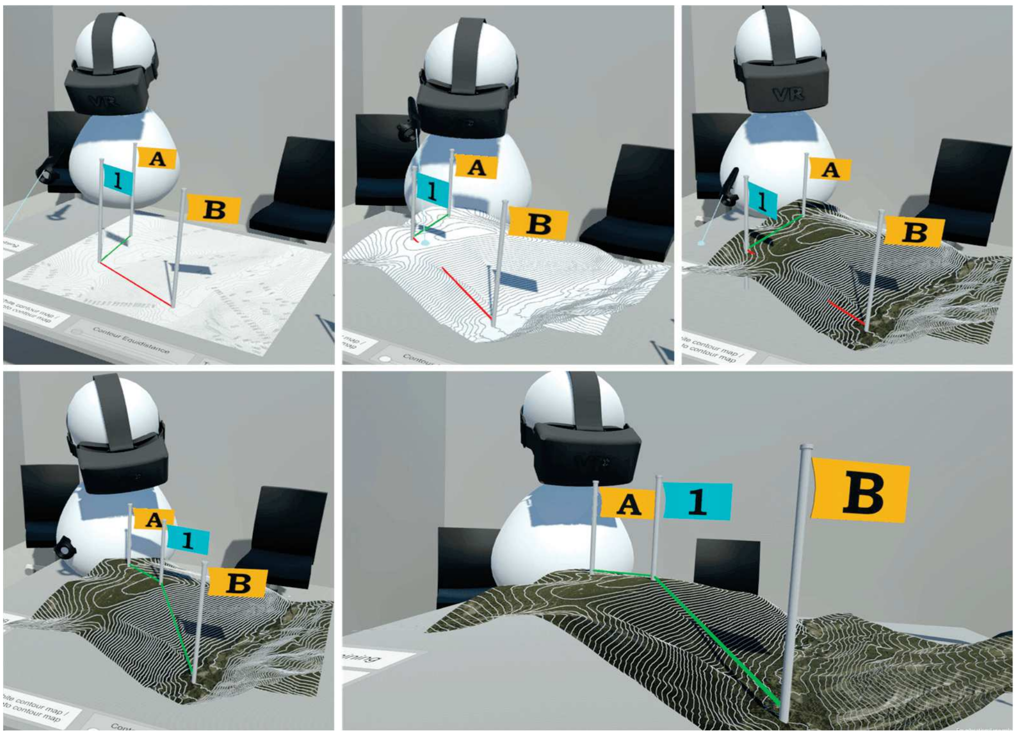

Figure 3. Incorrect (**upper**) and correct (**lower**) answers for the mirror signals task in the collaborative immersive virtual environment (CIVE).

As in Task 2—Flooded Valley, a 2D map was presented to the participants that included houses (orange rectangles) in a recognizable valley surrounded by mountain ranges and a dam (red line) (Figure 4). Just as in the previous task, five flags numbered 1, 2, 3, 4, and 5 were next to the map and could be picked up and placed onto the map. The scenario and task were as follows. *A new dam has been built to transform a valley with houses into a water reservoir. The water in the valley will gradually rise and flood the houses one by one. Use flags with numbers to mark the order in which the houses will be flooded.* After submitting the solution, the participants could watch the rising water gradually flood the houses (see Supplement for Video S2). The water level can be manipulated by user too, which lets the user gradually flood the terrain to see water flooding one contour line after another.

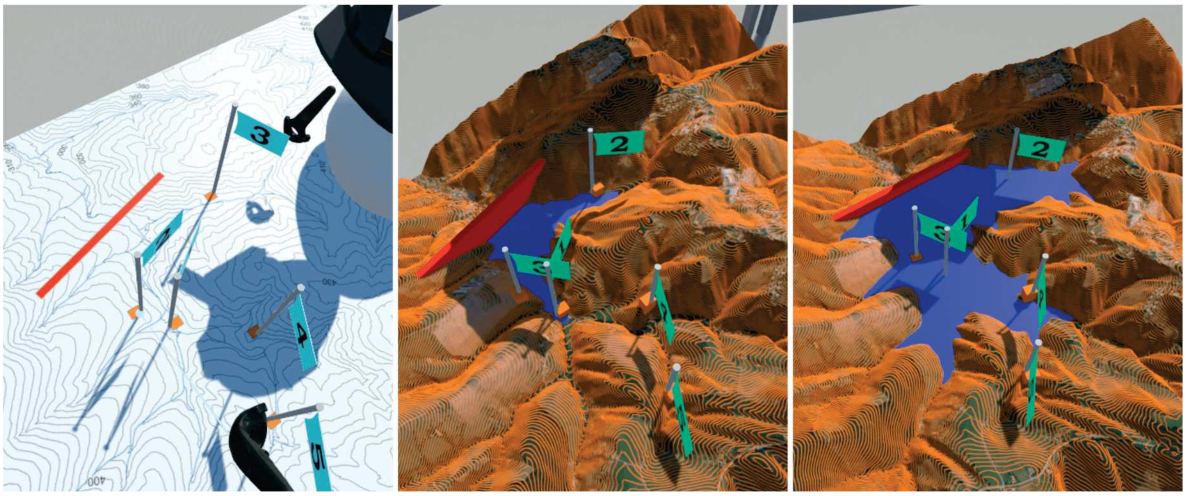

Figure 4. Flooded valley educational task in the CIVE. **Left**—flags with numbers are placed onto the 2D contour line map, **middle**—water level starts rising in the 3D visualization, and **right**—3D visualized dam is completely flooded.

2.3. Research Approach

To examine the user experience in our geography learning CIVE application, an experiential qualitative approach of Interpretative Phenomenological Analysis (IPA) was applied. This approach explores the lived experience of a person and the meaning he or she attributes to it while exposed to a specific phenomenon, for example, a short-term event or a long-term process. Its aim is to create an in-depth description of a person's lived experience during exposure to a particular phenomenon.

IPA is a frequently used strategy for research topics in weakly examined areas where the background theory has not yet been sufficiently developed. It is flexible in dealing with unexpected data that occur during research. It is therefore an ideal tool for gaining insight into and understanding the innovative use of a CIVE for geography learning or learning in general [75]. A research question in IPA is open, and although IPA is not a theory-driven approach, literature usually contributes to formulating a research question [76], as was also the case in our study. IPA does not test hypotheses and attempts to avoid creating preconditions before research. It is an inductive approach which is rather "bottom-up" than "top-down" [77].

The number of participants in IPA research depends on the richness and saturation of individual cases. Participants are experts on their own experiences and can offer the researcher an understanding of their ideas, associations, and feelings. The recommended upper limit of participants is ten [78]. Creating a research sample is based on purposive sampling and participants are selected according to relevance criteria for the research question.

Data collection in our IPA study implemented triangulation [79,80] from three research techniques (Figure 5). Using three different and complementary research techniques for data collection makes it possible to harvest the strongest aspects of all the techniques and mutually compensate their weak spots.

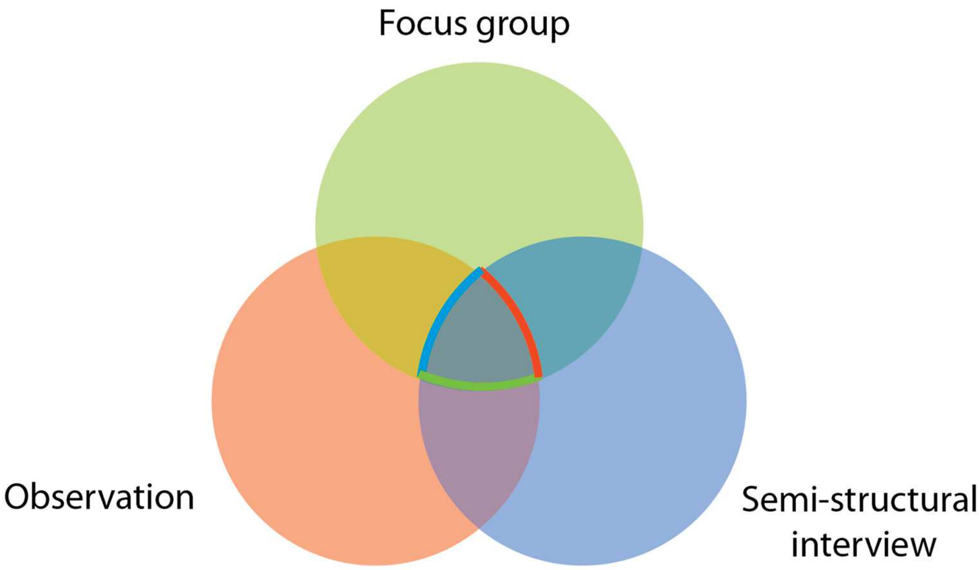

Figure 5. Triangulation of research techniques for data collection.

Half of the participants involved in the study were interviewed in pairs in a semistructured interview. The researcher sets up the key topics before interviewing, such as learning experience, gained understanding of the learning topic, and means and effectiveness of communication with a collaborator. The advantage of an individual or dyadic interview is a controlled, detailed, and deep exploration of an individual's unique experience. The other half of participants was interviewed in a focus group. As a research technique, the focus group minimizes the influence of the researcher and any preconceptions which could direct or distort the participants' statements. The researcher moderates a discussion and gives participants free space to share their individual experiences. However, some important topics can be omitted by participants, which is the most significant disadvantage of the focus group technique and the reason for our choice to use semistructured interviews to compensate for this potential weakness. Nevertheless, the key advantage of both techniques mentioned is that they bring new topics to light.

Subjectivity of the acquired data also poses a challenge. To overcome the potential risk of low validity, we conducted observations. All participants were observed and video recorded during their experience of the CIVE. We monitored voice communication, movement in objective reality and the avatars in virtual reality as tasks were completed. This data provides researchers not only with objective complementary information to the subjective reports, but also captures reactions and behavior performed unconsciously by the participants.

2.4. Research Environment and Equipment

The study took place at Masaryk University in Brno, Czech Republic, in two separate rooms. Each room was equipped with a computer (Intel® Core™ i5-6500 processor, Nvidia GeForce GTX 1080 graphics card, 16 GB RAM) connected to an HTC Vive headset (1080 × 1200 px resolution for each eye, 90 Hz refresh rate), sensors, and a controller. A participant and a researcher were present in each room. The rooms offered enough space for participants to move around and were sound insulated from the outside environment.

2.5. Participants

To design and structure the interview questions, one pair of participants was interviewed in the preparation phase. It was an in-depth phenomenological interview with a pair of "experienced" VR users conducted after collaboration in the CIVE application. Researchers themselves were involved as preparation phase participants to gain personal experience with the CIVE and educational tasks. The initial analysis resulted in a few changes to the research procedure, task setup, and virtual control panel being made. The interview with preparation phase participants also focused on their overall experience in the CIVE. Based on the information acquired, a semistructured interview schedule was created for interviewing research participants.

Research participants were recruited from the pool of volunteer students and academic teachers from the Faculty of Arts. Two exclusion criteria were applied. The first exclusion criterion was previous formal training in cartography. The second exclusion criterion was the occurrence of cybersickness in previous experiences with virtual reality or during this study. Participants were asked to report any cybersickness and were briefed on options to end participation at any moment if required.

The final research sample consisted of 12 participants who collaborated on geospatial tasks in the CIVE application in pairs. The pairs were established randomly. Seven participants were women and five were men. The mean age of the participants was 27.58 years, the minimum age was 22, and the maximum was 43. None of the participants had undergone specific GIS user training and none were significantly experienced VR users (including, for example, VR gaming).

2.6. Procedure

Participants who volunteered to this study underwent a procedure consisting of five steps: 1. Informed consent and collection of demographic data; 2. VR manipulation training; 3. Research procedure instruction and contour lines principle explanation; 4. Collaboration in the CIVE (Figure 6); and 5. Inquiry. With a pair of participants, the procedure varied from one to two hours.

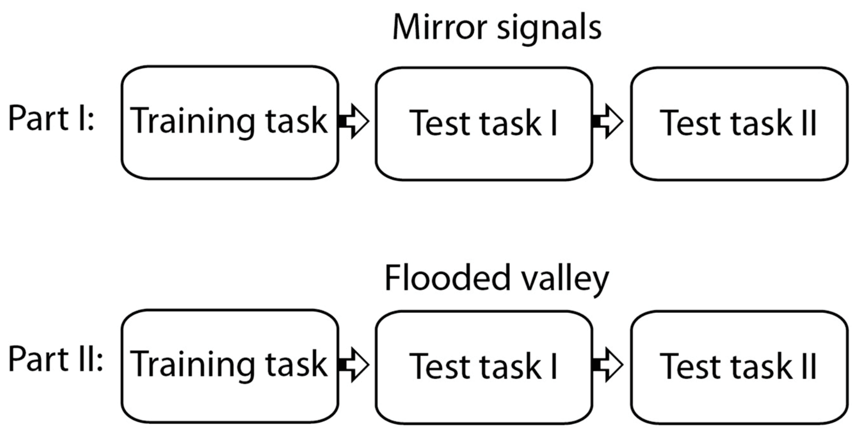

Figure 6. Step 4: collaboration in the CIVE—research tasks administration in detail.

2.7. Analysis

We employed specific idiographic case study data analysis in the IPA and the variation for multiple cases (respectively, multiple participants) as described in Smith et al. [78,81,82]. This analysis focused mainly on the shared experience (common characteristics of experience) of participants, but also mentioned significant and distinct experiences [77]. An analysis is slowly built-up by reading individual cases and creating statements about the whole group of participants. The analytic process is cyclic (iterative). The themes are reconsidered and rebuilt many times [78]. The results are transparent because they are evidenced by data examples (quotations). The results are structured according to theme. As shown in Figure 7, the analytic process cycle is as follows.

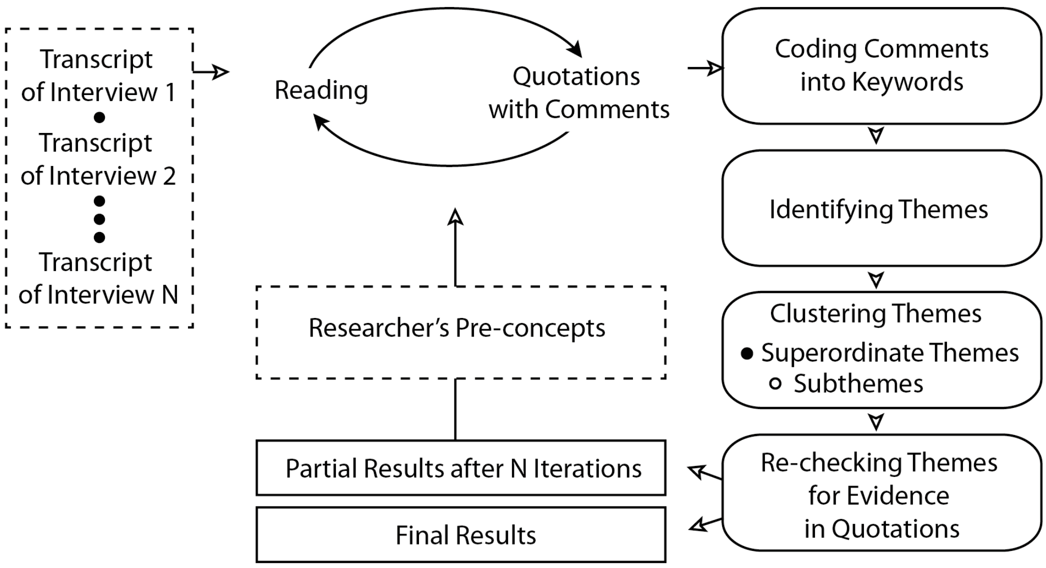

Figure 7. Scheme of the interpretative phenomenological analysis.

After transcribing the first interview, its content was read by a researcher repeatedly and significant quotations were marked and annotated (comments included preliminary interpretations and ideas from the researchers). This phase was repeated several times and the comments were then coded into keywords from which important themes were identified. These themes were then structured into a list of superordinate themes and subordinate themes belonging to each superordinate theme. Next, the themes were rechecked for evidence in verbatim excerpts (participant quotations), after which the analysis could proceed to another participant using the preliminary concepts gained from the previous interview as a framework for analysis of the next interview (Figure 7). Each participant's interview analysis was thus thoroughly considered when the next interview was analyzed, and the final list of themes applying to all participants (as described below) was based on in-depth analysis of all interviews.

3. Results

Four superordinate themes emerged from the analysis. Under these superordinate themes, several subthemes were identified, all of which are introduced in detail in the text below. The themes are well illustrated by verbatim excerpts from the data corpus, which are included in the tables. The main structure follows the most relevant topics: collaboration, learning, map literacy, communication, and cognition.

3.1. Appreciation for Having a Collaborator

The first superordinate theme relates to the thoughts and feelings of the participants towards their collaborative partners and is characterized by the appreciation of having a collaborator to solve the tasks. The collaborator motivated them and provided the opportunity to consult on the solution.

This superordinate theme includes two subthemes which we called 'Lost without a collaborator' and 'Verification and consensus with a collaborator' and are also described below.

3.1.1. Lost without a Collaborator

A key aspect prevalent throughout the accounts of collaboration was that the participants would have felt lost without a collaborator. They expressed doubt as to whether they would be able to solve the task individually. Collaboration helped them solve the tasks. They were very happy they could talk to their collaborator. Participants talked a lot, which made it easier for them to understand the task. They believed that they would have been staring at the task for a long time if they had not been working with a collaborator and would have felt uncertain and stagnated. Participants estimated that a collaborative solution was more effective than solving the task individually and did not believe that independent work on this task would have had any benefit (Table 1).

Table 1. Verbatim excerpts of statements by participants: Lost without a collaborator.

P13	"I wouldn't have managed it myself, so, like, I don't even have experience with it, so I was really glad that there was someone with me who would say to me: 'Yeah, this . . . '"
P14	"I was quite pleased to hear the other person's opinion. If I had done it like alone, it might have been a bit sad (. . .) would've had to think about whether it was correct, whether I'd made the right decision. But this way, when I had you and you helped me with it . . . "
P09	"We were looking at it together and solved it together, because we talked a lot the whole time, so . . . it seemed more, like, understandable to me."
	"It helped me a lot to have a collaborator, because I would have stared at it for a very long time and would have been very uncertain, because I was wandering a little in it, so it helped me a lot when the collaborator said: 'Let's just solve it in one minute and go to the next one' . . . and that was just great, because we just needed to try it and we tried it."
P12	"This way, it was even more fun and faster." "This interaction is always as if time always flies faster. If I had been there alone, I would have looked around more."
	"If I had been there alone, I would've looked half an hour somewhere else where something else was, but because there were two of us, I focused more on the task, because you always pulled me back to it."

3.1.2. Verification and Consensus with the Collaborator

Participants described that as they made decisions about solutions to the task, they usually consulted their collaborator to verify the answer before submitting it. They sought consensus on the right solution together. Participants discussed their viewpoints and the specifics of a particular task which could influence the answer. They talked to the collaborator about which strategy or key they should use to solve the task. The usual modus operandi among the pairs of participants was to talk about a strategy for the solution, reach an agreement on the correct answer and then submit it. They were therefore much more confident when submitting the answer and felt better about it. It also helped them to inspire each other. When anyone in the dyad discovered a useful strategy, they shared it and both then used it. Solving the task with a collaborator was reported as more effective. Participants usually discussed and decided on a solution together (Table 2).

Table 2. Verbatim excerpts of statements by participants: Verification and consensus with the collaborator.

P04	"I consider collaboration as good, because it verifies that I thought about something. I asked the collaborator whether he saw it the same way, and he said that he did, and in that case we submitted it."
P03	"We just agreed on how to do it." "It seemed to me as less ambiguous and so we found some . . . consensus about the right solution, and whether we saw something special about that case."
P09	"We discussed the task, searched the key which we would establish as a solving strategy, and using laser pointers, showed each other the things we were currently talking about."
P11	"We always talked nicely about it, to both agree on it before we completely submitted it."
	"If the collaborator was thinking the same thing I was, then it was easier to submit the answer, but individually I would maybe have thought about it more or . . . but I think it also helped me to understand it, because both of us found something relevant and then we both used it further, so we were enriching each other."
P12	"I think that thanks to the fact that we evaluated it little by little, the process was more efficient than it would have been if I had been there alone, then I would either think about it more or have made more mistakes."

3.2. The Surprising "Fun with Maps"

The second superordinate theme relates to the reported level of excitement the participants felt while working on geospatial tasks in the CIVE application, although most participants verbalized that they usually did not enjoy working with maps and considered them boring. Moreover, working in CIVE also enhanced the educational effect.

This superordinate theme includes the two subthemes. Finally, seeing what contour lines represent in reality and learning a skill to work with maps.

3.2.1. Finally Seeing What Contour Lines Represent in Reality

Many participants explained that thanks to being able to switch the 2D map to the 3D model of the terrain, which they could examine and walk around freely, an association developed in their minds between what a contour line looked like on paper and what it represented. Virtual reality helped them solve the task and see the correct answer more clearly. They found it helpful to use educational tools for visualization in 3D, for example, raising the terrain's water level to see how contour lines were flooded one by one. All of this helped them learn about contour lines and create associations between 2D maps and real 3D terrain (Table 3).

Table 3. Verbatim excerpts of statements by participants: Finally seeing what contour lines represent in reality.

P03	"On one hand it was great, because now you know where the contours are and what they look like and stuff, and then the virtual reality is turned on and then it (the 3D model) emerged, which I think is great."
P09	"It really was helpful and I could see it in that more clearly . . . It was like it allowed me to concentrate really well on the task."
P12	"And I think it really helped us to gain insight, so in the next task our imagination was better, that we could imagine it better, and that what we created is some model of how those contours look like in reality."
P11	"Yes, I think it helped even in understanding what contours actually are, when the person then really sees it as the real differences in height, that it's not just lines."
P14	"In fact, normally a person can't see it like this, as in that virtual reality."
	"With that flooding, certainly, like flooding, imagining that water, as it rises. When we evaluated it, it was then easier to shift it and see how the water would rise than if I had to imagine it on the table."
	"In fact, this can be utilized in many ways, even, like, only in education when a person imagines how it looks in reality. So this was great."

3.2.2. Learning a Skill to Work with Maps

An additional and clearly identifiable subtheme which emerged from the analysis relates to the new skill participants learned for working with maps. Participants explained that they had acquired a better understanding of contour lines and that if they came across similar tasks in the future, they would be able to solve it faster. Our educational application was seen as a good learning and training tool for improving map orientation skill and decreasing the time it occupied. For some participants, maps were an alien territory, but with our CIVE application, their map orientation skills improved. Their map reading speed increased and it was now easier for them to imagine terrain (Table 4).

Table 4. Verbatim excerpts of statements by participants: Learning a skill to work with maps.

P04	(if they had to solve a similar task in the future) "Well, certainly it would be better. On that level, we wouldn't be looking at it for five minutes and . . . (participant laughs) . . . and wouldn't be trying to understand contours."
P11	(if they had to solve a similar task in the future) "Like, I would probably be pretty much orientated in it . . . such good training."
P03	"We learned to read contours much better, perceive them and search for them even in that not completely biblical environment, because neither of us is a geographer and we weren't used to using contours every day, and that ability to orientate gradually improved."
P04	"We are certainly a little, or at least I am, someone who doesn't work very often with contours. I have oriented myself in that environment, so now I'm on . . . now it would take me less time to recognize, where the hills and valleys are."
	"I actually didn't see that terrain at all, so I think that actually for a long time both of us only looked at it." "Later we were faster reading the map."
P13	"Much better, I can imagine it better as, like . . . now I can imagine it better."

3.3. Communication as a Challenge

The third superordinate theme relates to the effort participants made to communicate their thoughts and feelings to the collaborator. Participants described that they had to concentrate more on facilitating communication by the means they had available in the virtual environment.

It includes three subthemes: Absence of avatar faces and invisibility of emotions, limited gestures via controllers, and having an intangible body.

3.3.1. Absence of Avatar Faces and Invisibility of Emotions

Many participants felt they had limited options when it came to communicating emotions to their collaborator. One of the first things they noticed was that avatars had no faces. Some of the participants looked at their collaborator's avatar when they talked to them, and some did not. Most of the participants considered faces as important and missed them in the virtual reality environment for conveying emotion. Besides, participants considered it important to see where their collaborator was looking. This was possible in our CIVE application, but they were not surprised at being unable to look their collaborator in the eyes, as they had expected it this way. Some of the participants wondered whether it would be strange or disturbing if their collaborator's avatar had some representation of a face, as there could be discrepancies between what the person was trying to communicate and the emotions the artificial face managed to convey (Table 5).

Table 5. Verbatim excerpts of statements by participants: Absence of avatar faces and invisibility of emotions.

P10	(collaborator having no face) "It seemed terribly comic to me, like, when we talked to each other—that alone made me laugh for a long time."
P12	"Yes, I had to adjust my ways a little in communicating, for example, gestures and . . . Basically, we didn't even see each other's facial expressions, and facial expressions are also quite important, so I didn't see what facial expressions she had . . . when I heard her laughing, I heard that, but when you can't see the other person's eyes, it's that different."
P04	"Sometimes I missed those, like, emotions there, that I was, like, smiling (participant laughs) . . . and there was no way of passing it over and then I always realized that I'm smiling in an empty room."
P03	"I considered it important to be able to see where that person was looking or what he was calculating or something."
P06	(collaborator having no face) "I probably expected it. I've seen it before." "Natural, it probably wasn't . . . (participant laughs) . . . but it was probably not surprising."

Table 5. *Cont.*

P10	"I wonder if it would have been stranger if it had simulated a person even more and then there was some discrepancy, even like, that it would have had a more realistic face, then it might have been even stranger."
P08	"There should rather be a square than a simulation of the shape of a head, or that, as you said, being deformed, that is probably not what a person really wants, for it to resemble a person."
P10	"Maybe it also then even evokes some emotions, and that is probably not what is intended, for people to act according to it."

3.3.2. Limited Gestures via Controllers

When participants were asked to describe their experience of communicating with their collaborator, they often described the need to modify their communications and actions because they had avatars instead of real bodies. Participants mentioned that the collaborator's representation was fine, but if the avatar had been more detailed, it would have been even better, as they wanted to see their collaborator's gestures. They would then look at their collaborator during communication more often. However participants say it was possible to read information from the posture and proximity of the collaborator's avatar. They had to think about how to depict something during communication when the collaborator could not see them fully. It was apparently demanding, but also fun. It required an unusual style of thinking which required the participants to consider the selection of gestures. They managed, however, to adapt to the visible parts of their avatar and used only those to communicate (Table 6).

Table 6. Verbatim excerpts of statements by participants: Limited gestures via controllers.

P04	"To me it seemed okay, but certainly if that avatar functioned better and I could even look at gestures, then it would be better. That probably . . . like I would use more, I would try to communicate more and I would even look at him more."
P12	"That is true, I actually also gestured with my hands and . . . it wasn't actually being seen . . . so I had to, like, with that controller."
P04	"Sometimes I looked where you were standing, but I couldn't make out a lot from that, and yeah, I saw for example, that he was currently leaned over the numbers, yeah, and . . . actually yes, when I think about it, you looked, for example, I saw, that he was currently leaned over the numbers, so I assumed he was currently solving something."
P12	"One tries out a little different way of communicating. Maybe he concentrates a little more on what he's doing with the hands, legs, what and how he moves and how to communicate something to the other person, so you have to take into consideration what he sees."
P11	"Well yeah, well, since it was a little bit more limited with those avatars, as with that, that there weren't all the details, then it was a little bit more interesting, so . . . that sometimes there's too much detail." "I actually had to think about it, how to show something considering that I will not be seen as a whole, and, like, when I show something with my hands, that the hands actually were not seen."
	"Yeah, I've been able to adjust to what is actually visible and somehow just move only with those things that are visible."
P12	"So I think a person gets used to it quickly . . . he learns how to work with what he sees."

3.3.3. Having an Intangible Body

All the participants dealt with the fact that their body in VR was not composed of any physical material. The situation when the avatars of both participants stood in the same virtual space or when an avatar stood "inside" a virtual object occurred. The physical area around a participant was always free, and the decision not to walk through virtual objects was always up to the participant. Participants tried to keep a usual personal distance between themselves and the collaborator, even though it was only an avatar.

Many participants mentioned the problem of obstructing or shadowing each other's view. When a collaborator stood in the map, it was quite a big problem and hard for the other person to read contour lines, but they did not realize they were doing it. Participants usually did not tell each other. They recognized the problem, but it usually only lasted a few seconds before the collaborator changed position and they could see the map again.

However, participants mostly did not mind that their avatar was not physical. It only bothered them at the beginning on account of habit (Table 7).

Table 7. Verbatim excerpts of statements by participants: Having an intangible body.

P04	"When my collaborator appeared in that first room during the first task, and when you, like, moved to the flags and I stepped out of your way, right, to like make space for you, so in that moment I was fully aware of the fact that I actually didn't have to move and that we could be both there, one through another, but, but I made a step back (participant laughs), because it seemed a little bit awkward."
P03	"I guess I would make him space, if I could. I would probably respect the personal zone even in cyberspace."
P11	"When I was looking at something and I was, like, leaned over it, like that I was thinking about something, and since she didn't see me as a whole, so I thought I wouldn't be obstructing and then I found out that I'm obstructing there with my whole body, and that she didn't see the map at all."
P12	"Well, there was such, such a funny thing, when you were standing there somehow through the table and it wasn't possible to see through it at all and it was so weird."
P04	"it was quite a big problem, but it didn't occur to me at all that I could be shadowing you, but because we both got in there, that we both walked inside that map since it was difficult to read, but then I didn't see those contour numbers or the contour heights actually in that moment, when the person was standing exactly through the map, that's true."
	"And we never said to each other: 'hey please make a step back'."
	"I was dealing with it as with a problem, certainly, but probably in the same moment you walked further on, so it didn't bother me anymore."
	"I think it was really a matter of a few seconds." "The fact that the body actually took up quite a lot of space was not okay."
	"I found it good that we could place the flags through each other in there, that you could place them here and I could place it there and you here and that we could cross over each other like this."

3.4. *Cognition in Two Realities*

The fourth and final superordinate theme relates to the cognitive aspects of simultaneously existing in two realities: objective and virtual reality. Participants were present in objective reality but also felt the sense of presence in virtual reality.

This superordinate theme includes three subthemes: Where are my legs? Immersion and involvement in the artificial world and confusion during the return to objective reality.

3.4.1. Where Are My Legs?

This question was asked by one of the participants, while other participants also wondered why their avatar looked so rudimentary. Many participants could not adapt to not seeing their own legs. They were strongly conscious of their absence, some even intrigued by it, as they were accustomed to seeing their legs as they looked down. Most participants would have been happier to have virtual legs in the virtual environment. By contrast, one participant did not mind that she had no legs, but did not like that the collaborator was missing legs (Table 8).

Table 8. Verbatim excerpts of statements by participants: Where are my legs?

P03	"When I put the headset on, I couldn't get used to, like, that I don't have any legs, I don't have a wristwatch. I was aware of these two things very strongly from self-perception."
	"I found it interesting not to actually see the legs. Because always when I put my glasses on and look, when a person looks down and he is walking somewhere, then he can see his legs and now I didn't see them, so that was interesting to me."
P08	"It wasn't very pleasant when I looked down, then I felt that I just have them (legs), but they're simply not there."
P11	"It was quite odd that I was actually in the table, or, like (participant laughs) . . . moving, not actually seeing my own legs, knowing that the legs are probably right where the table was (participant laughs) . . . kind of a strange feeling."
P09	"Maybe just because I didn't see the legs in there, then I didn't mind going through the table."
P11	"I was quite glad that if the legs had been displayed in there and I saw them go through the table, then it might have been even stranger."

3.4.2. Immersion and Involvement in the Artificial World

The experience of being in immersive VR was characterized by the loss of tracking objective reality and having a stronger sense of presence in the virtual environment. Immersed in VR and wholly engaged in the task, participants felt a stronger sense of presence in virtual reality. They did not perceive or think about what may have been happening around them in objective reality. While in VR, they had no need to be in touch with the outside world. Only when they bumped into something or heard the experimenter speak did they think about where someone or something was and feel disoriented (Table 9).

Table 9. Verbatim excerpts of statements by participants: Immersion and involvement in the artificial world.

P09	"On one hand, I was really, like, immersed in that task and in that activity, and on the other hand . . . so it was really, like, absorbing for me."
P13	"Well, I just bumped into something there, but otherwise I had no clue who was doing what in here." (in the objective reality room)
P11	"I was actually more in that virtual reality than in the real reality, actually. Sometimes I really didn't perceive the real reality, I put myself into it a lot."
P14	"I actually didn't have a clue what was actually happening around me."
P04	"I have to say that I didn't quite perceive that much." "Only when I took my headset off did I find out that I was terribly sweaty under it." "Then I, like, realized more that it was actually warm in there."
P12	"At first I was thinking about what it looked like from the outside, the things we were doing there, that it must have looked really funny."
	"At the back of my mind I knew that I was, like, in the real reality and that I'm doing those things others can't see, but I was also, like, quite able to put myself into it, that I'm simply in some room without a ceiling and where there's just some map on the floor."
P03	"When I was solving it, the task, I perceived more the virtual reality, but when there was nothing going on at time, then I perceived more the physical world again."

3.4.3. Confusion during the Return to Objective Reality

All of the participants liked the virtual environment and became accustomed to it, and most did not want to leave it. Although most of the participants described that they did not have any problems after taking their headsets off, some described specific feelings and perceptions which they experienced for a short time after they had returned from VR to objective reality.

For instance, one participant described how shocked he felt seeing his real hands again after leaving VR. A moment after leaving VR he felt lightweight and thought he would faint and felt strange even after some time. The time after exiting VR was more disorienting to him than the time spent in VR.

As mentioned above, though, most participants described no awkward feelings after taking their headsets off. They did not need to adapt to objective reality; it was completely normal for them to return to the objective reality room (Table 10).

Table 10. Verbatim excerpts of statements by participants: Confusion during the return to objective reality.

P08	"For me it was a shock to see my hands again after I took the headset off, and I had a clear feeling that when I was standing in that other room, I could simply walk through the person in there, that my hand could just pass through that person."
	"It's still strange. For a moment after sitting down, I felt as if I'd pass out."
	"So that one feels lightweight and just feels as if the wall isn't there, that I could walk through it. For me, it was probably a much more shocking experience after than with the headset on. And I wondered how I would feel if I layed down now, because I actually didn't even see my hands, I perceived it as those hands when I looked, like: "Wow" and I would probably, I would certainly not want to willingly go out of the room and go, for example, out onto the street, because I would be afraid that I, like, can't control it and that something could happen."
P11	"Yeah, I liked it there, that I didn't want to come back, but then when I took the headset off, then it was actually . . . quite strange, that it was, like, drawn, the real things. So I had to acclimatize a little bit."
	"It seemed to me that things were a little bit smaller, or as the details displayed there, like in reality, those details are displayed normally, so it was, like, more detailed."
	"Then I had problems with reality, that it's, like, too detailed and that I, like, can't perceive it. Because in the virtual reality I could perceive everything, because it was simpler, so there were, like, simple stimuli, but in the genuine reality a person has to distinguish what he actually perceives, because there's a lot of it, so that he can no longer see it as an overall picture with all the things that are actually there. It's, like, more understandable in there."
	"Yeah, yeah, a little bit yes, just only on those details, that I had to perceive reality again, as to distinguish what I would actually look at, as I already said. Well, but it was just for a moment . . . in about three minutes I was okay again. But it wasn't even unpleasant, so it's stupid to say 'okay', but simply, that I wasn't even perceiving it anymore after I adapted."
P12	"I didn't want to go back, I liked it there very much. It was, like, when I took the headset off, it was like, like at first unpleasant, until the eyes got used to it, that I was used to that virtual reality and to that light and to how it looked there, and then I took the headset off and it was, like, "Ouuu", a little bit unpleasant."

4. Discussion

In this section, we discuss the results of our study in the context of referenced literature and challenge it with our preliminary expectations and recommend further research and applicational options. The results are already interpretative and deeply descriptive, therefore the discussion to each subtheme will be concise.

One of the main findings of this study was that participants would have felt **lost without a collaborator** and that working in a dyad brought more entertainment and better results. From a social psychological perspective on collaborative learning [83], collaborators can be explained as providing social and emotional support to each other, enjoying mutual interaction, and having a positive effect on satisfaction and results. Participants in our study felt motivated by their collaborator. A social psychological perspective considers motivation as a precursor to effective cognitive processes during collaborative learning. Motivation in collaborative learning can be viewed from two points of view. From a socio-motivational point of view, collaborators are motivated to work together because they share the rewards for completing the task. From a social cohesion point of view, cohesiveness arises between collaborators and draws them into looking after each other and cooperating and working together. Slavin [84] and Johnson and Johnson [85] discovered that students are more motivated during collaborative learning than individual learning.

Another important finding is that collaborators debated a lot during the problem-solving process and sought **verification and consensus with their collaborator**. From a cognitive perspective on collaborative learning [86], collaboration with a peer can be explained as achieving better quality in basic information processing components such as coding, rehearsal and retrieval of information, activation of strategies and metacognition. Participants in our study claimed it would have taken them longer to solve the tasks individually. O'Donnell and Dansereau [87] explain that the presence of collaborator helps the student stay focused on a task and gives them an opportunity to verify understanding of the subject matter.

According to Webb and Farivar [88], if a student explains the task to the collaborator, it allows the student to identify flaws in their own reasoning. Collaborative learning and negotiation of meaning between people can support greater coherence in understanding subject matter [89].

Participants also explained that **finally seeing what contour lines represent in reality** helped them gain insight. From the perspective of Piaget's theory of cognitive development, specifically of the concept of mental schemas [90], the educational tools implemented in our CIVE application, which enabled participants to switch between a 2D map and 3D model or to raise water level in the terrain, served as a means to confront the participant's understanding of the subject matter. In Piaget's terms, participants underwent the process of accommodation, during which their preexisting schemas were adjusted according to the new experience. The importance of experience was emphasized both by Piaget's predecessors as Dewey [91], and his followers, who further elaborated his work: Kolb [92] understands learning as a circular process of creating knowledge via transformation of experience. Participants in our study first tried to complete the task on a 2D map. Their assumptions and understanding were then challenged by the 3D model which visualized their solution. In the case of an incorrect solution, cognitive conflict or disequilibrium occurs as a result, which drives the student to reduce this state and to renew equilibrium. The collaborator serves as another potential source of cognitive conflict. This is in accordance with the general educational approach proposed by Neale, Smith, and Johnson [93], to first give students an opportunity to create assumptions about the subject matter and then let them test it against evidence to discover contradictions. This strategy aims to make students aware of their predictions and present contradictory evidence to create cognitive conflict.

The participants expressed that they had a better understanding of contour lines after the experiment. Several aspects could contribute to **learning a skill to work with maps**. One of them is from the perspective of Vygotsky's theory of cognitive development [94]. According to his concept of the zone of proximal development, if a student receives appropriate support during interaction with another person during the task solving process, they can internalize the process, reorganize cognitive structures, and develop new competence. This concept resembles the concept of scaffolding, which, according to Hogan and Pressley [95], is a support enabling a student to solve new tasks, teaches competence and fades over time. Modern usage of this term often incorporates not only interpersonal support but also software based educational tools. Our CIVE application provided scaffolding for learning through problem solving, which according to Guzdial et al. [96] helps students acquire deep understanding of subject matter and new competence. Our application was also a case of scientific discovery learning, which Chen and Zhang [97] consider as a learning process during which students generate and test their hypothesis. In their study, they found a prominent effect of collaborative scientific discovery learning in VR on intuitive understanding and discovery outcomes. The results of the study by Okada & Simon [98] show that collaborative discovery learning in pairs is more effective compared to individual discovery learning.

Participants had problems with the **absence of avatar faces and invisibility of emotions**. According to Ekman and Friesen [99], people gather information about another person from four main sources in the visual informational channel: the face, tilts of the head, body posture, and skeletal muscle movements. They described that during conversation people do not continuously look at a listener but look to determine the listener's emotions or find out whether they are paying attention, agreeing, or attempting to respond with their own speaking. The participants of our study did not have a virtual face and could not make these distinctions. Some of them therefore did not even look at their collaborator's face while they were speaking. Most participants, however, missed having a face as a channel of information and did not know how to substitute its role.

Participants described their experiences with **limited gestures via controllers** and how they had to learn to work with it. Tu [100] explained that virtual communication differs from communication in objective reality. According to him, because of the limited communication channels, participants miss the clues for social context, and communication may be impersonal or cold. Virtual communication therefore requires different communication styles and strategies to maintain personal and social communication. In our study, we observed that participants sought personal contact with their collaborator, and even though the communication channels were limited, found innovative ways of using controllers and avatars for communication.

Participants described that **having an intangible body** created situations of obstructing each other's view but did not influence the proximity and personal space rules they followed. Bailenson et al. [101,102] discovered in several studies that participants seek to maintain the same interpersonal distance in immersive virtual reality as in objective reality. This is in accordance with our observations and what participants expressed in the focus group and interviews. They used their avatars as nonverbal communication tools and kept the same proximity to the collaborator as they would in objective reality. However, because they did not have full control over the avatar's movements and position, obstruction of each other's view sometimes occurred.

Some participants described strange sensations related to the cognitive discrepancy between their tactile sensations of objective reality and their visual perception of virtual reality. Some of them asked themselves **Where are my legs?** It is important, though, that this was not a case of cybersickness, which, according to LaViola [103] and Davis, Nesbitt, and Nalivaiko [104], is a type of motion sickness caused by cognitive discrepancy between the tactile sensations of a static position and the visual perception of movement. It seems, however, to be based on the same principle of cognitive discrepancy.

A common experience shared by participants was **immersion and involvement in the artificial world**. Witmer and Singer [105] describe immersion and involvement as preconditons for a sense of presence. Immersion as a psychological state can be characterized as perceiving the particular environment which surrounds us and perceiving self as a part of that environment. In the context of virtual reality, it means ignoring the medium and being absorbed by the simulation [106]. The participants of our study described losing track of objective reality and not knowing what was happening around them in objective reality. Involvement occurs as a result of being engaged in a meaningful task and focusing attention on specific content. Csikszentmihalyi's [107] well-known psychological concept of flow describes a similar state characterized by being fully involved and absorbed in a task, feeling energized focus and enjoyment, and losing a sense of time and space. The participants of our study described the task as capturing their whole attention and eliminating the perception of external stimuli. According to Witmer and Singer [105], participants feel a stronger sense of presence in virtual reality than objective reality as result of both immersion and involvement, which is precisely what out participants described.

Several participants in our study described their **confusion during the return to objective reality**. Two of the participants described states of derealization, which is defined by DSM-5 [83] as the detachment from a person's surroundings (world, people, or objects) and experience of the surroundings as unreal, dreamlike, or visually distorted. Research conducted by Aardema et al. [108] demonstrated that exposure to immersive VR induces a dissociative experience and temporarily increases the symptoms of depersonalization and derealization from objective reality.

5. Conclusions

In this study, we explored the experience of geography learning in a CIVE. The experiment centered on collaborative learning, development of geography competences and cognitive and social aspects. The objective was to broaden knowledge and understanding of these areas in the specific context of a CIVE. Using a uniquely-developed geography learning CIVE application, twelve participants experienced an educational intervention during which they collaborated in pairs on geospatial tasks. By means of observation, semistructured interviews, a focus group, and an interpretative phenomenological analysis, we gained deep insight into the participants' experiences. From these data, four superordinate themes emerged, each including the above depicted subthemes.

From these superordinate themes, we concluded the following:

1. Appreciation for having a collaborator. Collaborative educational interventions have previously been shown as more efficient than individual task solving [85–87] (among others). Whether this applies to a VR environment is yet to be empirically tested at a quantitative level, but based on our study's results, we may conclude that collaborative VR education has great potential both in terms of improving learning outcomes and decreasing task related anxiety.
2. The Surprising "Fun with Maps". Motivational potential is believed to be one of the greatest expected advantages of VR educational interventions. As far as we can estimate from the qualitative analyses, when the topic of the educational session is well chosen, VR offers ways of exciting learners and making them interested in a topic they would find (or expect to be) boring. However, such a qualified choice needs to be based on the necessary knowledge of the lesson's subject (geography in our case), educational principles and VR technology specifics.
3. Communication as a challenge. As some participants reported that communication with their partner was challenging when no facial expressions were transmittable and because gestures were not precisely transferred into VR, the means of communication in a CIVE appear to be one of the key topics for future research. However, since we observed that many of the participants managed to innovate ways of communicating within a relatively short time (approx. 60–120 min), we believe that in a long-term educational intervention (for example, a regular semester course) learners would likely adapt and communication would no longer feel challenging. This is also yet to be confirmed experimentally.
4. Cognition in two realities. Since some of the participants reported negative or confused feelings after the VR session during their return to objective reality, some future research challenges have emerged. The first will be to eliminate the negative impact of VR immersion in some participants. Predictors of the depersonalization and derealization states need to be identified in order to provide special care to those learners at risk (or to exclude them from the intervention before they are allowed to begin). The second and a worthwhile consideration will be to search for ways of adapting the VR environment or sessions to decrease the risk of such states. However, most of the participants showed no indications of negative feelings, and hence, the overall results of our study are more than motivating for further elaboration of the CIVE intervention design.

This IPA-based study identified key areas that may play a key role in using collaborative iVR technology and suggested its potential benefits and limits in the field of education. In future studies, quantitative confirmation of the findings will be extensive and include effectiveness comparisons with traditional tools such as GIS (Parong & Mayer) [109]. Broadening the list of learning tasks is also yet to be done. Challenges for further research will include the impact of intervening variables such as the level of user experience with iVR, educational intervention length (repeated measurements), and interindividual differences (e.g., cognitive style or map literacy).

Supplementary Materials: The following are available online at http://hci.fi.muni.cz/CIVE-papers/Task_1_Mirror_signals.mp4 (Video S1—task 1) http://hci.fi.muni.cz/CIVE-papers/Task_2_Flooded_valley.mp4 (Video S2—task 2).

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Article

Effect of Size, Shape and Map Background in Cartographic Visualization: Experimental Study on Czech and Chinese Populations

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Abstract: This paper deals with the issue of the perceptual aspects of selected graphic variables (specifically shape and size) and map background in cartographic visualization. The continued experimental study is based on previous findings and the presupposed cross-cultural universality of shape and size as a graphic variable. The results bring a new perspective on the usage of shape, size and presence/absence of background as graphic variables, as well as a comparison to previous studies. The results suggest that all examined variables influence the speed of processing. Respondents (Czech and Chinese, N = 69) identified target stimuli faster without a map background, with larger stimuli, and with triangular and circular shapes. Czech respondents were universally faster than Chinese respondents. The implications of our research were discussed, and further directions were outlined.

Keywords: cartography; cross-cultural research; geometric map symbols; graphic variables; visual perception; visualization

1. Introduction

Research on methods of cartographic visualization has a long tradition and implications for many fields of human activity, including crisis and disaster visualizations [1,2]. The issue of graphic variables defined by Jacques Bertin [3] is mentioned in many scientific cartographic publications. Most of the works on graphic variables focus on Bertin's work and try to expand on his conclusions, which are considered generally valid in cartography. Many scientific works focus on this theory [4–13], and some papers try to extend the usage of the principles defined [14–17], but only a small part of published research focuses on verifying his theories (see further). For example, in his presentation at the International Cartographic Conference in 2017, Alan MacEachren mentioned that Bertin's work is " ... often uncritically accepted" and highlighted the few uses of multivariate data/graphics [18]. Another example is the work by Christophe and Hoarau [19], where the influence of aesthetics is emphasized, whereas aesthetics in cartographic visualization is missing from Bertin's concept.

Bertin [3] postulated that map elements are a specific graphics system: a set of six basic variables mapping each character, of which variable characteristics are dedicated more to the graphic system, describing their features, characters and relationships. Bertin defined the basic variables as follows (see also Figure 1):

- Size (taille): variation in the area size covered by a sign at a constant shape
- Value (valeur): variation in the ratio of the total amount of black and white in the perceived color of a given area
- Texture (grain): variation in the amount of discernable uniform marks per unit area at a constant value (there should be no variation in value, which is often ignored in the literature about Bertin's variables)
- Hue (couleur): wavelength variation within the visible part of the electromagnetic spectrum between two areas at a constant value
- Orientation (orientation): angular difference between several arrays of parallel signs
- Shape (forme): variation in the outline character (form) of a sign at a constant size

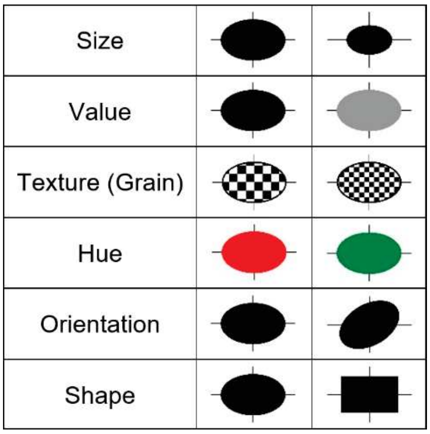

Figure 1. Bertin's six basic variables ([3]; depiction adapted from [20]).

These variables can be used to express quantitative and qualitative characteristics while also representing an aesthetic function. Bertin assigned five basic characteristics to the six basic variables: association, qualitative difference, selection, arrangement, and proportionality. Features and variables make up a total of 63 combinations available for map symbol creation. For a detailed description of graphic variables, see [10,21,22]. MacEachren [18] also mentioned that the main challenge currently is to focus on pre-cognitive perception rather than the further stages of cognitive processing.

Based on the above-mentioned theoretical issues, we researched using methodological approaches inspired by psychology and focused on verifying the perceptual aspects of selected graphic variables (specifically shape and size) in cartography and the cross-cultural universality of selected graphic variables.

2. Perception

A psychophysics movement in psychology was inspired by methods of natural sciences and concerned with the relationship between physical stimuli and the perception they produce was established. It introduced, among others, the key concept of sensory threshold as respectively differential and absolute sensitivity [23]. Later, at the start of twentieth century, the perceptual organization was first studied by a Gestalt psychologist, who investigated the principles of how elementary sensation is grouped into more complex structures and how figure-ground segregation proceeds [24].

Gestalt laws are also applied in cartographic visualization [8,25]. The basic assumptions and principles of the Gestalt school are still accepted in the scientific community [26], although the influence of top-down processes was later incorporated into this theoretical approach, which formally stressed only a bottom-up direction [27]. The work of Ulric Neisser [28] led to a cognitive turn in psychology. He highlighted the role of attention and anticipation in perception and stressed the importance of past experience. Based on this, it can be assumed that different individual experiences including socio-cultural context may cause differences in visual perception. Visual perception is determined by neurophysiological aspects (e.g., "the oblique effect" describes the decrease in performance when users deal with oblique shapes compared to cardinally (vertical and horizontal) oriented figures [29,30]), as well as by environmental (cultural) factors shaping the human experience.

It may be possible to use the findings from psychological research as guidelines for cartographers during map creation. However, in our opinion, several limitations do not allow for the direct application of findings from psychological studies. Psychological experiments do not fit the criteria of representative research design and an ecological approach [31,32]. Stimulus material in psychological experiments is usually very simplified to ensure the high internal validity of conducted studies and is also abstract without meaning. By contrast, maps are complex visual representations that always communicate meanings. Both factors lead to a lack of external validity in the results and limit their use in the field of cognitive cartography.

3. Research on Graphic Variables in Cartography

As previously mentioned, much research on graphic variables has been done in the field of cognitive cartography. A detailed description is provided, for example, by Montello [33].

Some of the foremost research focusing on the practical verification of graphic variables was done by Czech cartographer, Antonín Koláčný, in the 1960s on school atlases [34]. A crucial part of the extensive, empirical research dealt with differential thresholds, which are the smallest variation in the height of various shapes of map features sufficient to be noticeable. Table 1 shows the final summary of recommended differential thresholds for each specific shape [34]. Figure 2 shows the minimum size of certain shapes at a reading distance of 40 cm. Figure 3 displays the influence of the quantity of signs on the map on the user speed.

Table 1. Difference threshold for each shape [34].

Shape		Threshold (%)
Square	■	8
Circle	●	12
Rectangle	▬	12
Equilateral triangle	▲	8
Isosceles triangle	▲	15

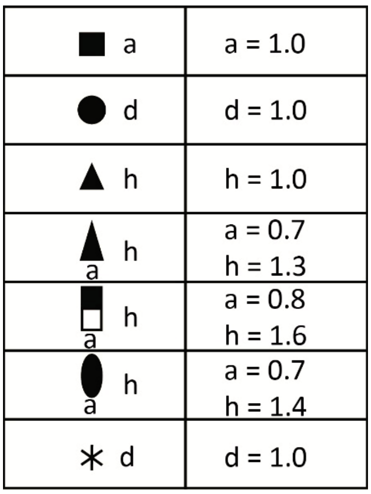

Figure 2. Minimum size (mm) at a reading distance of 40 cm (adapted from [34]).

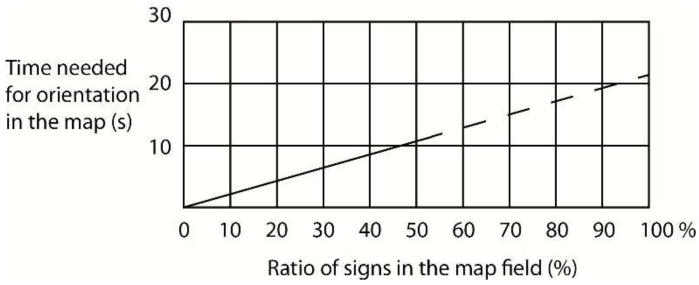

Figure 3. Map reading speed (adapted from [34]).

In their 2011 article titled "The influence of Jacques Bertin", Deeb et al. [35] examined the applicability of Bertin's variables for the purposes of labelling. In this particular study, testing was performed on two types of map users (laymen and professionals), who expressed certain preferences. In the conclusion, additional research is recommended on user groups matched by other criteria, such as age, culture, education or gender.

Although Bertin's theory is well known and widely used in the field of cartography and geoinformatics, a certain amount of research tacitly rejects his entire theory of visual variables. Garlandini and Fabrikant [36] mentioned that Bertin unfortunately did not use any citation of published researches from the field of psychology that could possibly support the designed system. Reimer claims, in his 2011 article titled "Squaring the Circle? Bivariate Color Maps and Jacques Bertin's Concept of 'Disassociation'" [37], that Bertin's concept of associativity and disassociativity of relevant visual variables is mostly ignored or misinterpreted, especially in the English-speaking world. Anglo-American tradition follows an evolutionary path that is heavily influenced by computer technology and the representation of color in a color space, while continental European tradition is influenced more by heuristics, which uses cartographic best practices. The differences mentioned brought us to the additional focus on the influence of different cultural backgrounds on the perception of certain graphic variables.

4. Cross-Cultural Research and Cartography

Cross-cultural research is still a neglected area in cartography. As Rundstrom [38] described, it started in the 1970s and 1980s [17,39–41] and since then, has mainly dealt with historical and indigenous cartographies. Cultural aspects are only occasionally the focus of studies concerning mainstream contemporary mapping procedures and their products. Cross-cultural aspects are taken into consideration even more rarely. As a consequence, we often need to rely on the results obtained from related fields, such as cross-cultural user interface design or more general subjects such as cross-cultural psychology, to get a better understanding of how cultures might influence maps and mapping.

Not surprisingly, it is difficult to find any cross-cultural research on the application of graphic variables in maps. In a comparative study on Swiss and Chinese regional planning maps [42], the use of extended variables, such as transparency, color gradient or shading (in both countries), is mentioned but not further discussed. In a recent study by Stachoň et al. [43], Czech and Chinese students had to identify differently shaped figural symbols in a map reading task. Main differences between the two used symbol sets were the degree of schematization and the presence or absence of a figure background with outline. Results showed that the Czech participants identified symbols from both sets faster than the Chinese participants, but this difference was only significant for the less schematized (more iconic) symbols without backgrounds/outlines. As such, an identification task is more analytic in nature, and this result could be interpreted as a consequence of the more analytic cognitive style of Czech participants. However, the also conducted framed-line test resulted in a different picture. There, the Czech students performed significantly worse than the Chinese students in the absolute task, which indicates a more holistic cognitive style of Czech participants. Such contradictory results show the need for further research.

One starting point for our study was the comparison of point symbol sizes used in printed German and Chinese city maps (published from 2000 to 2009) with recommended minimum size dimensions [44]. In this study, striking average size differences were documented. Based on the longest side measurement, more than 90% of the German point symbols were larger than the recommended minimum size dimensions, while this held true only for a third of the Chinese point symbols. This raised the question whether minimum size recommendations are universally valid and what the reason for this result could be. Among the potential answers discussed in that paper, the most interesting answers are briefly summarized below.

One factor considered was the influence of Chinese script. It consists of several thousand symbols with varying complexities. Consequently, Chinese students must invest a lot of time in learning the written form of their language. However, this effort also brings some additional benefits. Referring to several studies [45–50], Choong and Salvendy concluded that "Chinese tend to have superior visual form discrimination abilities." [51] (p. 420). However, this does not automatically lead to an increased ability to discriminate very small signs or shape details. In other words, it is not clear whether Chinese possess a culturally induced increased visual acuity as a consequence of their script learning efforts (a kind of "trained eyesight").

Another study discussed here [52] determined the minimum legible sizes of Chinese characters with different complexities and the readability of strings four characters long. Its results document a higher influence from character string familiarity than from legibility according to the minimum legible sizes found. This is supported by a recent study [53] that discovered evidence for a "holistic neural representation of Chinese characters" (p. 32), which is also in line with the characterization of cognitive styles, analytic and holistic thinking [54] (p. 293). Even if parts of a symbol are illegible, the character can still be read based on its overall impression. As a consequence, it seems less likely that increased visual acuity evolves from learning the Chinese script, and yet a certain training effect on eyesight cannot be ruled out.

This view is supported by two other cultural dimensions (sometimes called cultural variables): communication orientation and uncertainty avoidance. The first, described by Nisbett [55] (pp. 60–61), differentiates between a Western transmitter and an Asian receiver orientation. In transmitter-oriented cultures, it is the transmitter who is mainly responsible for a successful communication, i.e., a message is understood as intended, while in receiver-oriented cultures, the responsible person is the receiver. A transmitter orientation is more likely adopted by cultures that usually try to avoid uncertainty and therefore will not accept symbols that are very small, and hard to identify. Cultures scoring high on Hofstede's "uncertainty avoidance" [56] (p. 336) dimension usually tend to "shun ambiguous situations" [57] (p. 197). As expected, countries like Germany (score: 65; all scores are from [57] (pp. 192–194, Table 6.1)) and the Czech Republic (score: 74) score considerably higher than China (score: 30). We can therefore argue that while it is important for Germans or Czechs to discriminate all parts of a symbol without undue difficulty, it is enough for Chinese to identify a symbol as a whole, i.e., being able to match it with its counterpart in the key. Acceptable minimum symbol dimensions would then be considerably lower for Chinese than for Germans or Czechs.

Besides small size and readability issues, another difference might exist between Chinese and European point symbols regarding preferences for basic geometric shapes. Angsüsser [20] found more frequent use of circles and squares and near absence of triangles as point symbols in Chinese city maps compared to German city maps. On the other hand, diamonds were sometimes found in the Chinese sample while being absent in the German sample. As this shape has an important significance in China's everyday life (e.g., as an ornament or background for Chinese characters), we can assume that the three main geometric shapes in China are circles, squares, and diamonds, whereas in Germany and the so-called Western world, the circle, square, and triangle dominate.

5. Materials and Methods

5.1. Experiment

The general objective of the study was to observe the differences in how map symbols of various shapes and sizes were perceived and the influence of different map backgrounds and cultural backgrounds. The experiments were based on the theories [3,8] and experiments [34] described in the first section. From the previous research, we hypothesized:

At the general level:

- Greater complexity of the map background significantly decreases the speed of processing map stimuli during the search task.
- Increasing size significantly increases the speed of processing map stimuli during the search task.
- The shape of the point symbol does not significantly influence the speed of processing map stimuli during the search task.

At the cultural level:

- Chinese are faster than Czechs in search tasks performed with small map stimuli.

5.2. Stimuli

The test consisted of two parts, each using a different type of visual stimuli. Both types of stimuli differed in the presence or absence of a background map. While the stimuli in the first part of the test were free of any background map and contained only point map symbols, the visual stimuli in the second part also contained a background map (Figure 4 as an example).

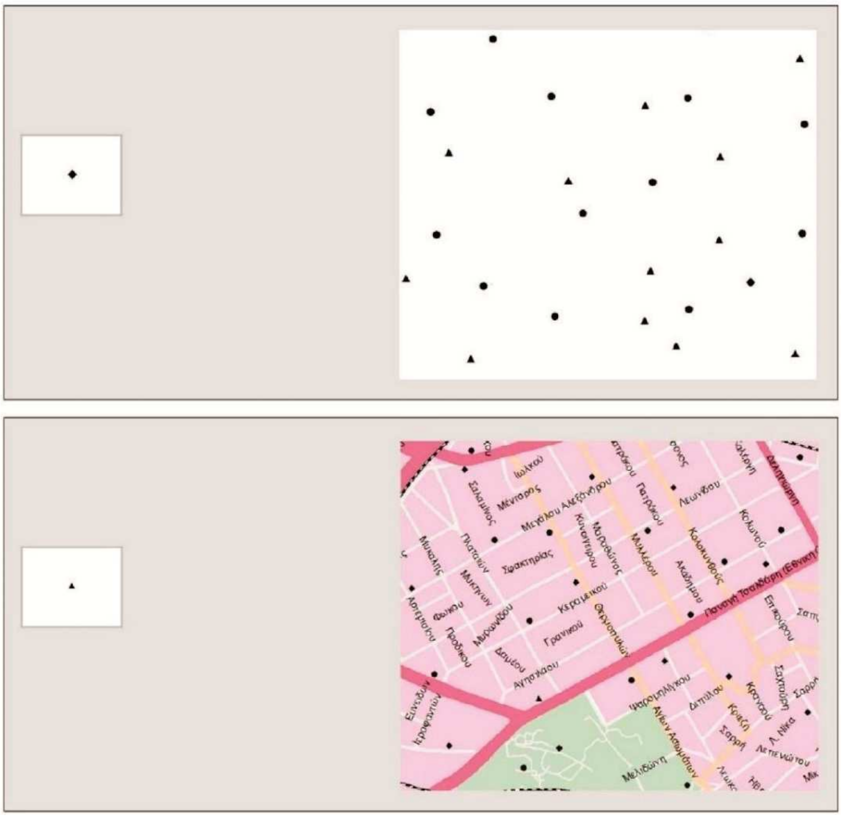

Figure 4. Differences in the stimuli used with and without a map background (task instruction: find the shape shown at the left side of the screen).

The point symbols used, which were identical for each of the presented tasks, were simple geometric symbols in black color: a circle, a triangle, and a diamond (square rotated by 45 degrees). The use of three different shapes should have provided enough elementary shape diversity, generally typical for a cartographic visualization, which may have also helped increase the ecological validity of the experiment. Each task contained 25 point symbols that were randomly placed in the map field, one symbol being the attractor and the other 24 symbols being distractors, i.e., symbols with a shape different from the attractor (12+12 symbols of both remaining shapes). Eight sizes were used for each symbol, each differing in size by 1 pixel (from 6 pixels to 13 pixels). The absolute dimensions calculated from the pixel size of used 22 inch monitors varied from 1.68 mm to 3.64 mm. The first three categories (6, 7, and 8 pixels) close to the limits defined by Koláčný (Figure 2) were considered as small, two middle categories (9, and 10 pixels) as medium size and the last three categories (11, 12, and 13 pixels) as large. The sizes of the symbols were designed to accommodate 24 tasks and combined both parts of the test. Tasks in the first part did not include any background. Tasks in the second part of the test included a background map covering a randomly chosen area with different proportions of built-up and un-built areas. For the 24 tasks with map backgrounds, 24 different map sections were used, identical for both cultural groups. For these purposes, we used OpenStreetMap data (of a Greek city) that were visualized to be distinct from the most commonly used web map portals of either cultural group (i.e., Google maps and Mapy.cz for the Czech group; Baidu maps for the Chinese group).

5.3. Participants

To analyze the speed of detection of selected graphic variables in a cartographic visualization, we gathered data from two groups (Czech and Chinese) of participants (69 participants in total) in our study. The first group, located in Brno in the Czech Republic, consisted of 33 participants (57.5% males). All the participants were Czech citizens and cartography and GIScience students at Masaryk University (2nd and 3rd year of bachelor's degree) in the Czech Republic. The second group consisted of 36 participants (41.6% males). Participants of the second group were Chinese students of GIS (3rd year of bachelor's degree) from the University of Wuhan in China. The mean age of all participants was 21.3 years (SD = 1.2 years). The mean age of the Czech group was 21.6 years (SD = 1.4 years) and the mean age of the Chinese participants was 21 years (SD = 0.80 year). Based on the information given by the participants, they all had normal or corrected-to-normal vision. All participants took part in the experiment voluntarily and were told that the better half of each group would be rewarded with a small gift (which was identical for both groups).

The minimum sample size was calculated using G*Power 3 [58] for repeated measure ANOVA with within–between interactions (medium effect size f = 0.25, $p = 0.80$, $\alpha = 0.05$, number of groups = 2, number of measurements = 3, and estimated correlation between measurements = 0.3). The required total sample size was estimated to the minimum of 38 participants. From this perspective, the number of tested participants was sufficient to provide the adequate test power.

5.4. Procedure

The test started with a short questionnaire requesting basic personal information (age, sex, nationality, education, etc.). The two parts of the map reading test were then presented to respondents. Both parts consisted of 24 stimuli. Altogether, the test presented 48 stimuli (Figure 5).

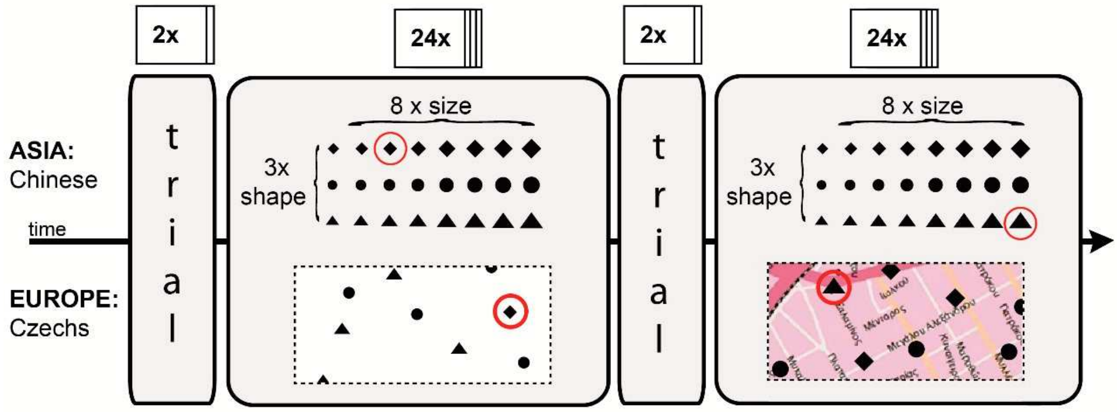

Figure 5. Schema of the procedure used for testing.

Each respondent conducted the entire test via the interactive web-based application *Hypothesis*, which was designed to aid in creating and administering effective visual perception and cognitive tests. For more information about the application, see Šašinka et al. [59] and Popelka et al. [60]. Both Czech and Chinese participants conducted the test using this application. We attempted to create the same ambient conditions for testing, such as similar lighting conditions and the same number of participants tested at one time (usually 15 participants). Nevertheless, we could not absolutely exclude other factors that may have influenced the results. The most challenging task was to provide the same stability for the internet connection at both locations. This was the reason for excluding several Chinese participants from further analysis. Additionally, several participants in China did not complete the test and were therefore removed from further analysis.

6. Results

Data analysis was performed using IBM SPSS Statistics 22 statistical software. Prior to data analysis, an outlier analysis was performed on the reaction times for each of the 48 items. Based on outlying reaction times (values below Q1-1.5 IQR or above Q3+1.5 IQR), 169 data points were deleted from the data matrix. The number of deleted values in each item varied between 0 and 10; the mean number of deleted values per item was 3.5.

As mentioned above, the size of the point symbols in the test items varied (eight size levels). We calculated the average time required to identify the items that contained the three smallest and the three largest point symbols. The items that contained the two medium-sized point symbols were eliminated from further analysis. We analyzed the mean reaction times for each type of stimuli (background—no background, and map background; size of point symbol—large, and small; shape of point symbol—circle, triangle, and diamond). We also calculated the overall mean reaction time for each participant and performed a stepwise linear regression with backward elimination, including gender and nationality as explanatory variables and overall mean reaction time as a dependent variable. We did not include age in the model because of its low variance. Gender was not a significant predictor of overall reaction time. A significant regression equation ($F(1, 67) = 18.59$, $p < 0.001$, $R^2 = 0.35$) was found for nationality as a predictor of point symbol detection speed. Descriptions for stimuli with and without map backgrounds, combined point symbol size and shape, and shape are in Figures 6 and 7 and Table 2 respectively.

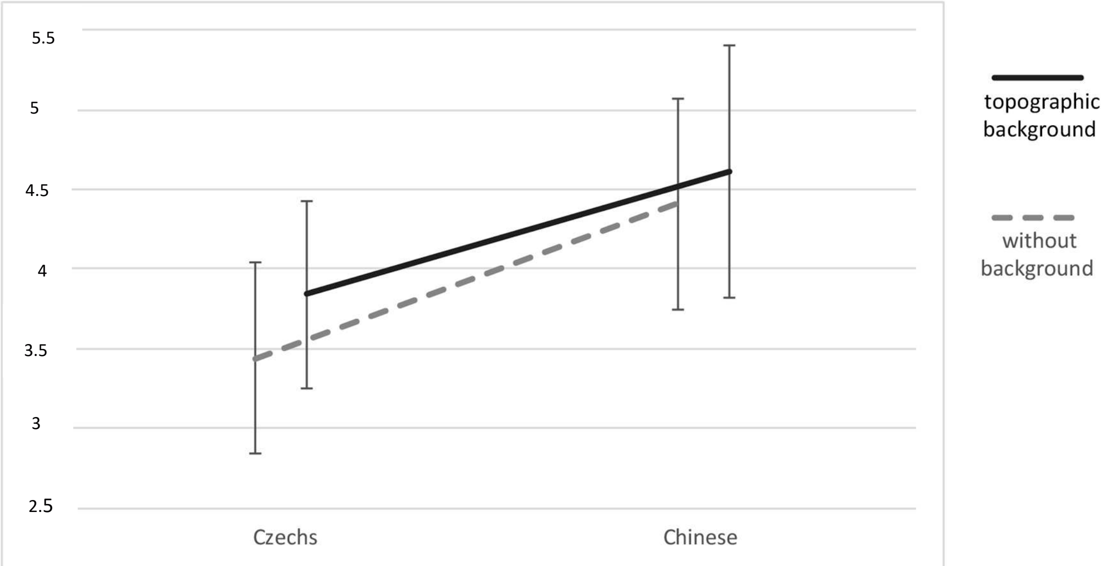

Figure 6. Comparison of mean detection times with background and without background (in seconds, N = 69).

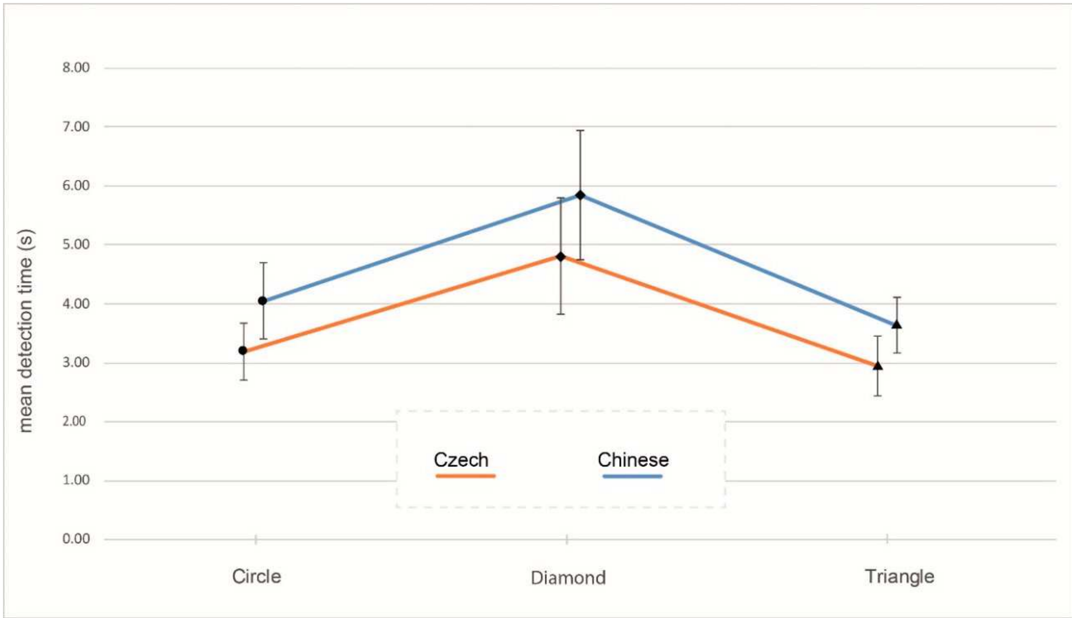

Figure 7. Mean detection times regarding point symbol shape (in seconds, N = 69).

Table 2. Mean detection times regarding point symbol size (in seconds, N = 69).

Symbol Size	Group	All Shapes: Mean Time (SD)	Circle: Mean Time (SD)	Diamond: Mean Time (SD)	Triangle: Mean Time (SD)
Small	Chinese	5.24 (0.93)	4.88 (0.99)	7.06 (1.73)	3.75 (0.52)
	Czech	4.19 (0.72)	3.75 (0.77)	5.85 (1.57)	3.12 (0.62)
	Total	4.74 (0.98)	4.34 (1.05)	6.48 (1.75)	3.45 (0.65)
Large	Chinese	4.25 (0.60)	3.81 (0.58)	5.51 (0.96)	3.75 (0.66)
	Czech	3.37 (0.59)	3.01 (0.49)	4.15 (1.16)	3.03 (0.65)
	Total	3.83 (0.74)	3.43 (0.67)	4.67 (1.17)	3.40 (0.75)

The results show that reaction times were generally higher for items with a topographic background (M = 4.24 s, SD = 0.79 s) compared to items with no background (M = 3.95 s, SD = 0.79 s). The results were consistent across the subsamples. Czech participants were faster in both conditions (Czechs: no background, M = 3.44 s, SD = 0.60 s; with a topographic background M = 3.84 s, SD = 0.59 s; Chinese: no background, M = 4.41 s, SD = 0.66 s; with a topographic background, M = 4.61 s, SD = 0.79 s; see Figure 6).

Reaction times were generally higher for items with small point symbols (M = 4.74 s) compared to items with large point symbols (M = 3.83 s). The results were consistent across subsamples. Czech participants were faster in both conditions.

Diamonds had the highest mean detection times (M = 5.35 s) in the entire sample. The mean detection time for circles (M = 3.64 s) was slightly higher than for triangles (M = 3.30 s). The patterns of detection speed for diamonds, circles, and triangles were consistent across nationalities.

To test the above-mentioned hypotheses, we subjected the mean reaction times to a series of repeated measurements ANOVA, with nationality as a between-subjects factor (nationality—Czech vs. Chinese) and one within-subjects factor (background—no background vs. topographic background; symbol size—small vs. large; symbol shape—circle vs. diamonds or vs. triangles, etc.). Because of the number of groups (2), post hoc tests were not performed.

As predicted, we found that respondents detected symbols on a blank background (M = 3.95 s) significantly faster than symbols on a topographic background (M = 4.24 s), $F(1,67) = 20.86$, $p < 0.001$, $\eta p^2 = 0.24$. We also found a significant between-subject effect in the Czech respondents, who were faster than the Chinese, $F(1,67) = 34.93$, $p < 0.001$, $\eta p^2 = 0.34$. The effect of interaction between the background type and nationality was not significant.

Furthermore, we found an expected significant relationship between the speed of detection of small and large point symbols. Large point symbols (M = 3.83 s) were detected universally faster than small point symbols (M = 4.74 s), $F(1,67) = 130.24$, $p < 0.001$, $\eta p^2 = 0.66$. Again, Czech respondents detected the symbols faster than the Chinese, $F(1,67) = 38.10$, $p < 0.001$, $\eta p^2 = 0.36$. The effect of interaction between symbol size and nationality was not significant.

Finally, we tested for the potential effects of symbol shape on the detection speed. The detection of triangles was significantly faster in both background conditions (M = 3.30 s), followed by circles (M = 3.64 s), and then diamonds (M = 5.35 s), $F(1.5,100.8) = 300.1$, $p < 0.001$, $\eta p^2 = 0.82$ (Greenhouse-Geisser correction was applied due to the violations of sphericity). Czech respondents were significantly faster in detecting all point symbol shapes, $F(1,67) = 34.93$, $p < 0.001$, $\eta p^2 = 0.34$. The effect of interaction between symbol shape and nationality was not significant.

7. Discussion and Conclusions

The results of the study show significant differences in the speed of perception of the investigated graphic variables (size and shape) of basic geometric figures presented with and without map backgrounds. Consistent with the first hypothesis (see Section 5.1), we found that the effect of a topographic background on user performance significantly increased the time spent on the task. This finding corresponds to the findings of Koláčný [34] in that reading speed significantly decreases with increasing graphic density of the map (Figure 3).

In terms of point symbol size (second hypothesis), we concluded that increasing symbol size brings a positive effect on lessening the time required to complete a task. Significant differences were observed between the small (6–8 pixels) and large point symbols (11–13 pixels). As the small symbols were close in size to the smallest possible symbol sizes identified by Koláčný [34], we concluded that smaller sizes have only limited usability for application in cartographic visualization.

Furthermore, based on the results, we claimed that certain shapes (third hypothesis) do not provide the same degree of comprehension, and therefore the shape itself affects the way how it is perceived. This conclusion sheds new light on the results published in Koláčný [34], Garlandini and Fabrikant [36] and others. This effect is demonstrated by statistically significant differences between circles/triangles and diamonds. The significantly poorer results with diamonds may have possibly been caused by the oblique effect mentioned by [29,30]. This finding is applicable in several ways. For example, when maps are used in time-critical situations like human and natural disasters, certain symbol shapes should be omitted or used only for the less important parts of the map content. A brief, worldwide analysis of map legends used for emergency management was conducted earlier by Dymon [61] and recently by Leitner [62]. Seven out of the nine analyzed map legends for emergency management purposes used diamonds for important map content (e.g., incidents, hazards, and units). According to our results, this might slow down the process of decision-making.

Another issue requiring discussion is the consistent differences in the speed of detecting target point symbols between the Czech and Chinese participants. The fact that Czech participants were universally faster in all conditions (our hypothesis was disproved) could be explained in several ways, such as the presence of a method bias [63], differences in motivation, different instructions (with regard to the task-solving speed), differential familiarity with this type of task, sample bias, or the presence of an interviewer effect.

Alternatively, it could be explained by genuine differences in the performance or perceptual style (e.g., attention to the field or field dependence; [54]). In this case, we would expect at least the presence of the main effect in no background vs. with background conditions according to the holistic vs. analytic attention paradigms. To be able to unequivocally interpret the differences in performance of both groups as the existence of genuine differences in the cognitive style during point symbol detection, more than two cultural groups would have to be compared in future research, with more variable research samples used, and more individual (e.g., perceived social class) and group level (such as affluence or religion) variables gathered and included in the statistical model.

The weaker performance of the Chinese participants sheds new light on the discussion about the very small point symbols often used in Chinese city maps [44] (see Section 4). Our results do not support the "trained eyesight" thesis assuming an increased visual acuity of Chinese people. More likely, cultural factors like the discussed communication orientation and uncertainty avoidance, among others, might play an important role. However, this research is still in an early stage and many potential influencing factors have not yet been tested.

We are aware that there are several limitations of this study. At first, even if the number of the participants is sufficient (see Section 5.3), there is still the issue of the specific user groups used for the study. As most of the participants were relatively young university students, it is debatable if the results are valid universally or only for a particular user group. Secondly, the majority of the participants have a background in geography or related fields which might also have influenced the results.

The presented study follows the research line focused on the cross-cultural differences in map perception. This paper ties up with the recently published study by Stachoň et al. [43] in some respects. We have also conducted an identification task on Czech/Chinese populations, but focused on different characteristics of point symbols, i.e., three geometric shapes varied by size instead of several pictorial symbols varied by degree of schematization. Despite these differences, the Czech participants were faster than the Chinese participants in both studies. A possible reason for these results might be differences in cognitive styles of the two tested groups. However, the framed-line test conducted by Stachoň et al. [43] did not support this hypothesis. In the research presented here, no test assessing cognitive style was included. Although the participating student groups were somewhat similar (age, education, etc.), we do not have valid information about our groups' cognitive styles. If we assume the same cognitive style prevalence found in [43], i.e., Czechs are more holistic than Chinese, this again would contradict our assumption that such identification tasks are completed faster by participants with a more analytic cognitive style. However, the presence of a topographic background would slow down holistic thinkers more, and indeed the Czech participants showed a stronger, although not significant, decrease in the detection speed than the Chinese participants (but Czechs were still faster than Chinese; see Figure 6). These contradictory results again show the need for a deeper scientific investigation, not only focusing on the cross-cultural differences but also on the role of cognitive styles in such tasks.

The obtained results support and extend the previous findings and also bring new directions for future research. Interesting topics are, for example, the comparison of more complex shapes routinely used in cartographic symbolization or the perception of cartographic information by people with different ages, education or profession levels. We are also planning an extension of the experimental sample to include worldwide participants for a better understanding of the identified differences.

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RESEARCH ARTICLE

A comparison of the performance on extrinsic and intrinsic cartographic visualizations through correctness, response time and cognitive processing

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Abstract

The aim of this study was to compare the performance of two bivariate visualizations by measuring response correctness (error rate) and response time, and to identify the differences in cognitive processes involved in map-reading tasks by using eye-tracking methods. The present study is based on our previous research and the hypothesis that the use of different visualization methods may lead to significant cognitive-processing differences. We applied extrinsic and intrinsic visualizations in the study. Participants in the experiment were presented maps which depicted two variables (soil moisture and soil depth) and asked to identify the areas which displayed either a single condition (e.g., "find an area with low soil depth") or both conditions (e.g., "find an area with high soil moisture *and* low soil depth"). The research sample was composed of 31 social sciences and humanities university students. The experiment was performed under laboratory conditions, and Hypothesis software was used for data collection. Eye-tracking data were collected for 23 of the participants. An SMI RED-m eye-tracker was used to determine whether either of the two visualization methods was more efficient for solving the given map-reading tasks. Our results showed that with the intrinsic visualization method, the participants spent significantly more time with the map legend. This result suggests that extrinsic and intrinsic visualizations induce different cognitive processes. The intrinsic method was observed to generally require more time and led to higher error rates. In summary, the extrinsic method was found to be more efficient than the intrinsic method, although the difference was less pronounced in the tasks which contained two variables, which proved to be better suited to intrinsic visualization.

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Introduction

The awareness that maps serve as tools for the creation of mental representations of the world and cannot therefore be considered transparent or direct depictions has long been discussed in cartography [1]. As a research topic, the cognition of maps is rooted in the early twentieth century [2]. A key question is how a particular form of cartographic visualization affects the effectiveness of cartographic communication [3–5]. The same data can be represented by different cartographic visualization methods. An unsuitable method not only reduces performance but also places various requirements which correspond to the type of cartographic visualization on different types of users and tasks [6, 7]. User characteristics (such as cartographic skills, [8, 9]) and the type of task [10, 11] must therefore be considered when we conduct empirical studies on the performance of alternative visualizations.

The primary aim of the present study was an empirical and objective comparison of two alternative bivariate visualizations (Fig 1) to assess the performance of a selected population which possessed a basic level of cartographic skill [12–16] through two different types of task. Another aim was to understand the cognitive processes which underlie the potential differences in objective performance [17–20].

Olson [21] stressed that maps are considered highly valuable visual stimuli in experimental psychology since the variables they represent can be accurately controlled. The manner of presenting geographic information can have a significant effect on user cognitive processing (internal mental processes) during map-related tasks. Larkin and Simon [22] presented the concept of informational and computational equivalence and argued that different visualizations can be informationally equivalent if all the information available in one of them is available in the other, and vice versa. The establishment of informational equivalence between bivariate cartographic visualizations permits us to investigate the extent of computational equivalence between the two.

Cartographic visualization offers numerous methods of presenting geographical data. These methods differ in their ability to visualize certain data types, the level of detail they provide, and the number of variables they simultaneously portray [23]. The graphic display of multiple geographic phenomena is known as multivariate mapping [24], and its purpose is to investigate the relationships between the given phenomena. Bivariate maps encode two separate variables simultaneously [25]. Bivariate mapping can be further divided into extrinsic (the variables carrying the information are visually separable) and intrinsic (the variables are visually inseparable [26]).

The present study applies both extrinsic and intrinsic bivariate encoding of geographic variables (Fig 1) to investigate the cognitive processes of map users.

The extrinsic bivariate method employs two visually distinct variables (the differences may represent, for example, size, shape or color lightness) to display two different geographical phenomena, such as soil depth and moisture. In the present study, each of the two phenomena had three levels of intensity (low, medium and high), which provided a total of six options in the map legend (Fig 1, EN1 left). From the map legend, the map users were required to create a mental representation of nine possible combinations (Fig 1, EN2 center). Intrinsic bivariate visualizations apply visual variables which are visually inseparable (typically, the visual variables include hue, color lightness and opacity), resulting in a map legend comprising nine combinations (Fig 1, IN right). In this latter case, the map legend was identical to the mental representation of all the possible combinations. Although, color lightness, hue and opacity are considered to interact with each other in the psychology of perception [27–29], cartography regards them as mutually independent entities [30]. Therefore, in cartography, these parameters are used as independent visual variables.

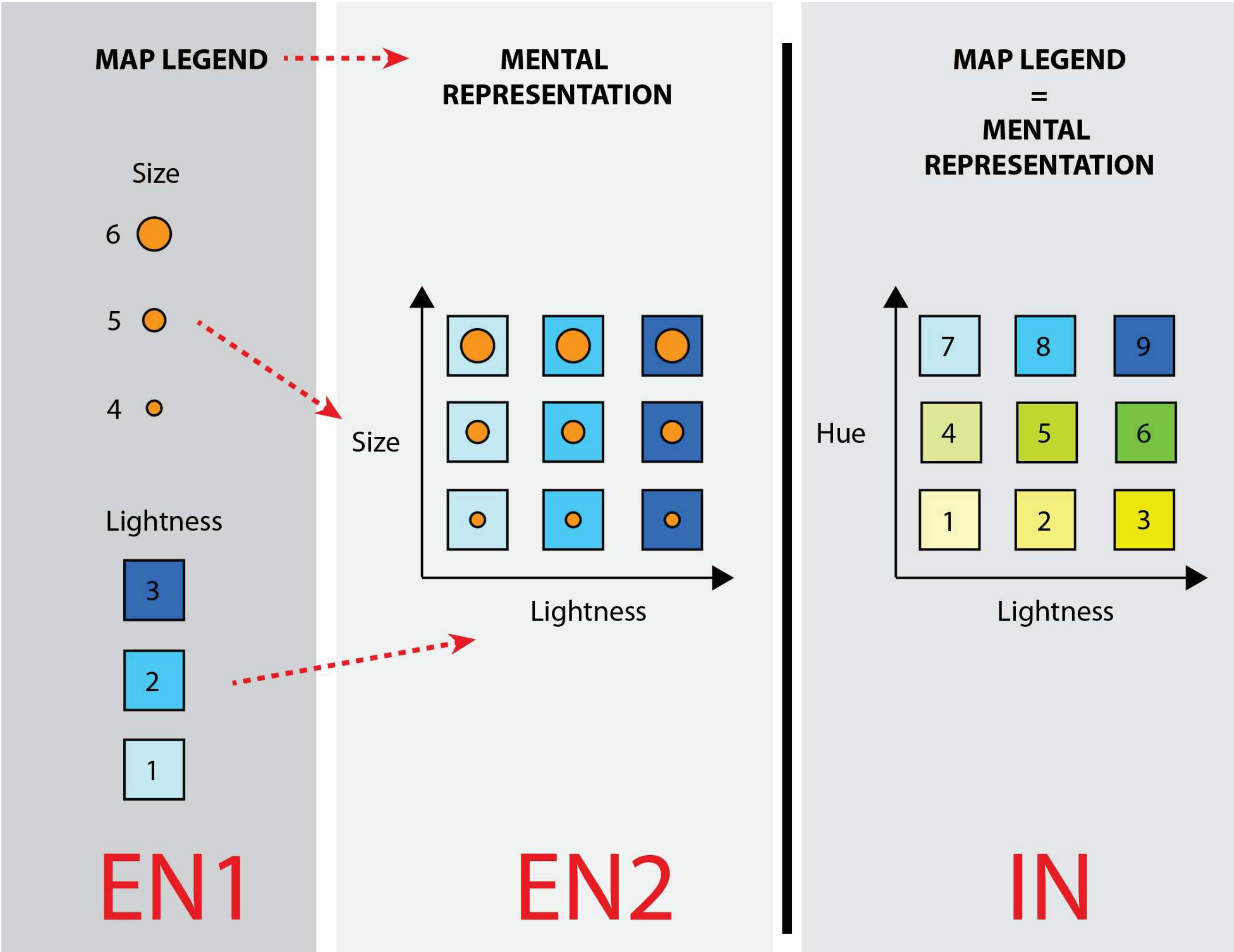

Fig 1. Examples of extrinsic and intrinsic bivariate encoding of geographic variables. EN1: extrinsic (separable) encoding of variables according to size and color lightness; EN2: mental representation of extrinsic visualization (all the possibilities); IN: intrinsic (inseparable) encoding of variables according to hue and lightness.

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Each visualization type can be expected to induce a different cognitive and perceptual load on the user [31–33]. The differences in cognitive processing relate to selective attention theory, which specifies that only a limited number of elements can be processed at one time [34]. The perception aspect can be explained according to pre-attentive visual processing theory [35, 36]. Some visual elements, designated pre-attentive, can be detected in a single glance and thereby serve as the central components of a visualization. In map reading, pre-attentive elements can aid in identifying boundaries and detecting the presence or absence of other elements; for example, size (an extrinsic variable) is pre-attentive, while lightness (an intrinsic variable) cannot be considered a pre-attentive feature. Since the processing of extrinsic and intrinsic visual elements is not only based on perception but involves a broader cognitive context, it appears reasonable to assume that the situation will be more complex when both extrinsic and intrinsic visual variables are employed.

Bivariate mapping and the use of various visual variable combinations have been the subject of numerous research studies [e.g., 21, 37–42]. Elmer conducted an extensive comparison of

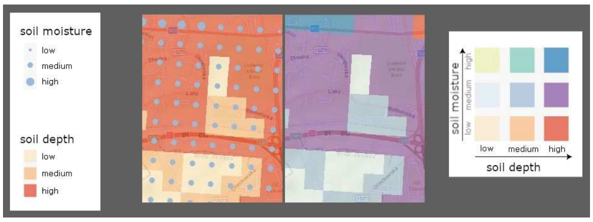

Fig 2. Examples of extrinsic visualization (left) and intrinsic visualization (right) used in the study. Legends for both extrinsic and intrinsic visualization are also given. Areas with identical values are depicted with two different encoding systems to enable a visual comparison of the differences between each visualization.

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visual variable combinations [43]. Kunz studied the use of bivariate visualization methods (extrinsic and intrinsic) to produce visualizations of natural hazards (avalanches) and the levels of uncertainty in the presented data (avalanche hazard prediction) [44]. Šašinka et al. investigated the differences in processing intrinsic and extrinsic visualizations, focusing mainly on cognitive style and map reading skills [45]. The results of the study (and of related eye-tracking studies) revealed significant differences between extrinsic and intrinsic visualizations associated with both map-reading performance and task processing. Although the aim of the study was not to compare methods of visualization, the results showed that a group of laypersons (psychology students) worked more effectively with the extrinsic method, while participants with better map reading skills (cartography students) demonstrated better performance using intrinsic visualization.

However, the authors noted an important limitation in their study, consisting in a relatively sophisticated topic (avalanche risk and its uncertainty) which the participants (especially psychology students) may have found difficult to understand.

The present study was designed based on the results of the above studies. The stimulus material included two bivariate maps with the same content; an example is shown in Fig 2. We selected soil depth and soil moisture as suitable phenomena for depiction since they are considered generally comprehensible and quantifiable. Information gathered from volunteers informed our selection of the topic during the experiment design process. It was critical that participants intuitively understood the relationship between the visual variables and the depicted phenomena in the legend's design. We followed the principle of cultural metaphors and applied a visual representation of the data to match the metaphors which aid conceptual thinking [6, 46]. We used a combination of color and size for extrinsic visualizations and different colors for intrinsic visualizations. Fig 2 illustrates examples.

Methods

To compare the performance of working with maps which use different cartographic visualizations, we conducted an experiment with two tests (one for each of the two selected methods of visualization); for more details of the research design, see Fig 5. We applied a combination of confirmatory and exploratory data analysis methods [45, 47, 48].

The confirmatory analysis tested our hypotheses on the differences between extrinsic and intrinsic visualizations in map reading performance. The data collected were response time and correctness (as investigated by Elmer [43]). Several evaluation methods and concepts allow the measurement of user performance with an information system [49]. The most common parameters are effectiveness and efficiency. According to ISO 9241–11 [50], effectiveness is defined as the "accuracy and completeness with which users achieve specified goals", and efficiency corresponds to the necessary resources (e.g., time) to achieve a desired result. We calculated effectiveness as the rate of correctness and efficiency as the task completion time [51]. The aim of the exploratory analysis of the eye-tracking data [52] was to gain deeper insight into the differences between the visualizations at the level of individual elements and to employ eye-tracking as a means of collecting objective data [53–55]. Eye-tracking is a valuable tool for studying eye behavior which occurs during map reading since it provides objective measurement of the visual strategies employed by map readers. The review article from Krassanakis and Cybulski [56] provides an overview of existing eye-tracking studies which have appeared in cartographic research over the last decade. The review showed that cartographers used eye tracking mainly in the evaluation of cartographic symbolization and design principles.

Map and items design

The task layout was identical in both tests (Figs 3 and 4): instructions for the tasks were displayed in the upper area of the screen, the map legend was at the right, and the visual field of the map was in the center. The lower area of the screen displayed a button bar with four possible selections for the correct answer. The participants selected an area which satisfied the given condition (e.g., "Find the area with low soil moisture."). In subtest A (Fig 3), the marked areas covered four square units; in subtest B, the marked area only covered one square unit (Fig 4). To answer the questions, participants were required to click on the correct button. Only one correct answer was possible.

We generated the visualization using ArcMap (version 10.7) using the color schemas from ColorBrewer 2.0 [57]. The extrinsic visualization used three circle sizes (6, 10 and 14 pts; #deebf7) to indicate soil moisture, and three color classes (#fee8c8, #fdbb84 and #e34a33) to indicate soil depth. The colors were selected to suit a realistic representation of the phenomena as they occurred in reality, such as blue for moisture and brown for soil depth. Three colors were used to create the intrinsic visualization (A: #e0f3db, #a8ddb5, #43a2ca; B: #e0ecf4, #9ebcda, #8856a7; C: #fee8c8, #fdbb84, #e34a33). A brown color scheme was used to indicate dry areas, and green-blue was used to indicate wet areas. Soil depth was indicated using a geographical principle, darker shades representing greater depth. All colors had a transparency of 40% to allow the base map to be visible. To create the base map, OpenStreetMap data was used [58].

Procedure

The study was designed to illustrate the effect of various types of task. As mentioned in the introduction, we evaluated the maps / visualizations according to their purpose. We therefore designed the study to depict two types of phenomena. In the first scenario, the aim was to answer a question which related to only one variable (either soil moisture or soil depth). In the second scenario, participants were required to think about both phenomena in parallel. We assumed that the extrinsic method would be more suitable for an isolated assessment of phenomena because of its properties (both variables are presented separately through different visual qualities). The intrinsic method, however, is relatively more suitable for tasks which involve a unified search. Another reason for diversifying the task types (division into subtests 1 and 2) was to produce greater informative value and reliability in the achieved results. If performance of the extrinsic method possessed greater stability for each of the types in all tasks, the assumption that this method produces better results from the examined lay population would be more strongly supported.

The test involved a total of 30 items. The first parts of each subtest (A.1 and B.1) contained six items which focused on a single phenomenon (Fig 3). The items covered six possible

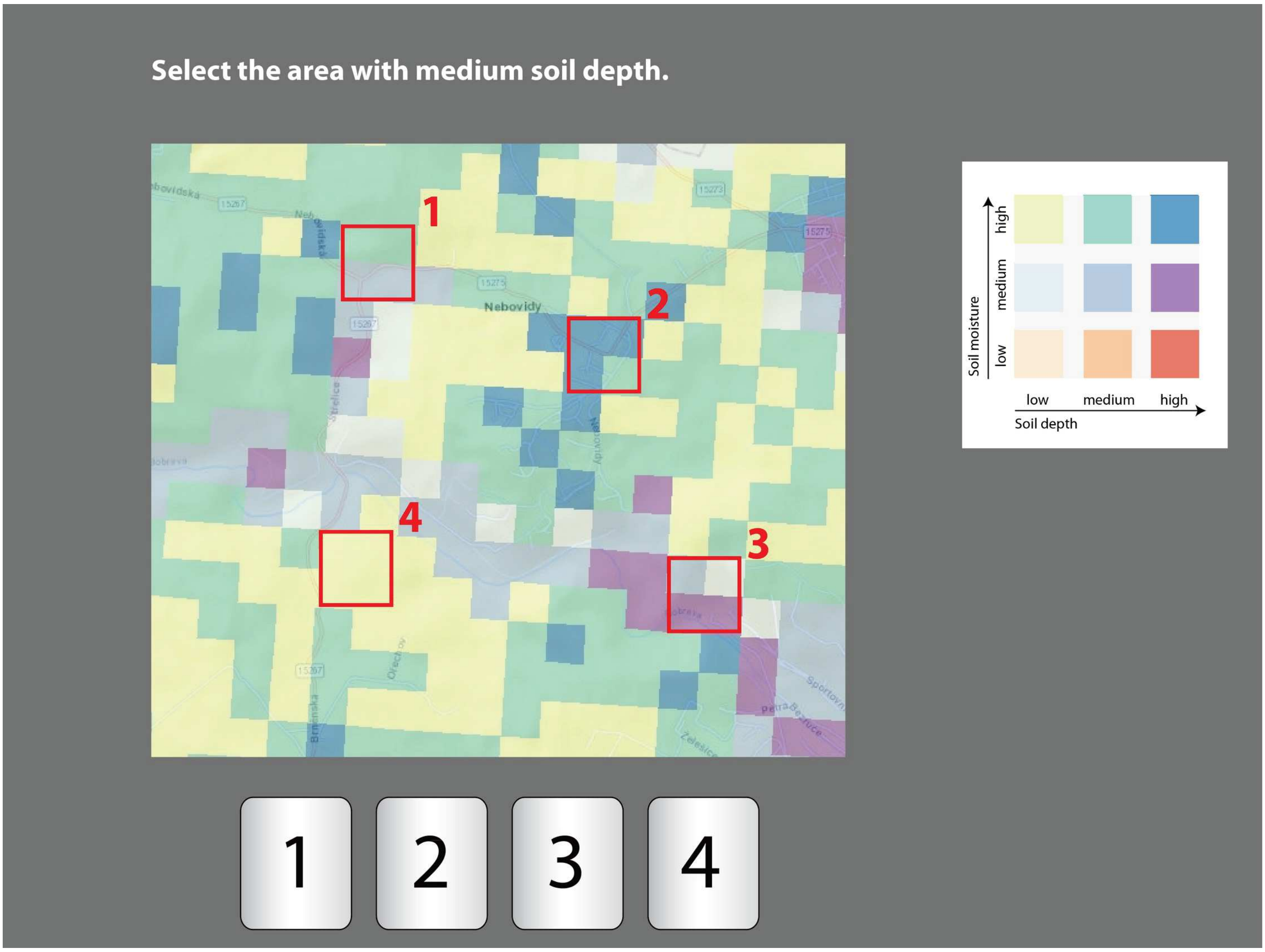

Fig 3. Example of an intrinsic visualization item (subtest A–part A.1.). The task was to select the area which contained "medium soil depth"; the correct answer was area No. 1.

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options: low, medium and high soil moisture, and low, medium and high soil depth. In the second parts of each subtest (A.2 and B.2), participants were asked questions about the two phenomena in each item item (Fig 4), with both A.2 and B.2 covering nine options (low moisture and low soil depth, low moisture and medium soil depth, etc.). We employed a between-subject design (Fig 5) to eliminate the effect of interference caused by experience with the given type of task.

Each participant completed an informed consent form, received a financial reward and was randomly allocated to one of the two research groups. Before the experiment, they were informed about the expected duration of the tests and given the opportunity to ask the experimenter questions. The instructions required the participants to work without interruption during the assessed part of the experiment. No participant required any additional explanation, and during a brief follow-up inquiry, no participant reported any problem in comprehending the content of the tasks. The participants received feedback on the correctness of their

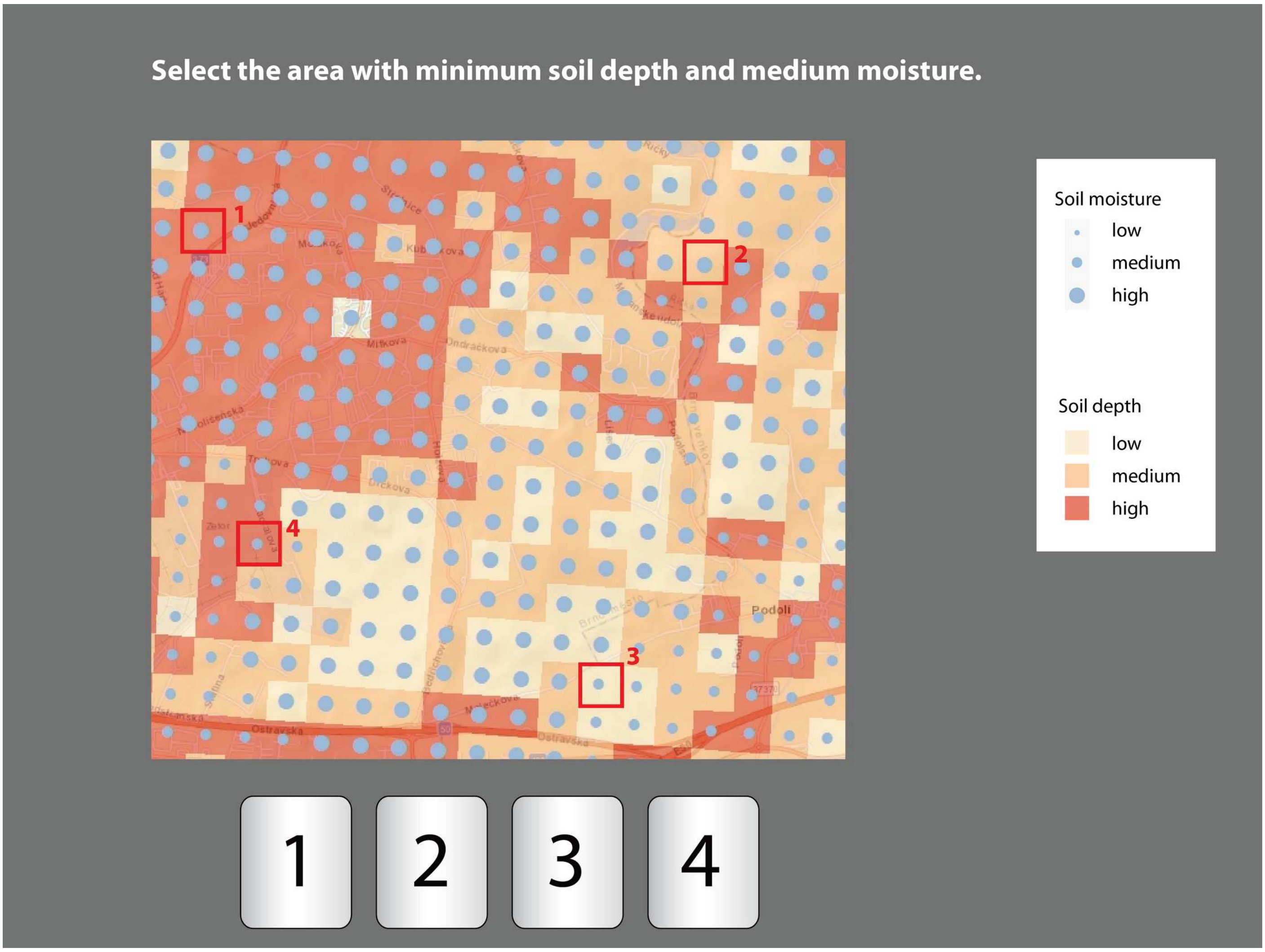

Fig 4. Example of an extrinsic visualization item (subtest B—part B.2). The task was to select the area which best satisfied the conditions of "low soil depth" and "medium soil moisture"; the correct answer was area No. 3.

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responses for the two sample items (one sample item was presented at the beginning of each subtest, A and B). No feedback was given during the assessed component of the tests. Each test item was preceded with a fixation cross displayed for 500 ms in the same position each time in the upper area of the screen.

Apparatus

The test was administered using a DELL Precision M4800 notebook with a 22″, 60 Hz AOC E2260P external monitor. The resolution was set at 4:3 (1024 x 768) to correspond exactly to the stimuli (Figs 3 and 4). The participants used a mouse to select their answers. The experimenter was present throughout the experiment to monitor its course. Mounted to the monitor was a remote SMI RED-m eye-tracker with a sampling rate of 60 Hz to collect eye-tracking data. Eye-tracking data collection, calibration and validation was done using the SMI Experiment Center 3.7 software. The calibration procedure was only considered satisfactory when

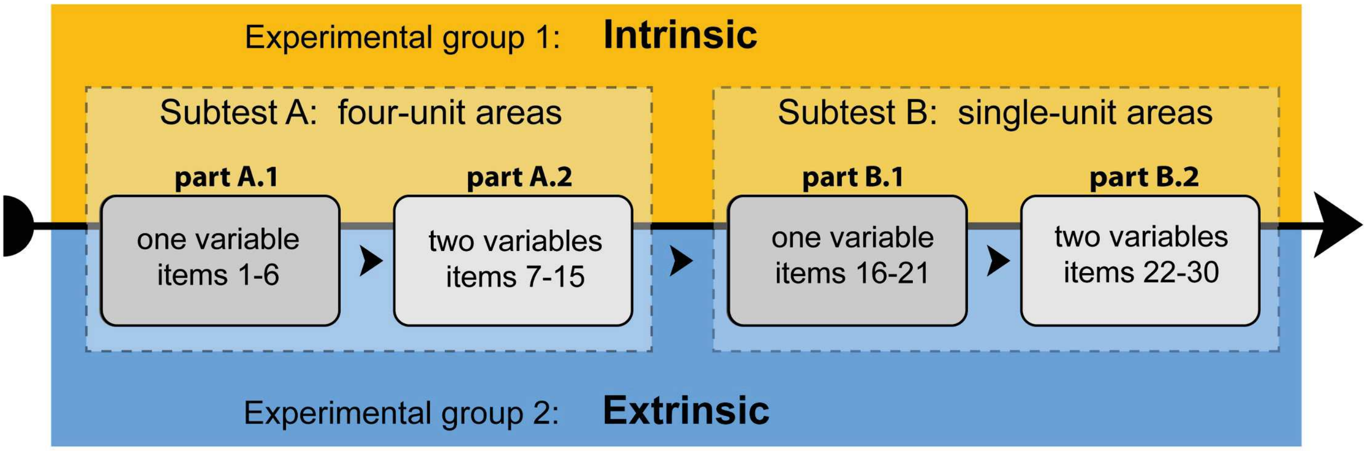

Fig 5. Between-subject experimental design (subtests A and B; parts A.1, A.2, B.1 and B.2). Both independent experimental groups, Intrinsic and Extrinsic, performed the test in exactly the same manner. The order of all items was constant for both groups, and all participants.

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the values returned by the eye-tracker were within 0.5˚. The experiment was administered using the Hypothesis software tool [45, 53] (a web-based tool used in research and psychological diagnostics [59]). The behavioral raw data were exported from Hypothesis in ".xlsx" format and then processed using *R* (version 4.0.0) with the "rstatix" [60], "rcompanion" [61] and "multicon" [62] packages. Because of the relatively small sample size, we incorporated several specific procedures in our analyses. First, we used non-parametric statistical tests (i.e., Wilcoxon's rank-sum test for independent samples and Wilcoxon's signed-rank test for paired samples), which do not require Gaussian data distribution and can process potential outliers. Second, we reported not only the related effect sizes (i.e., rank-biserial correlation; *r*) but also their 95% confidence intervals (*CIs*), which were computed on the basis of 10,000 bootstraps. Third, we computed 95% *CIs* for the descriptive statistics of means and medians. This step gave us deeper insight into the obtained results, especially with respect to the small sample size since *CIs* tend to be very wide in small samples, and therefore for reliability, any potential significant differences should not be permitted to overlap. Eye-tracking data were imported into the OGAMA 5.0 software and paired with the behavioral data via HypOgama [53]. The fixations were calculated using the I-DT model with the parameters set to the following values (as recommended by Popelka et al. [53]): maximum distance = 20 px, minimum number of samples = 5; "do not merge consecutive fixations".

Participants

The Research Ethics Committee of Masaryk University approved this project (No.: 0257/2018). Participants were recruited via social networks and each signed an informed consent form. They received a financial reward (approx. 8 euros) for participation in the study.

The research sample was composed of 31 students (8 males and 23 females), aged between 19 and 28 (m = 21.8, med = 21). The sample was randomly divided into an "intrinsic" group and an "extrinsic" group (block randomization was used). The former (intrinsic) group consisted of 15 students (2 males and 13 females; m = 21.4). The extrinsic group consisted of 16 students, 6 males and 10 females (m = 22.3). All the participants were students of social sciences and humanities (Faculty of Arts or Faculty of Social Studies) at Masaryk University. Students of geography and related fields were excluded from the study.

The eye-tracking part of the study yielded 23 datasets; for the remainder of the participants (8), no data were recorded during the session for technical reasons. The data were from 4 males and 19 females, aged between 19 and 28 (m = 22.22, med = 22). The "extrinsic" group was composed of 12 students; the "intrinsic" group consisted of 11 students.

After completing the experiment, we performed a quality check of the eye-tracking data. The total data loss was 2.65% for the extrinsic group and 4.1% for the intrinsic group. All items with a dropout rate of above 10% were excluded from the analysis: this was 22 data points (out of a total 330 data points) in the case of the intrinsic method and 6 data points (out of a total 360 data points) in the case of the extrinsic method. No participant was excluded completely (because of a high dropout rate throughout the test).

Results

We used several metrics which employ extrinsic and intrinsic methods of visualization to evaluate the differences between the groups in participant performance. We examined both behavioral (correctness, response time) and eye-tracking (dwell time, direct saccades) metrics. Details of the metrics calculations are specified in the respective section of the Results chapter. Non-parametric statistics were used to calculate the differences between and within the groups. A Wilcoxon rank-sum test was applied to compare independent groups (i.e., extrinsic vs. intrinsic); a Wilcoxon signed-rank test for dependent samples was used to compare performance between subtests. Effect size (r) was calculated for all results to determine the size of the differences [63].

A post-hoc sensitivity analysis of the differences between two independent means according to G*Power [64] ($1\text{-}\beta = 0.80$, $\alpha = 0.05$, $n1 = 16$, $n2 = 15$, two-tailed) showed that with the given sample, we would only be able to detect medium to large effect sizes with differences between the two groups greater than a standard deviation of 1 (non-centrality parameter $\delta = 2.899$, critical $t = 2.8987$, $df = 29$, $d = 1.042$). We therefore did not interpret any results with small effect sizes.

Split-half reliability coefficients performed on two random halves and adjusted with the Spearman-Brown prophecy formula were also calculated for each subtest. The results indicated that all the task subtests were reliable (mean of the split-half correlations for A1 = 0.847, A2 = 0.835, B1 = 0.889, and B2 = 0.736).

Correctness

Response correctness was one of the key parameters observed in the map-related tasks. Using the Wilcoxon rank-sum test, we compared the overall correctness of the responses related to the extrinsic and intrinsic groups. The extrinsic visualization showed a significantly higher overall correctness (N = 16, 96.3%) than the intrinsic visualization (N = 15, 90.0%), with a moderate effect size ($Z = 173$, $p = 0.031$, $r = 0.390$ [95% *CI*: .059, .656]). The results are charted in Fig 6.

We also investigated incorrect responses to explore the error rate at the level of individual items (i.e., the distractors selected). Particular attention was given to items with a significant difference between the two visualizations, namely items No. 1, 2, 9, 21 and 28 (Fig 7). In the case of all items with the exception of No. 2, the intrinsic method was associated with higher error rates (item No. 2 showed a reverse scenario). A plausible explanation of the above phenomenon was identified only with respect to item No. 21 (Fig 7). The item required the participants to select the area with the lowest soil depth. The correct answer was unit No. 1 (lowest soil depth/highest moisture). In the intrinsic visualization, participants tended to select unit No. 3 (medium soil depth/medium soil moisture), which can likely be explained by unit No. 3 being surrounded by a darker color and thus appearing lighter (see [65–67]) and could

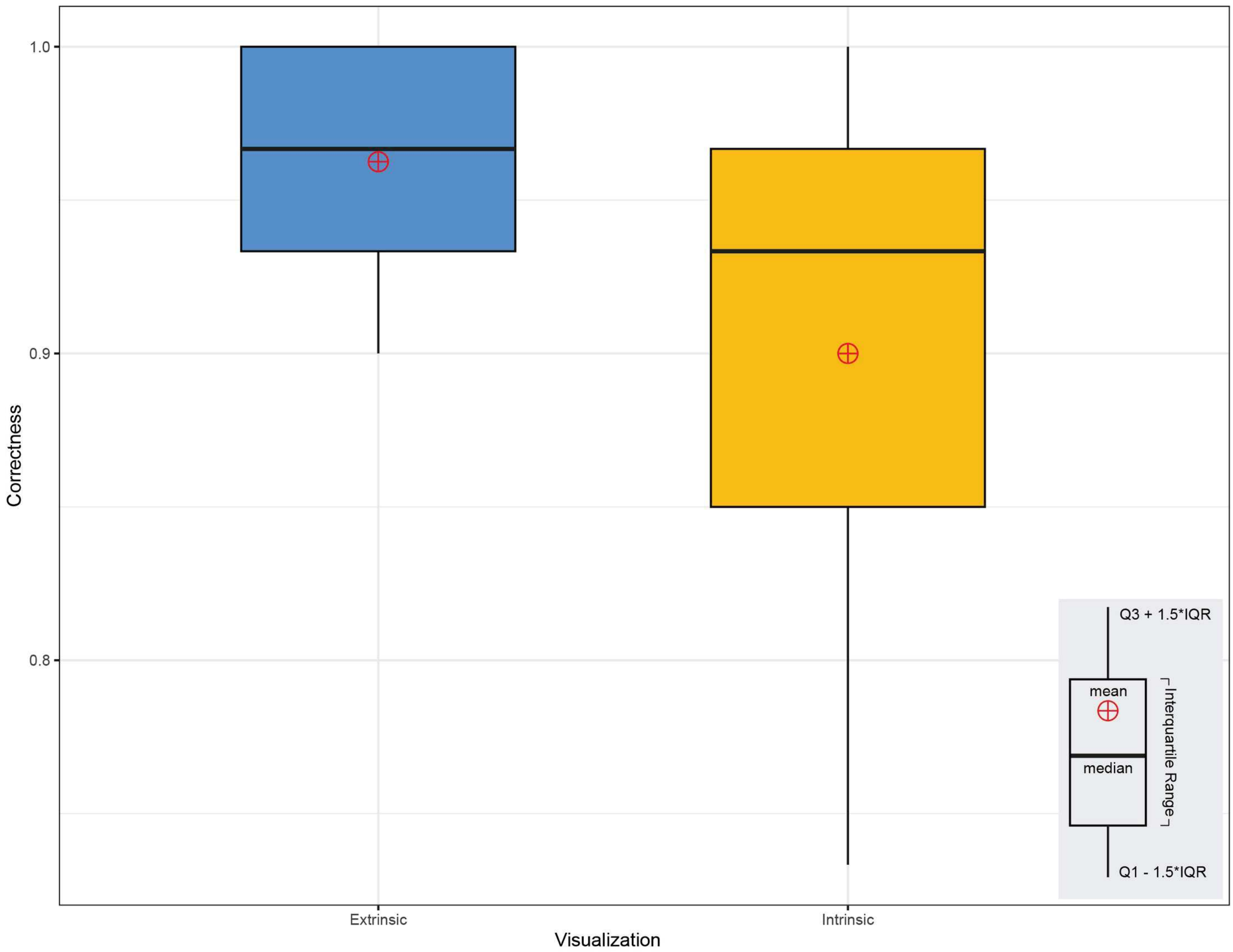

Fig 6. Response correctness for the entire test. Correctness was calculated as a ratio of the number of correct answers to the number of all answers.

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therefore have been misinterpreted as the neighboring value (lowest soil depth/medium soil moisture). We identified no other trends.

Response time

For a comparison of processing speeds (response times; RTs), we applied the Wilcoxon rank-sum test. For each subtest, we performed a separate univariate outlier analysis. The analysis revealed three cases of extremely long and irregular response times (over 20,000 ms, different participants) and were excluded from further analysis. However, reaction times are usually distributed ex-Gaussian and demonstrate a rapid rise on the left and have a long positive tail on the right [68, 69]; the traditional outlier detections (e.g., ± 2 SD or 1.5 IQR) are therefore not recommended [70] since these extreme values should not be understood as outliers. Hence, we decided to keep the remainder of the outliers and applied non-parametric statistical analyses

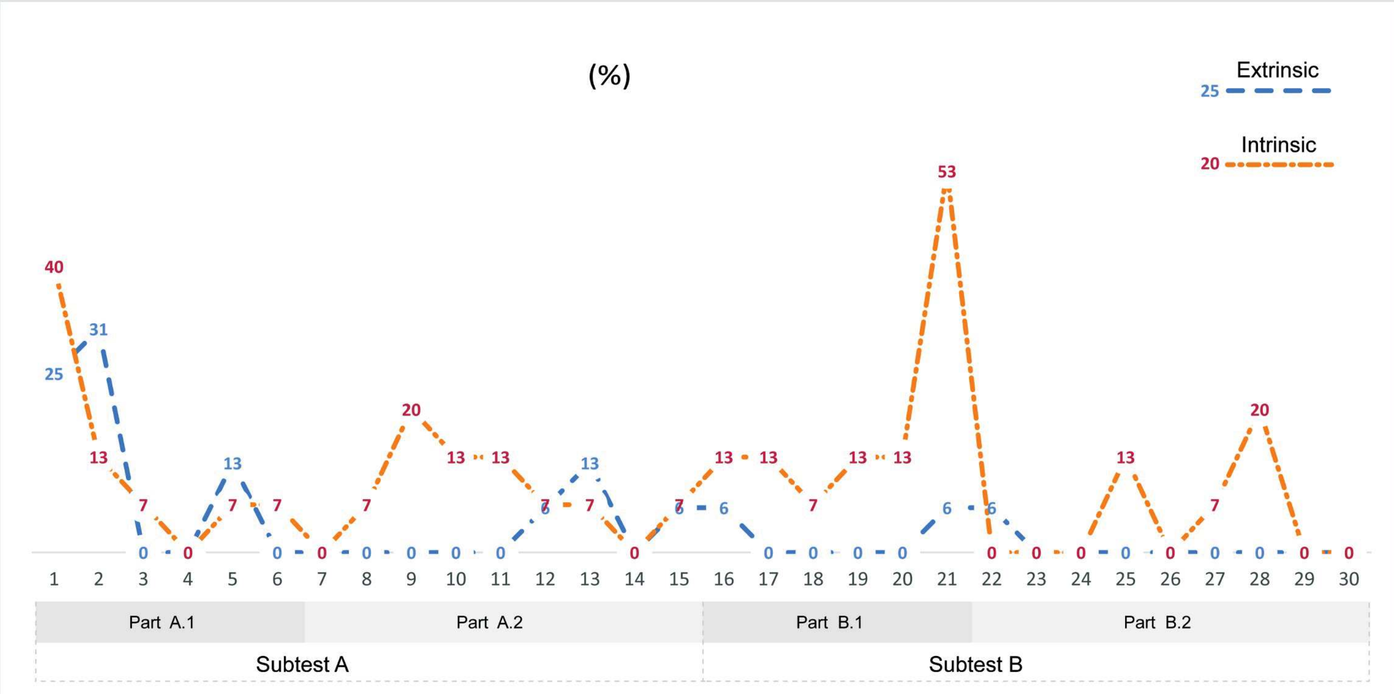

Fig 7. Error rate per item. INT–red/yellow, EXT–blue. Particular attention was given to items with a significant difference between the two visualizations (1, 2, 9, 21, 28). The error rate was calculated as a percentage of incorrect answers of all answers.

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instead. The response time analysis therefore covered both correct and incorrect answers. The total response time was significantly less for the extrinsic method (N = 16, median = 6.494 ms [95% *CI*: 5536, 8726]) than for the intrinsic method (N = 15, median = 10.217 ms [95% *CI*: 9588, 11597]), with a large effect size (Z = 12, $p < 0.001$, $r = -0.767$ [95% *CI*: -0.844, -0.607]; see Fig 8 and Table 1).

The same pattern was observed in a comparison of the RTs of individual subtests. The extrinsic stimuli consistently indicated lower RTs than the intrinsic stimuli. We identified the largest differences between visualizations in parts A1 and B1; the differences between visualizations in parts A2 and B2 were moderate. All the differences, with the exception of those related to A2, were significant at a significance level of 5% (Table 1). All the differences, with the exception of those related to A2 and B2, yielded large effect sizes; we also observed large gaps in the upper bounds in the confidence intervals of the extrinsic group and the lower bounds of the confidence intervals in the intrinsic group, suggesting that the obtained statistically significant results were reliable.

At the individual subtest levels (A1, A2, B1, B2), we examined the differences between the test items with one and two variables using the Wilcoxon signed-rank test. An exploration of response times at the subtest level revealed an interesting pattern (Fig 9). In the extrinsic "A" levels, A2 (two variables) resulted in significantly longer response times than A1 (one variable), with a large effect size (Z = 7, $p < 0.001$, $r = -0.789$ [95% *CI*: -0.880, -0.558]). We observed a similar effect in relation to the extrinsic "B" levels, where B2 showed significantly longer response times than B1 (Z = 0, $p < 0.001$, $r = -0.880$ [95% *CI*: -0.882, -0.879]). However, we noted an inverse pattern in relation to the intrinsic visualizations, where A1 (one variable) received significantly longer response times than A2 (large effect size; Z = 68, $p = 0.021$, $r = 0.655$ [95% *CI*: 0.227, 0.886]), and similarly, B1 resulted in significantly longer response

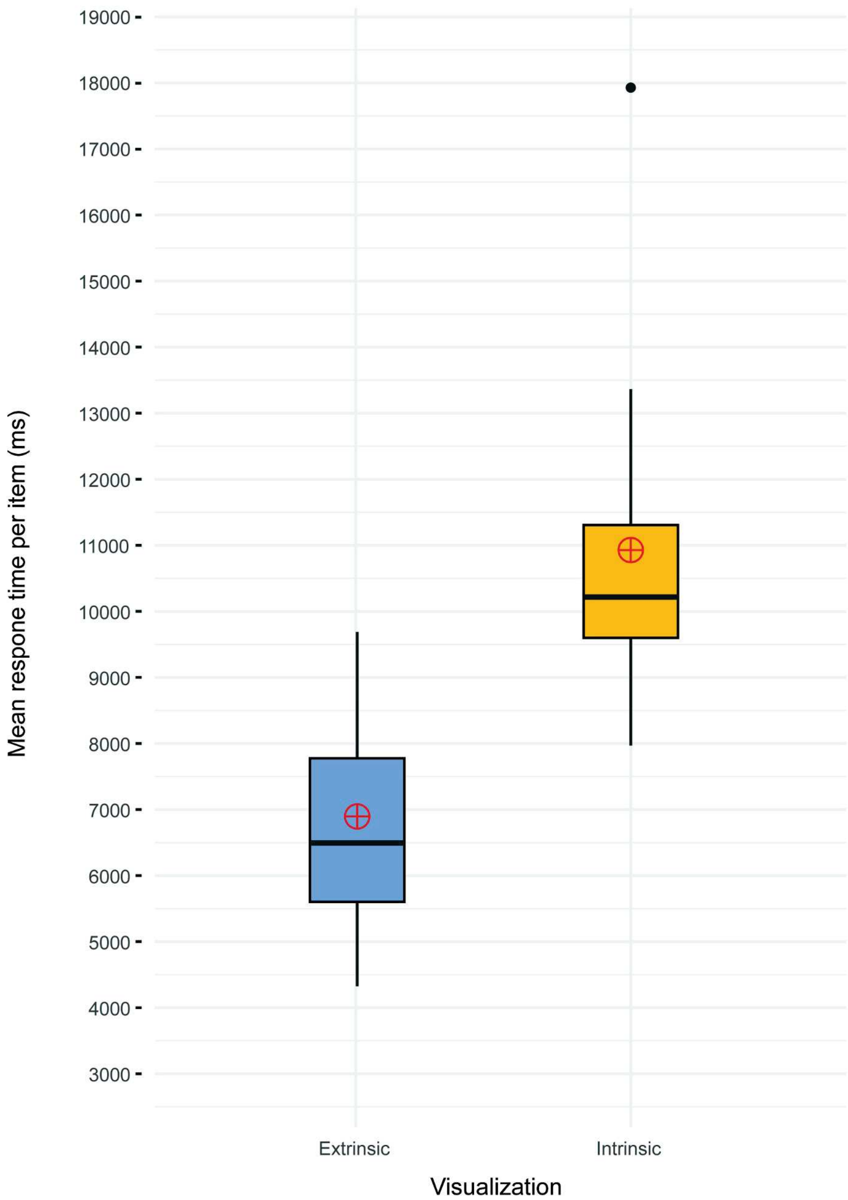

Fig 8. Mean response time per extrinsic/intrinsic visualizations (calculated from the response times to all extrinsic/intrinsic items for all participants).

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times than B2 (Z = 115, $p < 0.001$, $r = 0.806$ [95% *CI*: 0.589, 0.883]). In a comparison of the effect sizes for both the extrinsic and intrinsic visualizations, we can see that the effect sizes of the differences between one and two variables were greater in the extrinsic group. It can therefore be assumed that extrinsic visualization is more efficient when a single variable is applied, while intrinsic visualization is more suitable for two variables.

In addition to the above, we performed a response time comparison at the item level. For most items, extrinsic visualization resulted in shorter response times than intrinsic visualization. The opposite was true for only four items, intrinsic visualization only inducing slightly

Table 1. Response times for the individual subtest parts (ms).

	Extrinsic				Intrinsic				Wilcoxon rank-sum test		
part	mean [95% *CI*]	sd	median [95% *CI*]	iqr	mean [95% *CI*]	sd	median [95% *CI*]	iqr	Z	*p*-value	Effect size *r* [95% *CI*]
A1	6622 [5571, 7673]	1972	6406 [5094, 7286]	2007	13634 [12009, 15260]	2934	14917 [10800, 16056]	3436	5	$p < 0.001$	-0.779 [-0.839, -0.650] large
A2	8609 [7272, 9946]	2509	7827 [6749, 10230]	3066	10102 [8944, 11259]	2090	10184 [7912, 11915]	3237	71	0.093	-0.305 [-0.607, 0.043] moderate
B1	4945 [4266, 5623]	1273	4762 [3992, 6041]	1781	10798 [8928, 12668]	3377	9825 [8275, 14162]	4416	3	$p < 0.001$	0.831 [-0.853, -0.735] large
B2	6666 [5861, 7470]	1509	6638 [5132, 7708]	2159	8192 [6996, 9388]	2159	7738 [6542, 9604]	2359	68	0.041	0.369 [-0.643, -0.036] moderate
whole test	6896 [6035, 7756]	1615	6494 [2172, 5536]	2172	10929 [9576, 12281]	2442	10217 [9588, 11597]	1705	12	$p < 0.001$	-0.767 [-0.844, -0.607] large

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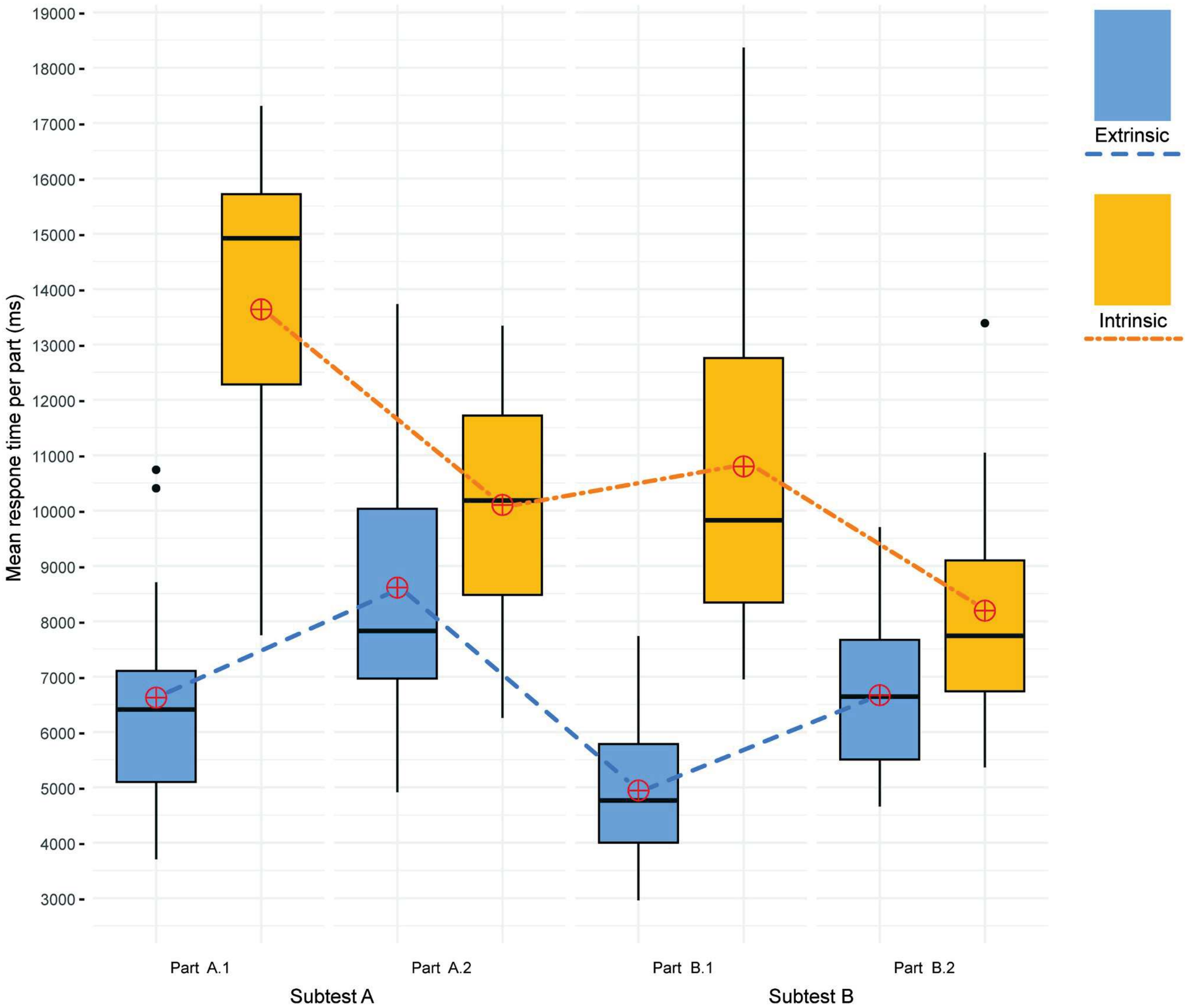

Fig 9. Mean response time (ms) per item (calculated for the individual subtest levels).

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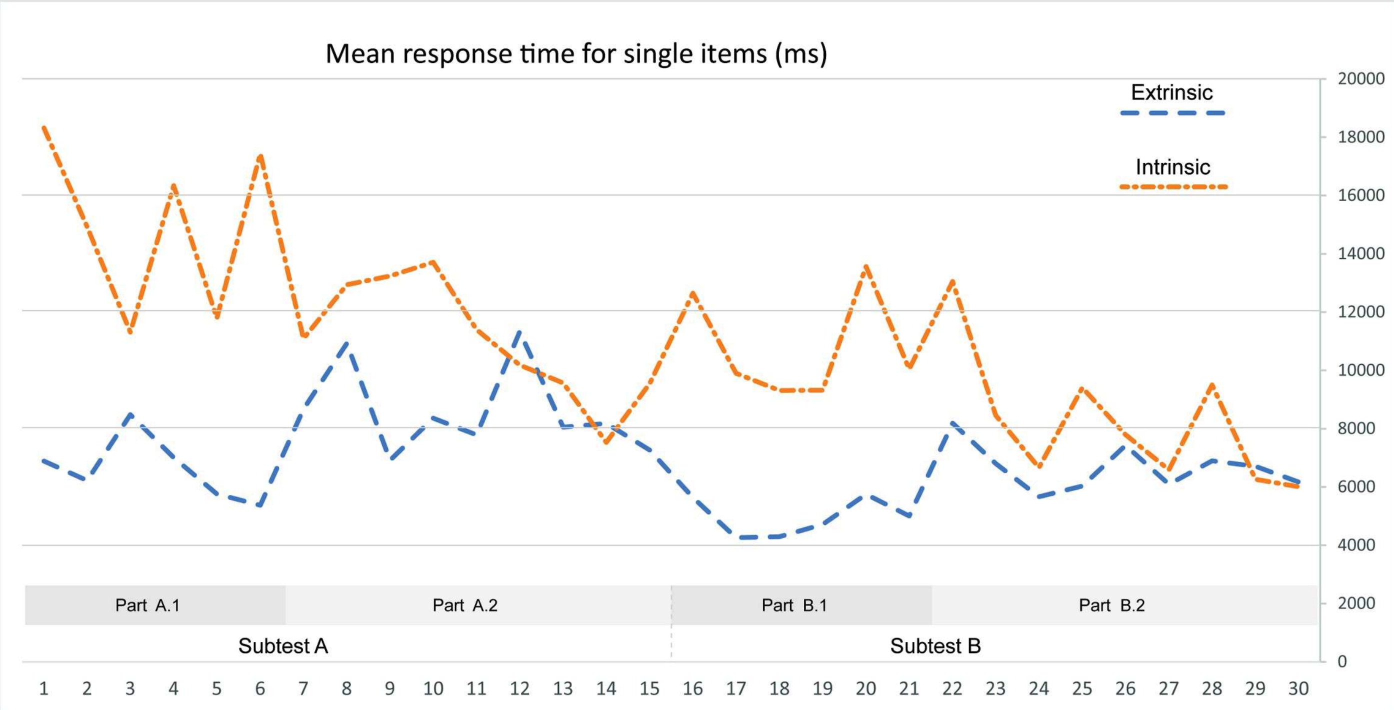

Fig 10. Mean response times (ms) per individual items for extrinsic and intrinsic visualization (all items).

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shorter response times (Fig 10). The differences were significant for most items. An analysis at the item-level also revealed two other interesting phenomena: the first consisted in significant variability across the items observed, even within the individual subtests. This variability reflected the complex nature of maps as research stimuli. The difficulty of a test item depended on an array of interacting factors, including the type of correct answer, the distractors selected and the visualized territory. The second observed phenomenon was that the obtained performance curves associated with both visualization types did not overlap, meaning that the difficulty of the test items varied depending on the type of visualization. In other words, the items that were relatively simple to solve in combination with intrinsic visualization were more difficult with extrinsic visualization, and vice versa.

Eye-tracking analysis

For the purposes of the eye-tracking analysis, the stimuli were divided into three key Areas of Interest (AOI): instructions (the textual component), map legend and map. The analysis consisted in a comparison of the dwell times related to the AOI of the individual items (Fig 10 and Table 2). We were also curious about a comparison of the total dwell times for the extrinsic

Table 2. Summary of AOI dwell times (ms).

	Extrinsic				Intrinsic				Wilcoxon rank-sum test		
AOI	mean [95% *CI*]	sd	median [95% *CI*]	iqr	mean [95% *CI*]	sd	median [95% *CI*]	iqr	Z	*p*-value	Effect size *r* [95% *CI*]
Instructions	2514 [2172, 2856]	539	2570 [2193, 2703]	470	2566 [1807, 3325]	1130	2350 [1579, 4252]	1366	74	0.6505	-0.103 [-0.338, 0.53]
Map Legend	216 [84, 348]	208	180 [62, 246]	127	3740 [2921, 4559]	1219	3675 [2411, 4864]	1841	***0***	***p < 0.001***	***-0.847 [-0.851, -0.749]***
Map	3773 [3048, 4497	1141	3592 [2683, 5117]	1785	3769 [2895, 4642]	1300	3188 [2771, 5847]	1354	70	0.833	- 0.051 [-0.363, 0.49]
All AOI	6503 [5549, 7457]	1502	5970 [5052, 8326]	2712	10075 [8350, 11800]	2567	9142 [8014, 13853]	2192	***10***	***p < 0.001***	***-0.719 [-0.842, -0.475]***

https://doi.org/10.1371/journal.pone.0250164.t002

(N = 12) and intrinsic (N = 11) groups (see S1 File). The results showed significant differences in total dwell times, the extrinsic visualization indicating shorter dwell times with a large effect size. A closer examination revealed that the differences were caused by map legend dwell times. The "extrinsic" group displayed significantly shorter dwell times on the map legend than the intrinsic group, with a large effect size and also with a very large gap between the upper bounds of the confidence intervals of the extrinsic group and the lower bounds of the confidence intervals of the intrinsic group. No significant differences were observed in the dwell times during the instructions.

We also visually inspected the oculomotor data in this study at both the item and subtest levels. The times spent on AOI were converted into percentages. The graphs in Figs 11 and 12 show the ratio of time spent on the instructions, map and map legend. We can observe that at the beginning of the experiment, the participants in the extrinsic group needed approximately 10% of the total time-on-task to decode the map's legend; as their experience increased, the time needed to decode the map legend decreased to as little as zero for some items. The "intrinsic" group, by contrast, initially spent about 40% of the time exploring the map legend, with the percentage decreasing with experience, although it remained relatively high (30%).

A comparison of direct saccades (transitions) between the map legend and the visual field of the map reveal a pattern similar to that described for dwell times. Four AOI were defined (instructions, map, map legend, button bar), and a matrix of transitions between the AOI for each item was generated. Fig 13 displays the ratio of the direct map-to-legend/legend-to-map transitions to the total number of transitions between the AOI. It is clear from the graph that the "extrinsic" group only made use of the map legend at the beginning of the experiment; later, direct saccades occurred less. The "intrinsic" group, by contrast, made use of the legend throughout the tasks, with the number of repeated map-to-legend transitions being higher for the tasks with a single variable (A1 and B1).

Discussion

The results of the present study showed that the intrinsic visualization employed was significantly less effective and efficient than extrinsic visualization. In the case of intrinsic visualization, the participants needed significantly more time to solve the tasks and simultaneously produced more errors.

Nevertheless, the response time differences between the two visualization methods were less pronounced when two variables were considered (soil moisture and soil depth). This levelling was caused by the increase in the time needed to solve the tasks with two variables in both extrinsic subtests (A and B). The effect was not observed with the intrinsic visualization. The above finding is in accordance with the studies performed by Nelson [39] and Elmer [43]. We emphasize that the findings and differences between the visualizations can be generalized only with regard to the population on which the research was conducted. It is a lay population with a basic level of map skills and who may also achieve higher education in humanities and social sciences. Conversely, as the results of the study [6] suggest, a population with a higher level of map literacy may prefer the intrinsic method in certain tasks. Another potentially significant change which affects how we work with maps is the type of formal education or the cultural background of users [71–73].

An exploratory analysis of eye-tracking data provided a deeper insight into the above results. Dwell time analysis showed that both groups spent comparable time on the instructions and the map; the reason for longer response times of the "intrinsic" group consisted in the time needed to decode the map legend. While the "extrinsic" group took only a fraction of the total dwell time to interpret the map legend, in the case of the "intrinsic" group, it was over

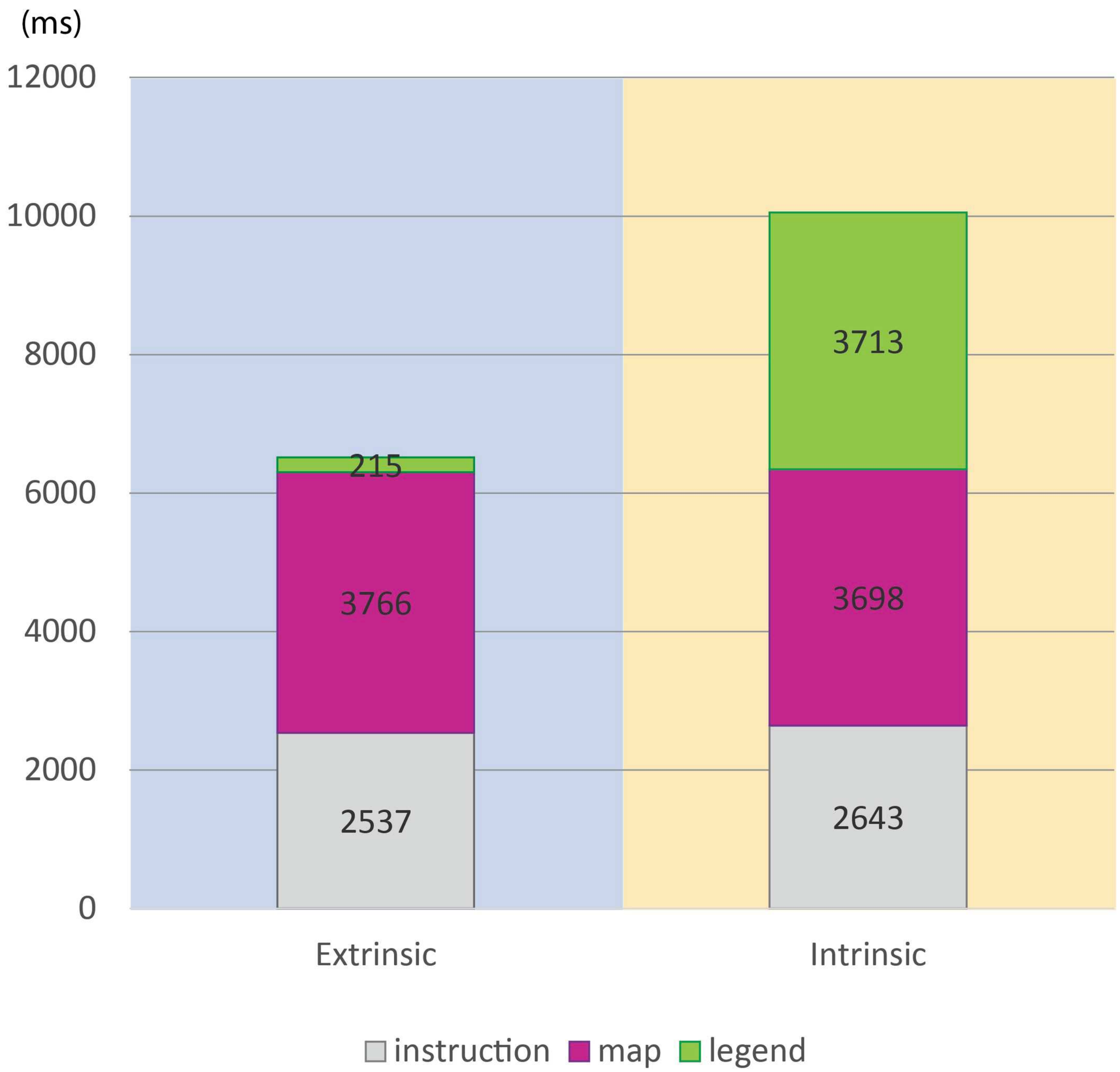

Fig 11. Mean AOI dwell time per extrinsic/intrinsic group (ms).

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a third of the total time-on-task. An analysis at the item level revealed yet another tendency: at the beginning of the experiment, the participants in the extrinsic group needed approximately 10% of the total time-on-task to interpret the map legend; as their experience increased, this time decreased to as little as zero for some items. The "intrinsic" group initially spent about 40% of the time decoding the map legend, and although this percentage decreased with experience, it remained as high as 30%. The above results appear to indicate that the map legend of an intrinsic visualization is so complex and essential that it needs to be referred to throughout

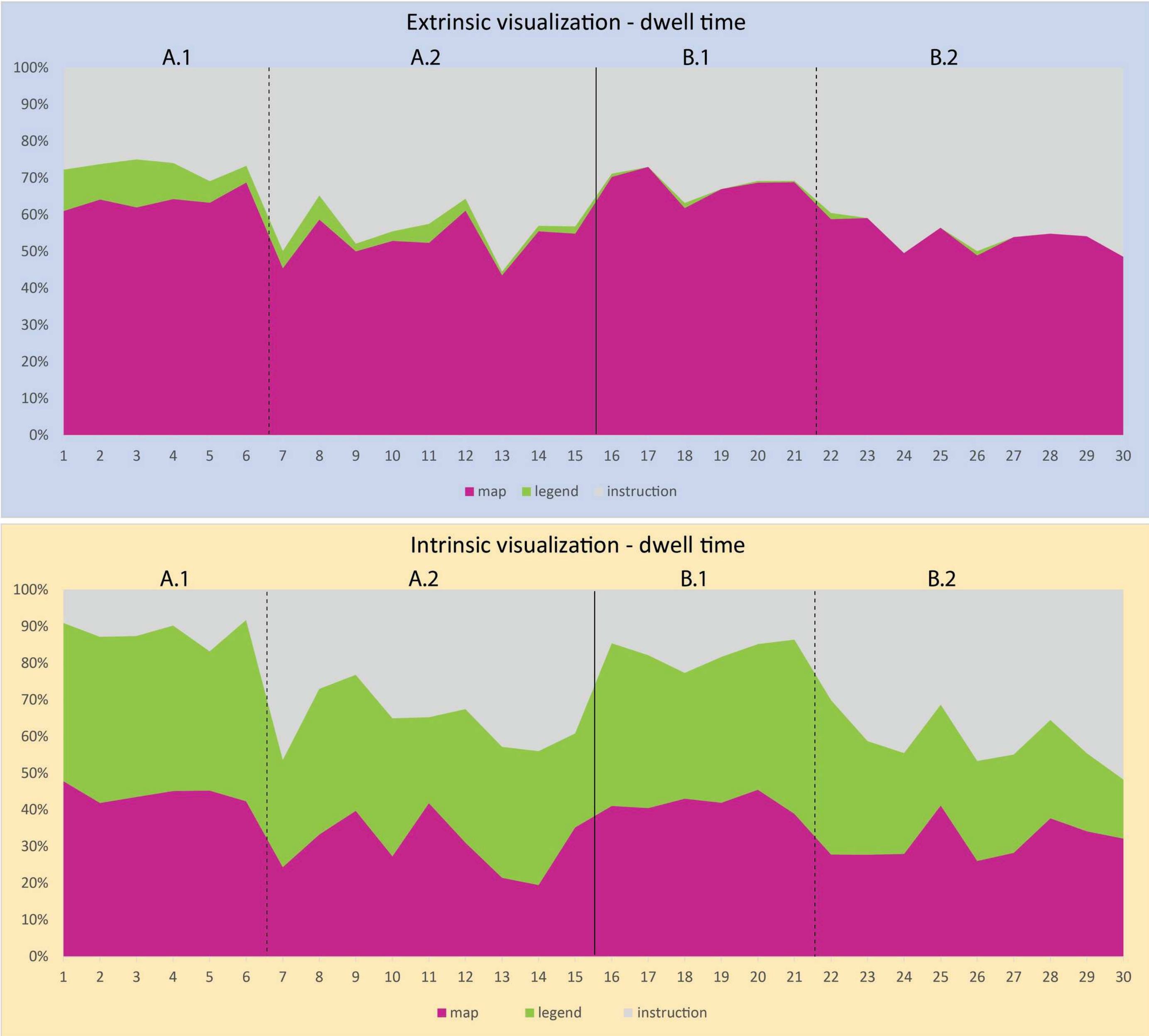

Fig 12. Dwell time on AOI (%) for the extrinsic visualization (top) and intrinsic visualization (bottom). Extrinsic visualization–proportion of dwell time at AOI in single items; (top); Intrinsic visualization–proportion of dwell time at AOI in single items (bottom).

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the task. The same conclusion could be drawn from an analysis of direct saccades between the defined AOI.

A comparison of the performance of the "extrinsic" and "intrinsic" verified the greater effectiveness and efficiency of extrinsic visualization. The results also showed that the type of task (i.e., whether it concerned a single variable or two variables) had a definitive effect on performance, which is in accordance with the statement [e.g., 7, 6] that the performance of map work partly depends on whether the given type of visualization is suitable for the task at hand.

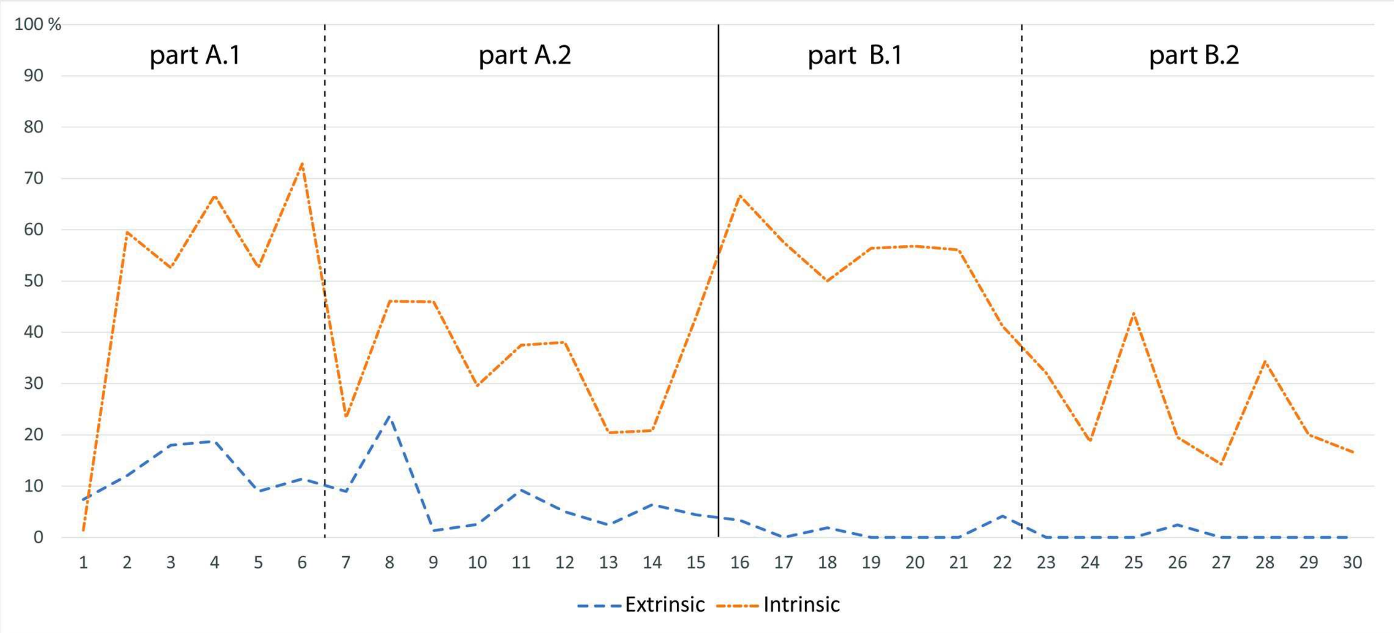

Fig 13. Ratio of the direct map-to-legend/legend-to-map saccades to the total number of direct saccades (%) between the defined AOI (instructions, legend, map, button bar).

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If we want to understand the effects of different forms of visualizations during the process of cartographic communication, we must first understand the underlying cognitive processes [17–20]. A particular type of task may require the activation of specific cognitive processes which are appropriate to a particular visualization type. Anderson [74] emphasized that visual representations differ not only in the coding system, but, importantly, in the cognitive processes they evoke.

The results of the present study indicate that in the case of extrinsic visualization, the map user first perceives and processes both visually distinct variables consecutively, subsequently "putting them together" in their working memory when solving the task. Intrinsic visualization, by contrast, requires only one variable to be kept in working memory at any moment when the task concerns two variables (soil moisture and depth). When the task involves a single variable, however, the user must first decode the map legend and keep all three levels of the variable in their working memory. In the above, the results confirm our assumption that the cartographic visualization must be selected according to the type of task or operation to be performed with the particular map.

Our study is not without limitations. One of the limitations was the small sample size and resulting low power in the statistical tests. Low power may lead to an increase of the risk that the existing differences in performance will be falsely not detected as statistically significant. However, we took several (mostly statistical) precautions to prevent the misinterpretation of our data. We conducted a post-hoc sensitivity analysis which suggested that with a given sample size, medium to large effect sizes could be acceptably interpreted (see the first section of the Results chapter), whereas results with small effect sizes would be inconclusive. Rigorous statistical procedures which allow the interpretation of results on smaller sample sizes were also employed in the study (including bootstrapped confidence intervals for means, medians and effect sizes). Regarding the research sample's composition, we attempted to form a sample which was as homogenous as possible (age, level of education, field of study, experience with maps, etc.) and randomly added participants to the extrinsic/intrinsic groups to obtain an equally balanced sample size for each experimental condition (block randomization) and to reduce potentially confounding effects.

Furthermore, the sample size in our study does not deviate from the standard practice of the field of research in question. King [52] pointed out that many studies work with the relatively small samples given by the high requirements for laboratory equipment. Cognitive cartography surely is one of the fields in which certain studies have contributed significantly to increasing knowledge, regardless of their sample sizes [75–78].

However, the size of the research sample and its composition (European university students of humanities and social sciences with common map literacy skills) permitted us to generalize the conclusions for similar populations. Further research with this method on different samples is required to expand the results of the present study and explore how different population characteristics (map literacy, level and type of formal education) affect the preference for specific types of visualization.

Conclusion

The performed confirmatory analysis verified the superiority of extrinsic visualization in the case of a population of individuals with higher formal education in humanities and social sciences, both in terms of effectiveness and efficiency. Complementary exploratory analysis of eye tracking data suggests that the reason is the character of the intrinsic map legend, which demands greater cognitive resources from map readers during processing. The present study's findings are significant not only for basic research in visualization and cognitive processes but also in their implications for cartographic practices. Even despite a relatively small sample size, the results were statistically significant, but also, importantly, very large effects were discovered. The extrinsic method can be considered convincingly proved as a more suitable visualization type for the given types of task and the lay population.

The results of the present study also raise the question of whether a higher level of efficiency and effectiveness would be maintained with the extrinsic method even if the target population was composed of individuals with high levels of map literacy and different formal education, and whether cultural background plays a role. The specific character of a cartographic visualization sets a significant limit on empirical testing. Even a relatively minor change in partial parameters (e.g., the absolute size of the circles in the case of the extrinsic method, or using a different color scheme in case of the intrinsic method) may affect, for example, the processing speed of visual search or the memorability of the legend, and consequently result in a difference in overall performance. Therefore, to maintain research rationality, it seems reasonable to conduct more partial studies with relatively smaller samples while comparing a wider variability in the applied visualizations and their partial modifications. That is also our objective for future research: if the trends we uncovered are confirmed in studies which examine modified legends, the findings may then be generalized to a wider population, and the principle of the varying methods which were applied can be verified as the cause of the differences in processing. Changes in visualization parameters may also explain the revealed differences at the level of individual items.

Supporting information

S1 File.
(DOCX)

S1 Fig.
(TIF)

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Cross-Cultural Differences in Cognitive Style, Individualism/Collectivism and Map Reading between Central European and East Asian University Students

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The article examines cross-cultural differences encountered in the cognitive processing of specific cartographic stimuli. We conducted a comparative experimental study on 98 participants from two different cultures, the first group comprising Czechs (N = 53) and the second group comprising Chinese (N = 22) and Taiwanese (N = 23). The findings suggested that the Central European participants were less collectivistic, used similar cognitive style and categorized multivariate point symbols on a map more analytically than the Asian participants. The findings indicated that culture indeed influenced human perception and cognition of spatial information. The entire research model was also verified at an individual level through structural equation modelling (SEM). Path analysis suggested that individualism and collectivism was a weak predictor of the analytic/holistic cognitive style. Path analysis also showed that cognitive style considerably predicted categorization in map point symbols.

Key words: cognitive style, cross-cultural differences, categorization, individualism/collectivism, analytic/holistic

Introduction

The objectives of the study were 1) to explore the cross-cultural differences between Central European and East Asian populations at three distinct levels and 2) to examine how these levels were connected. The presented research examined whether the selected populations differed in the degree of individualism/collectivism and the cognitive style measured by the Compound Figure Test (CFT), and whether cultural differences manifested during cartographic task solving, specifically in the categorization of multivariate point symbols.

The theory of analytic and holistic (A/H) cognition postulates the existence of distinct cognitive and perceptual styles – relatively stable ways of cognitive processing (for review, see Masuda, 2017; Nisbett & Masuda, 2003; Nisbett & Miyamoto, 2005; Nisbett, Peng, Choi, & Norenzayan, 2001). The majority of research in this field focuses on comparing the charac-

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teristics of cognitive processes in two world regions: the "West" (e.g., North America, Western Europe) and the "East" (mainly the countries of East and Southeast Asia such as China, Japan, South Korea, etc.; Nisbett, 2003). The theory of A/H cognitive style assumes that Westerners adopt relatively more analytic cognitive style and East Asians the holistic one. A/H cognitive style is defined as *"the tendency for individuals to process information either as an integrated whole or in discrete parts of that whole"* (Graff, 2003, p. 21). Although the primary focus of the theory is the comparison of cognitive processes among cultures, it does not rule out the existence of within-culture individual differences in these processes. In other words, if we compare two people from a certain cultural background, one can perceive relatively more analytically, while the other perceives more holistically.

The A/H model is based on the classic Witkin's model of field dependent/independent cognition (Witkin, Moore, Goodenough, & Cox, 1977) and the Gestalt principles of perceptual grouping and figure-ground organization (Wagemans et al., 2012). Recent findings suggest that many differences exist among people in higher cognitive processes, such as categorization, classification, decision-making, reasoning and causal attribution, and the lower perceptual processes related to attention, such as detection of change and field dependence (for review, see Nisbett et al., 2001; Nisbett & Masuda, 2003; Nisbett & Miyamoto, 2005). More precisely, people perceiving relatively more analytically tend to focus more on perceptually salient (focal) objects and less on background and contextual information, and on the relationships between objects in the perceptual field (Chua, Boland, & Nisbett, 2005; Masuda & Nisbett, 2001; Nisbet & Masuda, 2003). Furthermore, people perceiving relatively more analytically are also less dependent on external reference frameworks than their holistic counterparts (Ji, Peng, & Nisbett, 2000; Kitayama, Duffy, Kawamura, & Larsen, 2003), and are less sensitive to contextual changes while being more sensitive to changes in focal objects (Masuda & Nisbett, 2006). Researchers believe that cognitive style also affects the processes of categorization and classification. Whereas analytic individuals categorize objects by applying formal rules of reasoning, holistic individuals categorize objects by their overall (or holistic) qualities, similarity and mutual relationships (Chiu, 1972; Ji, Zhang, & Nisbett, 2004; Norenzayan, Smith, Kim, & Nisbett, 2002).

The value dimension of individualism and collectivism (I/C) in cross-cultural research is commonly related to A/H cognitive style and often used as a predictor of cognitive style and other psychological phenomena (for review, see Oyserman, Coon, & Kemmelmeier, 2002). Some research suggested that collectivistic individuals are field dependent and holistic, whereas people from predominantly individualistic societies are field independent and analytic (Ji et al., 2000; Nisbett, 2003; Nisbett et al., 2001; Triandis & Gelfand, 1998). However, the relationship between I/C and A/H cognitive styles is rarely measured at the individual level, and many authors have only assumed the aforementioned relationships. Other research has failed to find any empirical evidence at all of relationships at the individual level between I/C and A/H cognitive styles (e.g., Davidoff, Fonteneau, & Fagot, 2008; McKone et al., 2010).

In the current literature though, theoretical considerations (e.g., Hermans & Kempen, 1998; Matsumoto, 1999) and empirical evidence (e.g., Levine et al., 2003; Oyserman et al., 2002; Takano & Osaka, 1999; Takano & Osaka, 2018) can be found, criticizing this dichotomous approach as overly simplifying and reductionist. Post-communist European countries are significantly more holistic and collectivistic than Western Europe (Varnum, Grossmann, Katunar, Nisbett, & Kitayama, 2008). Other findings suggest the existence of significant cultural differences not only across national borders (e.g., Federici, Stella, Dennis, & Hündsfelt, 2011; Kitayama, Park, Sevincer, Karasawa, & Uskul, 2009; Varnum et al., 2008) but also between people from different regions in a single country (e.g., Kitayama, Ishii, Imada, Takemura, & Ramaswamy, 2006; Knight &

Nisbett, 2007; Uskul, Kitayama, & Nisbett, 2008).

These critical findings suggest that the dichotomous model of cognitive styles might be overly reductionist. An alternative model was proposed by Kozhevnikov, Evans, and Kosslyn (2014). Their model is based on an older model by Nosal (1990). It emphasizes the ecological nature of cognitive style that is viewed as a pattern of cognitive adaptation to the environment. Cognitive style is in this model environmentally dependent, flexible and task specific. This model is hierarchical in the form of a cognitive-style matrix organizing cognitive styles on two axes: a) levels of information processing (perception, concept formation, higher-order processing, metacognitive processing), and b) cognitive style families (context dependence and independence, rule-based and intuitive processing, internal and external locus, integration and compartmentalization). According to this model, various components of cognitive style would not have to be inevitably (cor)related – a specific environment could, for example, elicit development of local processing (analytic characteristic) and focus on holistic regions of the map (holistic characteristic). This theoretical model might explain the absence of correlations between various facets of cognitive style reported in some studies (e.g., Hakim, Simons, Zhao, & Wan, 2017; Kster, Castel, Gruber, & Kärtner, 2017).

It should be noted that the number of empirical studies that extend beyond the East-West dichotomy and explore the nature of cognitive style and related factors in other cultural regions, such as Central Europe, is rather limited (with the exception of, for example, Cieślikowska, 2006; Čeněk, 2015; Kolman, Noorderhaven, Hofstede, & Dienes, 2003; Stachoň et al., 2018; Varnum et al., 2008). The current research suggests that the people of Central Europe are rather moderately analytical in cognitive style and relatively, although not extremely, individualistic.

As mentioned above, the study employed cartographic tasks and stimuli in order to explore the manifestation of cognitive style. This follows research that has evaluated cartographic visualization methods that began with the publication *The Look of Maps* (Robinson, 1952). These methods gradually developed into the complex field of cognitive cartography. Subsequent to cognitive cartography, map-psychology research was later introduced by Montello (2002). This approach uses maps as stimuli in order to understand human perception and cognition. Examples of map-psychology research include studies on the influence of alignment and rotation on memory (Tversky, 1981) and the influence of cognitive style while working with bivariate risk maps (Šašinka et al., 2018). Categorization in cartographic stimuli was part of the work of Lewandowski et al. (1993), and research conducted around the same time anticipated cross-cultural differences in map reading (e.g., MacEachren, 1995; Wood, 1984) that was ultimately observed (e.g., Angsüsser, 2014; Stachoň et al., 2018; Stachoň et al., 2019). From the cross-cultural perspective, especially in A/H theory, a most interesting study was conducted by McCleary (1975), who examined the categorization of map point symbols. The author found differences in the clustering of dot symbols and identified two user groups from these findings: atomists and generalists, who analogously correspond to the concept of A/H cognitive style. Nevertheless, another study (Sadahiro, 1997) did not confirm this grouping, even though the author also discovered individual differences in the clustering of dot symbols in maps (cf. Sadahiro, 1997).

Consequently, the objective of this research was to further investigate the nature and manifestation of cognitive style in relation to variables such as individualism/collectivism in the culture of Central Europe (Czechia), compared to typical Eastern Asian cultures (China and Taiwan) – specifically, 1) to analyze cross-cultural differences between these two samples in I/C, visual perception (global versus local distribution of attention) and categorization (clustering) in map stimuli, and 2) to verify the entire theoretical model of relationships between I/C and A/H cognitive styles at an individual level and estimate the relationship be-

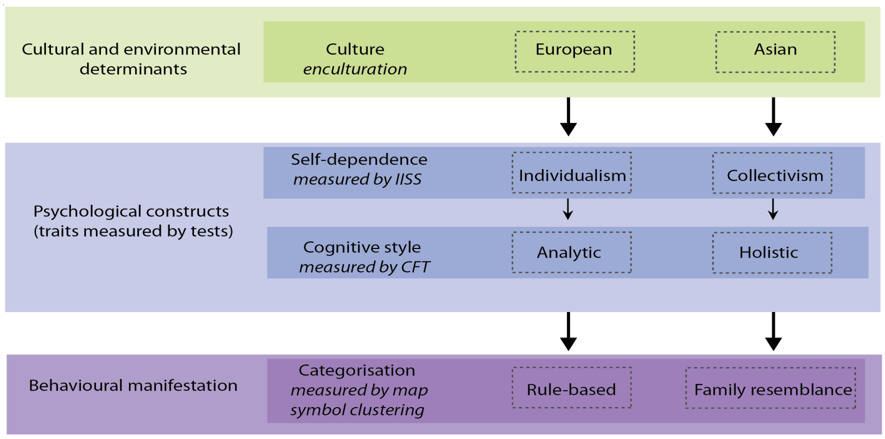

Figure 1 Research model

tween I/C and selected manifestations of A/H cognitive style (global/local attention) and map reading (categorization; see Figure 1).

Methods and Procedures

To achieve the above-mentioned objectives, we applied several methods (described in detail below) using Hypothesis online testing platform (see Procedure section). We also collected sociodemographic information such as age, gender, socioeconomic status (SES), cartography skills, eye defects, number of siblings, etc.

Independent and Interdependent Self Scale

To measure the individual-level I/C, we administered the *IISS – Independent and Interdependent Self Scale* (Lu & Gilmour, 2007). The IISS is derived from the CSC – Self-Construal Scale (Singelis, 1994), the Individualism-Collectivism Scale (Triandis & Gelfand, 1998) and the concept of independent/interdependent self-construal (Markus & Kitayama, 1991). The IISS comprises 42 (21 for the Independent and 21 for Interdependent Self-Construal Scale) seven-point Likert-type numerical items (1 = strongly disagree, 7 = strongly agree). The original version of the questionnaire was administered in simplified Chinese (Lu & Gilmour, 2007). It contains items such as "*I believe that people should try hard to satisfy their interests.*" (independent subscale) or "*I believe that family is the source of our self.*" (interdependent subscale). The Czech version of the questionnaire was translated from English in parallel by three independent translators. Europeans should have higher independent self-construal (individualistic), and East Asians should be more interdependent (collectivistic; Markus & Kitayama, 1991).

Compound Figure Test

The perceptual factors of cognitive style, more specifically the global and local distribution of attention, were measured using the *CFT – Compound Figure Test*, which is a modified version of the Navon method (Navon, 1977) and has been previously used in several studies (e.g., Kukaňová, 2017; Opach et al., 2018; Šašinka et al., 2018). The CFT comprises six practice trials and 32 test trials (blocked design, same 16 trials for both local and global processing). Number of trials was considered satisfactory based on previous research (Davidoff et al., 2008; von Mühlenen, Bellaera, Singh, & Srinivasa, 2018). Each trial involves presenting one "Navon figure" – a large number composed of copies of a smaller different number (Figure 2). In the local trial, participants were asked to identify the small numbers as quickly as possible. In the global trial, they were required to identify the large number. Participants used computer mouse to respond. Reaction time and correct identification were measured in each trial. The average reaction time and average success rate was calculated separately for the local (local reaction time, indicating analytic processing) and global (global reaction time, indicating holistic processing) trials.

The main output of the CFT is the global precedence score, which is computed as the difference between the absolute global and local reaction times (e.g., Gerlach & Poirel, 2018; McKone et al., 2010). High values of the global precedence score indicate a holistic cognitive style (global precedence), low or even negative values indicate an analytic cognitive style (local precedence). According to previous research, people should generally perceive global features more quickly than local features (Navon, 1977). Furthermore, analytic perceivers should be relatively quicker in local and relatively slower in global tasks than holistic perceivers (Peterson & Deary, 2006).

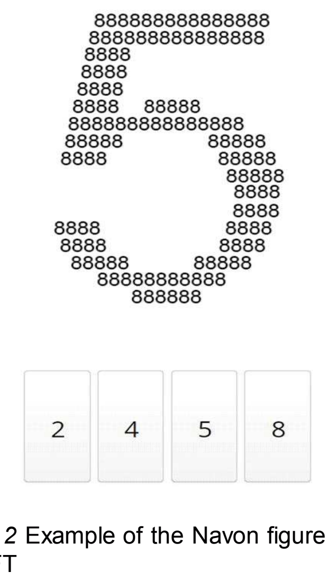

Figure 2 Example of the Navon figure used in the CFT

Categorization of Multivariate Map Symbols

Map reading and understanding is considered as a part of visual literacy (Peña, 2017). In addition, the maps represent the complex stimuli, which enable the user not only to understand the presented information but also to derive the additional information (Morita, 2004), therefore we used the cartographic stimuli. The cartographic visualization of multiple phenomena is known as multivariate mapping. Multivariate point symbols are one possible multivariate mapping method (Slocum, McMaster, Kessler, & Howard, 2005). We created specific cartographic tasks for purposes of our experiment. Categorization was measured with *CMMS – Categorization of Multivariate Map Symbols*, which is based on previous research in categorization (Chiu, 1972; Ji et al., 2004; Norenzayan et al., 2002) and on the relationship between cognitive style and map reading (e.g., Herman et al., 2019; Kubíček et al., 2016; Opach, Popelka, Doležalová, & Rod, 2018; Stachoň et al., 2018; Šašinka et al., 2018). The CMMS measures a specific component of categorization, namely clustering (cf. McCleary, 1975; Sadahiro, 1997).

The method comprised three practice trials and twenty test trials. The administration took between 15 and 30 minutes. In each trial, a fictional map comprising multiple territorial units was presented. Each territorial unit contained one map symbol (Figure 3).

The map symbols contained information about the four attributes of a particular spatial unit, namely food costs (originally blue color, top left position), housing costs (originally red color, top right position), transport costs (originally yellow color, bottom left position) and costs of leisure activities (originally green color, bottom right position), which were indicated by the color and size of the map symbol components (Figure 4). The position and color of the abovementioned attributes were kept constant, only their size was manipulated.

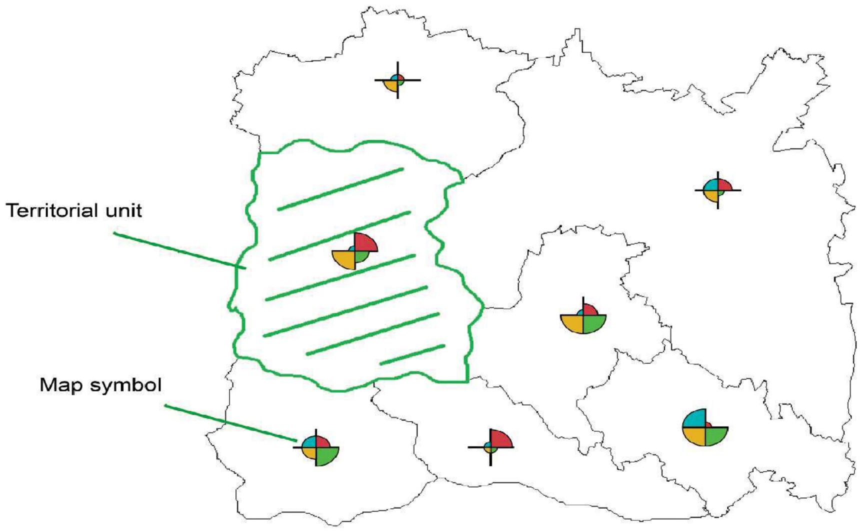

Figure 3 Territorial unit and map symbol in CMMS

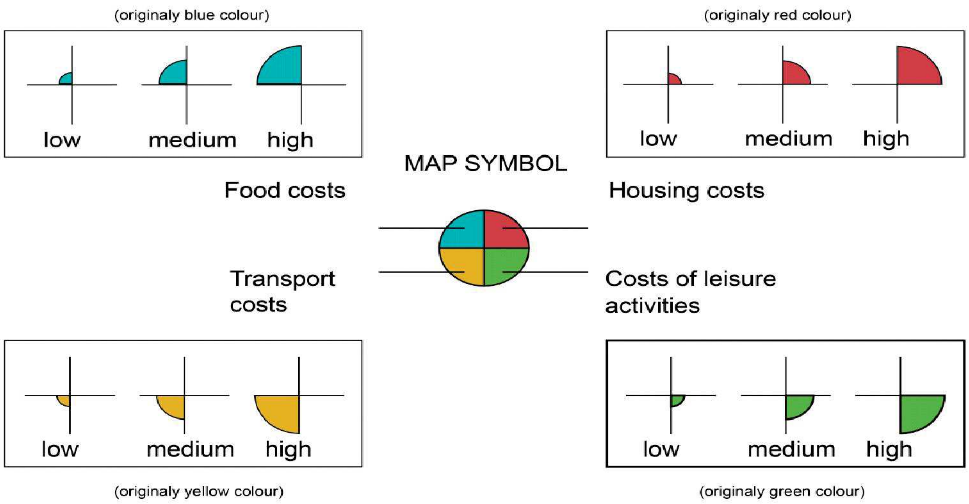

Figure 4 Multivariate map symbol (descriptions were in Czech and traditional/simplified Chinese languages)

Each map was intentionally created to contain one "holistic" and one "analytic" region comprising several territorial units defined by a specific combination of map symbol characteristics (Figure 6). In the analytic region, one of the map symbol components was kept constant and the rest were random (one-dimensional rule); in the holistic region, all map symbols had globally similar components, but none of them were constant (overall-similarity rule, see Figure 5). The remaining map symbol components were completely random to avoid any categorization rule. The analytic and holistic areas were balanced with respect to reading direction.

In group A) the maximum value of the blue parameter (food costs, upper left) was a common attribute in all symbols. In group B), no

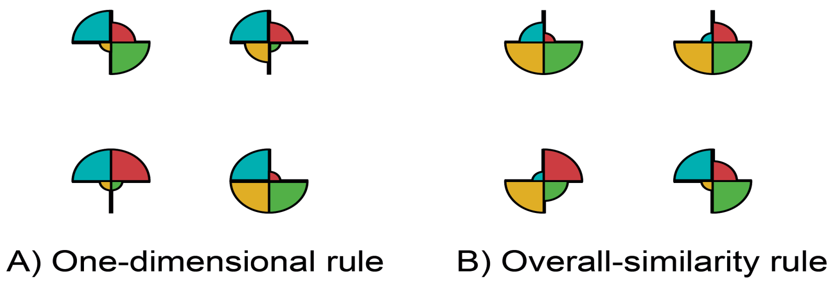

Figure 5 Example of the used analytic A) – left, and holistic B) – right, categorization rules

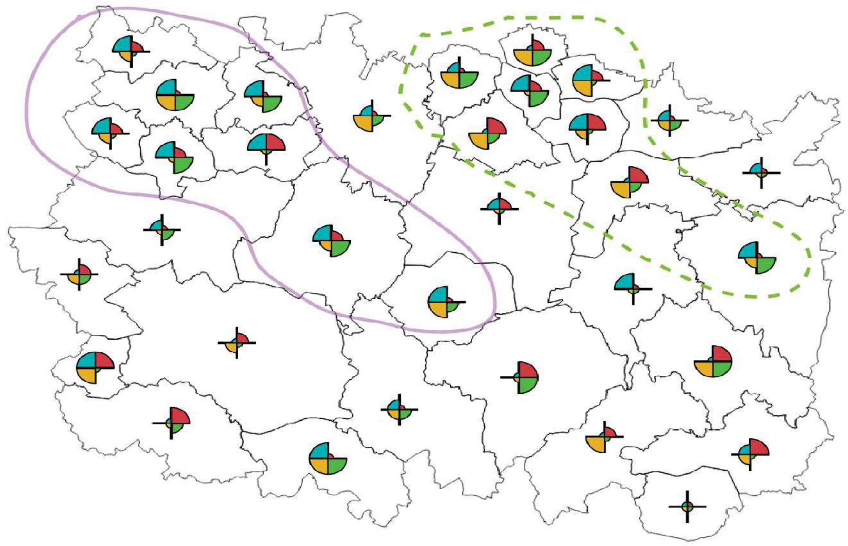

Figure 6 Example of constructed analytic (left solid line) and holistic (right dashed line) map regions

specific attribute was common to any symbol; they shared overall similarity and equal distribution of values in different parameters (2x maximum, 1x medium, and 1x minimum). Alternative map symbols were created according to principles published by Norenzayan et al. (2002).

Participants were asked to identify and mark a continuous map region comprising at least four territorial units that, according to their judgment, belonged together. The CMMS reported each trial result as a value between -1 and 1, where a negative value is defined as a holistic categorization and a positive value is defined as an analytic categorization. This value represented the agreement between the predetermined holistic and analytic regions and the real marked areas. A value of ±1 represented total agreement, while 0 did not represent any agreement. A control value, calculated as the ratio of marked territorial units within the predetermined areas to the sum of all marked territorial units, was also reported to exclude participants who had incorrectly marked only a negligible number of predetermined areas. A value of .60 and higher was considered a valid response, and therefore 40% or less marked territorial units beyond predetermined areas. For example, if a trial consists of 10 analytic, 10 holistic and 30 random areas and a participant marks out 11 areas (7 analytic and 4 random), his/her control value is valid (analytic marked areas/all marked areas = 7/11 = .636) and his/her score is .70 (analytic marked areas/all analytic areas = 7/10 = .70).

From the research mentioned above, we hypothesized that people with a holistic cognitive style will show a tendency to mark out holistic regions and people with an analytic cognitive style will mark out analytic regions. Analogously, we also assumed that East Asians will mark out the holistic area more often (and the analytic area less often) than Czechs.

Research Sample

Before data were collected, a power analysis in *G*Power* (v. 3.1.9.2) was conducted. Setting power at .80 and effect size *f* at .280 was sufficient to test at least 104 participants (52 from each culture).[1]

We gathered data from 103 participants. Five participants were excluded from further data analysis because of missing data. Out of the remaining 98 participants, 53 participants were Central Europeans (Czech), and 45 participants were East Asians (22 Chinese, 23 Taiwanese). All participants were university students, the majority (57.1%) were women and most of them studied psychology (69.4%). The age range was 16–55 years (M = 25.4, SD = 5.52). From previous studies it seems that several demographic variables are relevant to cognitive style, therefore, we gathered information about cartographic skills and experience (Ooms et al., 2016), SES (Grossmann & Varnum, 2011), marital status (Bartoš, 2010), size of residence (Jha & Singh, 2011), number of siblings (based on the number of family members in residence, see Grossmann & Varnum, 2011) or field of study (Choi, Koo & Choi, 2007). The detailed descriptive characteristics of the sample are shown in Table 1.

Our research sample was consequently adequate for testing the hypotheses in the first section of results (Cross-Cultural Differences). In the second section (Relationship between Sociocultural, Perception and Cognitive Factors), however, with respect to the sample size, more demanding methods of statistical analysis were used, such as SEM, specifically path analysis. The sample size was relatively inadequate in this case (according to Ding, Velicer, & Harlow, 1995, the minimum sample size for conducting SEM is about 100–150). The results of SEM therefore needed to be interpreted cautiously. Normality tests were performed for all subscales of the methods used. Non-parametric statistics were used, where the data were not normally distributed.

[1] The value of *f* was selected from previous cross-cultural research using the Navon method, in which the effect sizes were .229–.886 (M = .410, SD = .216; e.g., Fu, Dienes, Shang, & Fu, 2013; McKone et al., 2010; Tan, 2016). We selected the middle effect size value f = .280.

Table 1 *Demographic characteristics of the participants*

		Western Culture	*Eastern Culture*		
		Czechia	**China**	**Taiwan**	**East Asia Total**
Gender	**Male**	25 (47.2%)	7 (31.8%)	10 (43.5%)	17 (37.8%)
	Female	28 (52.8%)	15 (68.2%)	13(56.5%)	28 (62.2%)
Marital status	**Single**	31 (58.5%)	16 (72.7%)	13 (56.5%)	29 (64.4%)
	Married	-	2 (9.1%)	2 (8.7%)	4 (8.9%)
	In a relationship	22 (41.5%)	4 (18.2%)	8 (34.8%)	12 (26.7%)
Socioeconomic status	**Poor**	1 (1.9%)	-	1 (4.3%)	1 (2.2%)
	Low income	6 (11.3%)	4 (18.2%)	1 (4.3%)	5 (11.1%)
	Middle income	24 (45.3%)	6 (27.3%)	13 (56.5%)	19 (42.2%)
	Upper-middle income	19 (35.8%)	7 (31.8%)	6 (26.1%)	13 (28.9%)
	High income	3 (5.7%)	4 (18.2%)	2 (8.7%)	6 (13.3%)
Residence (population)	**< 1K**	6 (11.3%)	2 (9.1%)	-	2 (4.4%)
	1–10K	11 (20.8%)	1 (4.5%)	4 (17.4%)	5 (11.1%)
	10–50K	8 (15.1%)	1 (4.5%)	6 (26.1%)	7 (15.6%)
	50–100K	14 (26.4%)	2 (9.1%)	1 (4.3%)	3 (6.7%)
	100–500K	12 (22.6%)	4 (18.2%)	5 (21.7%)	9 (20%)
	500K–1.5M	2 (3.8%)	4 (18.2%)	1 (4.3%)	5 (11.1%)
	1.5M–3M	-	3 (13.6%)	4 (17.4%)	7 (15.6%)
	3M >	-	4 (28.2%)	2 (8.7%)	6 (13.3%)
Field of study	**Psychology**	39 (73.6%)	12 (54.5%)	17 (73.9%)	29 (64.4%)
	Other	14 (26.4%)	10 (45.5%)	6 (16.1%)	16 (33.6%)
Number of siblings	**0**	6 (11.3%)	3 (13.6%)	-	3 (6.7%)
	1	31 (58.5%)	14 (63.6%)	12 (52.2%)	26 (57.8%)
	2	11 (20.8%)	2 (9.1%)	10 (43.5%)	12 (26.7%)
	3	4 (7.5%)	1 (4.5%)	-	1 (2.2%)
	4 or more	1 (1.9%)	1 (4.5%)	1 (4.3%)	2 (4.4%)
Age range (mean, SD)		20–33 (*M* 23.6, *SD* 2.32)	18–46 (*M* 27.5, *SD* 7.43)	16–55 (*M* 27.5, *SD* 7.24)	16–55 (*M* 27.5, *SD* 7.25)

Procedure

Participants were volunteers contacted through university websites and social networks Facebook (Czech and Taiwanese) and WeChat (Chinese). The aforementioned methods were administered in either simplified/traditional Chinese or Czech on PCs using the Hypothesis online testing platform (Popelka, Stachoň, Šašinka, & Doležalová, 2016; Šašinka, Morong, & Stachoň, 2017) in the presence of an instructor. For their participation the participants got a small reward (USB flash disc) or course credits. The sequence of the tests was 1) CFT, 2) CMMS, 3) IISS, 4) sociodemographic questionnaire. The length of the entire procedure was approx. 35–55 minutes.

Results

The data were processed with *IBM SPSS Statistics* (v. 25), *IBM SPSS Amos* (v. 25) and *R* (v. 3.4.4, *Lavaan* and *SemTools* packages). The results are presented in two sections: *Cross-Cultural Differences* and *Relationship between Sociocultural, Perceptual and Cognitive Factors*. Analysis of the differences between Taiwanese and Chinese participants and also the individual differences between relevant sociocultural variables (e.g., SES, gender, number of siblings, age) were also performed, with no significant differences found in any of the variables. Because of these results, we combined Taiwanese and Chinese participants into a single "Chinese/Taiwanese" group for any subsequent statistical analysis.

Cross-Cultural Differences

The IISS Questionnaire had a satisfactory reliability in both the independent α = .895 (Czech version α = .815, Chinese version α = .929) and interdependent α = .872 (Czech version α = .795, Chinese version α = .906) subscales. Furthermore, the subscales did not correlate with each other (Spearman partial r_s = .155, p = .177, culture was a control variable).

The Chinese/Taiwanese were relatively more collectivistic (interdependent subscale) and less individualistic (independent subscale) than the Czechs. The Chinese/Taiwanese scored an average of 5.17 (SD = .761) in the collectivistic subscale and 5.18 (SD = .911) in the individualistic subscale, whereas the mean scores of the Czechs were 4.66 (SD = .564) in the collectivistic subscale and 5.35 (SD = .502) in the individualistic subscale (Figure 7). The statistical significance of these differences was tested with one-way ANOVA. The differences were significant only in the case of collectivism: $F(1, 96) = 14.456$, $p < .001$, with medium effect size (η^2 = .131). No significant differences were found between the groups in the individualism subscale (Mann-Whitney U = 1105.5, p = .535, r = .063). The data were also analyzed with respect to sociodemographic variables. No other significant relationships were observed (for the complete list of collected variables, see Table 1).

A medium correlation was found between both local and global CFT tasks (Spearman partial r_s = .564, p < .001, culture was a control variable). Two participants were removed from

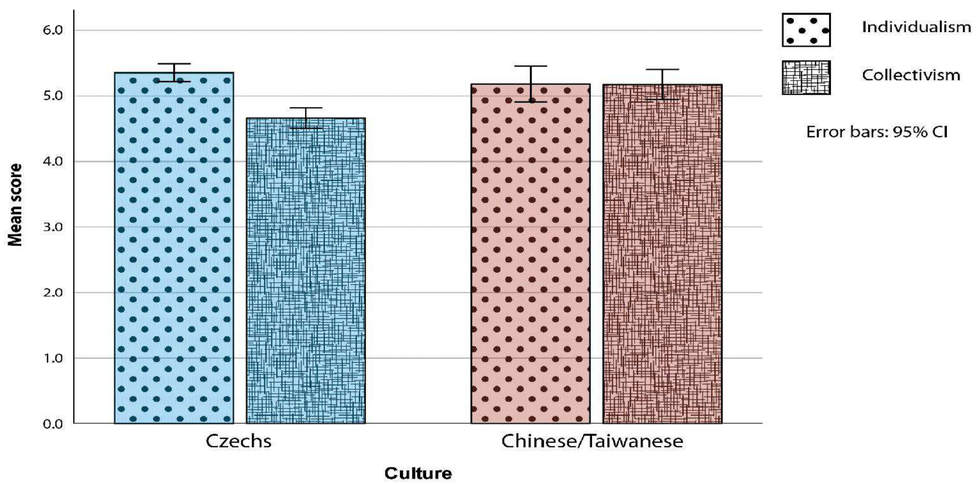

Figure 7 IISS – mean scores

further analysis because of their high error rates (more than four errors in each task).

The results suggest that all participants had significantly quicker reaction times in the global task than in the local task (Wilcoxon signed-rank test $Z = -6.634$, $p < .001$, $r = -.677$). The findings also show that Czechs were quicker than Chinese/Taiwanese in both local and global tasks. The average reaction time of the Czech participants in the global task was 0.99 sec. ($SD = .209$) compared to the Chinese/Taiwanese participants with an average reaction time of 1.66 sec. ($SD = .466$). A similar pattern was observed in the local task, where the average reaction time of the trial solution was 1.13 sec. ($SD = .144$) for the Czechs and 1.77 s ($SD = .387$) for the Chinese/Taiwanese participants (Figure 8). Czechs were significantly quicker in both the global ($U = 204$, $p < .001$, $r = -.711$) and local ($F(1, 95) = 121.960$, $p < .001$, $\eta^2 = .562$) tasks, with large effect sizes.

These differences in reaction times, however, cannot be interpreted in the A/H paradigm as any difference in cognitive style but rather as differences in the emphasis that both groups placed on the speed of the CFT solution (Kukaňová, 2017; Yates et al., 2010). We also calculated the global precedence score using the aforementioned procedure of difference, specifically by subtracting the local reaction times from global reaction times. Although the Czech participants had a relatively higher global precedence score ($M = .139$, $SD = .210$) than the Chinese/Taiwanese participants ($M = .108$, $SD = .574$), this difference was not significant ($U = 949$, $p = .083$, $r = -.175$) (Figure 9).

The final method applied was CMMS. Four participants were removed from further analysis because of their high error rate (participants that marked less than three territorial units into one continuous map region). The results on a scale between -1 (holistic) to 1 (analytic) show that Czechs categorized in maps more analytically ($M = .044$, $SD = .360$) and East Asians categorized in maps more holistically ($M = -.063$, $SD = .172$) (Figure 10). This cultural difference was statistically significant ($U = 795$, $p = .021$), with a small effect size ($r = -.235$). However, the results show that both groups used a similar cognitive style to categorize map symbols and only small differences in cognitive strategies were found. Moreover, both groups scored relatively close to zero, which is probably caused by using various categorization strategies across different trials,

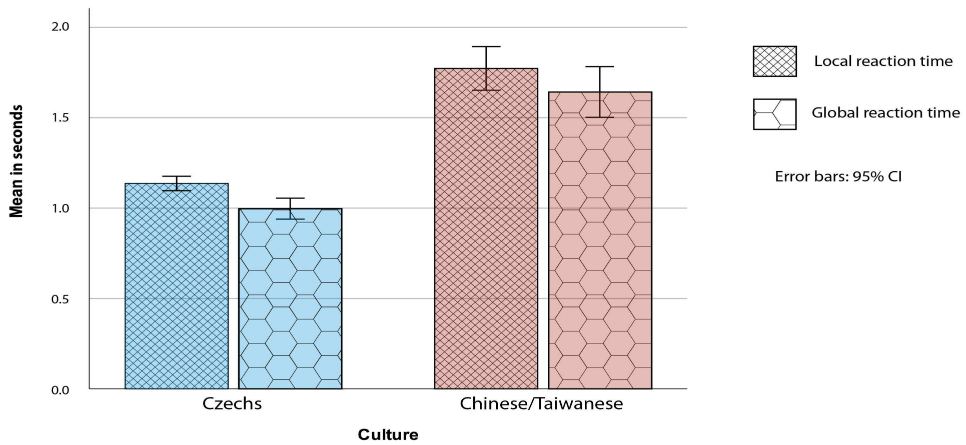

Figure 8 CFT – mean reaction times

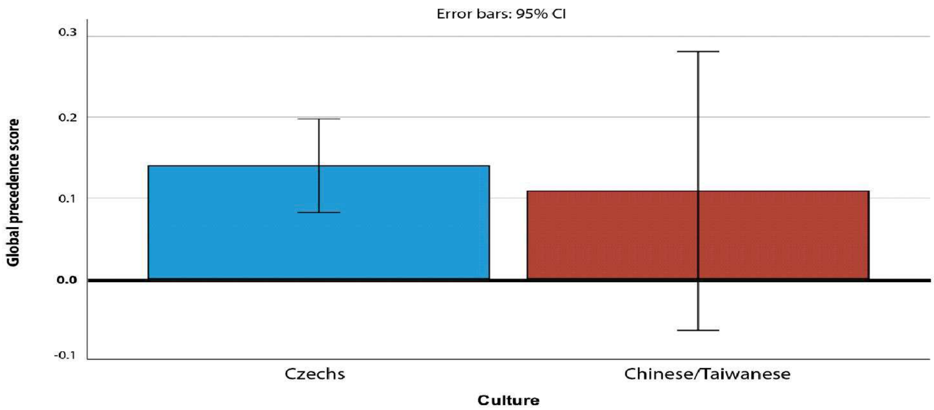

Figure 9 CFT – Mean global precedence scores (higher values mean higher global precedence)

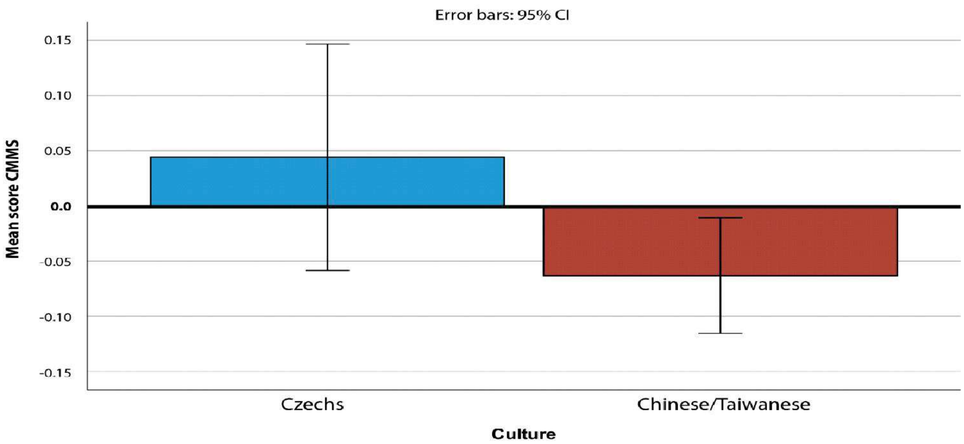

Figure 10 CMMS – Cross-cultural differences in map categorization (High value = analytic, low value = holistic).

because absolute scores were higher for both Czechs (M = .461, SD = .183) and Asians (M = .247, SD = .148).

Relationship between Sociocultural, Perceptual and Cognitive Factors

We performed a Spearman partial correlation and a path analysis (type of SEM) to verify the research model at individual level in order to obtain an improved and deeper understanding of the phenomena under scrutiny and their mutual relationships.

Using a non-parametric Spearman partial correlation with culture as control variable, only weak correlations were found between the CMMS scores and the CFT global reaction times (r_s = .222, p = .035) and between the

CMMS scores and the CFT global precedence scores (r_s = -.216, *p* = .040). The whole correlation matrix is shown in Table 2:

A path analysis was also performed using the expectation–maximization (EM) method to estimate missing values and an asymptotically distribution-free (ADF) method, which is adequate for non-parametric data. Since both cultures were analyzed together, culture was used as a "control variable". Two models were analyzed: Model 1 comprised CFT reaction times, and Model 2 was computed with the calculated CFT global precedence score (Figure 11). Both models showed a very good fit (Table 3).

Path analysis for Model 1 revealed a weak direct effect of individualism (IISS independent self-construal scale) on CFT local reaction times (*β* = -.250, *B* = -.167, *p* = .003) and a weak direct effect of collectivism (IISS interdependent self-construal scale) on CFT global reaction times (*β* = -.196, *B* = -.135, *p* = .047). The higher score in individualism therefore indicated a quicker reaction time in the local

Table 2 *Spearman partial correlation matrix*

	1.	*2.*	*3.*	*4.*	*5.*	*6.*
1. Individualism	–					
2. Collectivism	.155	–				
3. CFT local RT	.002	.073	–			
4. CFT global RT	-.026	-.140	.564**	–		
5. Global precedence score	.125	.183	.176	-.546**	–	
6. CMMS	.066	.147	-.063	.222*	-.216*	–

Note. * p < .05, ** p < .001

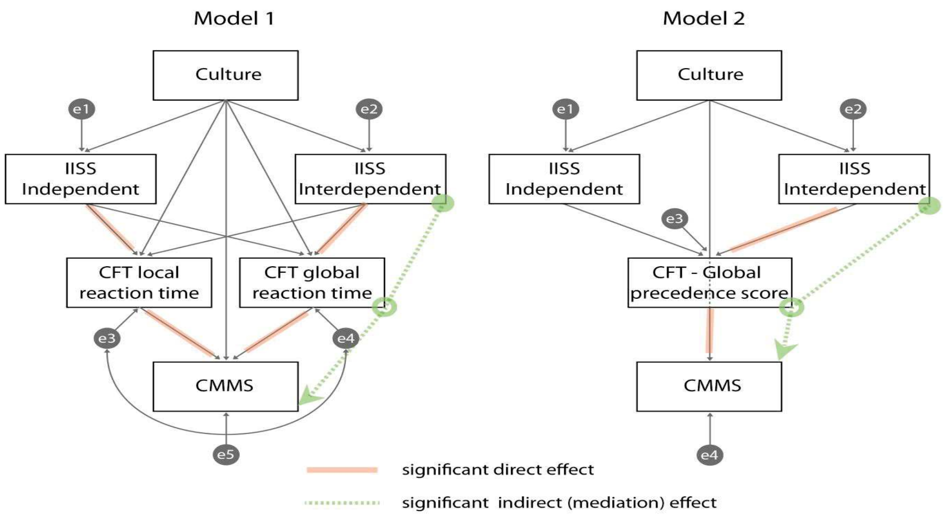

Figure 11 Path analysis models – Model 1 (left), Model 2 (right)

Table 3 *Models fits*

Model	*Chi-square*	*p-value*	*CFI*	*RMSEA*	*AIC*	*BIC*	*ECVI*
Model 1	$\chi^2(3) = 3.897$	.273	.995	.057	39.897	85.289	.438
Model 2	$\chi^2(3) = 4.435$	.218	.960	.073	28.435	58.697	.312

task, and the higher score in collectivism indicated a quicker reaction time in the global task, i.e., I/C scores weakly predicted the performance in CFT tasks. Moderate direct effects of the CFT global reaction times (β = .713, B = .450, p < .001) and the CFT local reaction times (β = -.776, B = -.521, p < .001) on the CMMS scores were also found. These results suggest that the analytic perceivers (persons with a quicker CFT local reaction time) tended to use an analytic manner of categorizing point multivariate map symbols, and that the holistic perceivers (persons with quicker CFT global reaction time) used a rather holistic manner of categorizing point multivariate map symbols. In other words, the CFT reaction times satisfactorily predicted the map categorization style. In order to estimate the indirect effects of I/C on point multivariate map symbol categorization, bootstrapping (N = 2000, CI = 95%) was performed, and a very weak indirect (mediation) effect of collectivism (IISS interdependent self-construal scale) on the CMMS score (β = -.175, B = -.077, p = .028) was detected.

Path analysis performed on Model 2 showed a weak direct effect of collectivism (IISS interdependent self-construal scale) on the CFT global precedence score (β = .357, B = .156, p = .017). This finding suggests that collectivistic people tended to use a more global distribution of attention that is characteristic of the holistic cognitive style. A moderate direct effect of the CFT global precedence score on map categorization (β = -.502, B = -.502, p < .001) was also observed, i.e., participants who showed a relatively more global distribution of attention, categorized symbols in maps according to relatively more holistic rules, and vice versa, participants who showed a relatively more local distribution of attention, were prone to use relatively more analytic rules of categorization. A very weak significant indirect (mediation) effect of collectivism (ISS interdependent self-construal scale) on map categorization (β = -.179, B = -.078, p = .026) was also found after bootstrapping (N = 2000, CI = 95%).

It should be noted that we reported only significant relationships. However, as shown in Figure 11, we included all plotted relations in the models (i.e., IIISS independent on CFT global RT and IISS interdependent on CFT local RT in Model 1 and IISS independent on CFT global precedence score in Model 2). Moreover, we also performed indirect (meditation) effect of individualism (IISS independent self-construal scale) on map categorization with no significant results in both models. The exogenous control variable “culture” had statistically significant and large regression coefficients on all endogenous variables in the models. Nevertheless, we did not report these results because we added it to our models only in order to weaken the influence of other variables. Moreover, the apparent dissension between insignificant correlation coefficients and significant regression coefficients of path analysis could be explained by suppression effect and Simpson’s paradox (see MacKinnon, Krull, & Lockwood, 2000; Tu, Gunnell, & Gilthorpe, 2008), which postulates that a more complex statistical model can reduce, reverse or even enhance the relationships between variables.

Discussion

The aims of the presented study were: 1) to compare I/C and A/H cognitive styles and map categorization in Czech and East Asian (Chinese/Taiwanese) university students, and 2) to investigate and verify the theoretical model of relationships between I/C and A/H cognitive styles and between A/H cognitive styles and their behavioral manifestation in the process of map categorization.

The results suggest that the Czech participants showed a significantly lower level of collectivism (interdependent self-construal scale) than did the Chinese/Taiwanese participants and a similar level of individualism (independent self-construal scale). Our results partly support the current theory that describes the West as relatively less collectivistic than the East (Hofstede, 1983; Markus & Kitayama, 1991; Nisbett et al., 2001; Triandis & Gelfand, 1998). Furthermore, a similar level of individualism corresponds to the empirical research in I/C in post-communist countries (Kolman et al., 2003; Varnum et al., 2008) and even with previous research in I/C in Czechia (Bartoš, 2010; Čeněk 2015). This finding also supports the claims of rapid individualization in the young East Asian populations (e.g., Moore, 2005; Steele & Lynch, 2013).

The results of the CFT show that all of the participants performed the global tasks more quickly than the local tasks, which is consistent with previous findings (Navon, 1977). However, our participants were generally slower compared to the original study (Navon, 1977). This fact was most probably caused by the way of responding (mouse click instead of keyboard buttons) because mouse response process has in contrast with keyboard response process one extra step (i.e., moving the mouse cursor above the response option). Our results also indicate cross-cultural differences in the general reaction times of CFT stimuli processing. The Czech participants were significantly quicker in both the global and local tasks. However, as mentioned above, these differences in reaction times demonstrated rather differences in the emphasis that both groups placed on the speed than differences in cognitive style (Kukaňová, 2017; Yates et al., 2010). The comparison of the global precedence scores (calculated from CFT global and local reaction times) showed no differences in global/local processing between the Czechs and Chinese/Taiwanese, which was contrary to our expectations. The results of the CFT could be seen as a contradiction to the notion of the “analytic West” and “holistic East” (Nisbett et al., 2001; Nisbett & Masuda, 2003; Nisbett & Miyamoto, 2005). However, it is still not clear whether Central Europeans count as the “analytic West”. For example, Varnum et al. (2008) showed that Central European post-communist countries are relatively more holistic in their patterns of attention than Western Europe. Other empirical research, comparing the sensitivity to the context of Czech vs. Czech Vietnamese (Čeněk, 2015), and Czech vs. Chinese (Stachoň et al., 2018, Stachoň et al., 2019), reported mixed or contradictory results in terms of the expected differences in cognitive style.

The results of the CMMS show that the Czech participants categorized more analytically in maps, whereas the Chinese/Taiwanese categorized more holistically. This result agrees with the theory that Westerners use slightly more analytic categorization patterns and Easterners use more holistic categorization (Chiu, 1972; Ji et al., 2004; Norenzayan et al., 2002). However, the effect size of this significant difference was relatively small.

Path analysis was used to test the validity of two structural models of relationships between the variables of interest. Both evaluated models (CFT local and global reaction times and the global precedence score) showed a satisfactory good fit. The results of the path analysis show that I/C is a weak predictor of the level of global/local distribution of attention, i.e., collectivist persons tended to use a holistic cognitive style, and individualistic persons tended to use a rather analytic cognitive style. These findings partly support the theory of holistic and analytic cognitive styles (Nisbett, 2003; Nisbett et al., 2001; Triandis & Gelfand, 1998), although the values of the path coefficients were relatively small. The path analysis also did not find all of the expected direct and indirect effects of I/C on the scores of the CFT and the CMMS. The aforementioned findings were, therefore not a conclusive argument to support the A/H cognitive style theory in cross-cultural context (cf. Nisbet et al., 2001). As with several other studies that did not find any relationship between I/C and A/H cognitive style (e.g., Davidoff et al., 2008; McKone et al., 2010; Takano & Osaka, 1999), it may be possible that this relationship could be different from what researchers expect, or perhaps even nonexistent. Our findings of unconvincing yet significant relationships could also be explained in theoretical arguments, which maintain that the I/C and A/H cognitive styles only manifest at a cultural (i.e., cross-cultural comparison) not individual level (i.e., SEM and path analysis; cf. Na et al., 2010). Nevertheless, we would like to emphasize that the sample size was, in this case, relatively inadequate for SEM, therefore its results should be understood as only exploratory.

The concept of I/C and its measurement with self-report scales have recently been subject to disagreement from many scholars. This criticism mainly cites the lack of concurrent, discriminant and construct validity, insufficient conceptualization, a reductionist and dichotomous approach and insufficient psychometric characteristics in questionnaires (for review, see Levine et al., 2003; Matsumoto, 1999; Oyserman et al., 2002; Vignoles et al., 2016). For example, if the individual level of I/C can be significantly influenced by priming, then it means that I/C is not as stable in time as it is generally assumed (Gardner, Gabriel, & Lee, 1999; Oyserman & Lee, 2008). Moreover, according to the results of meta-analytical studies and systematic reviews, the West should not be described as strictly individualistic nor the East as purely collectivistic (Levine et al., 2003; Oyserman et al., 2002; Takano & Osaka, 1999; Takano & Osaka, 2018). Most recently, for example, Hakim et al. (2017) compared the levels of individualism and collectivism of American and Asian international students and found, contrary to expectations, that Americans were significantly more collectivistic, whereas the Asian students were significantly more individualistic.

Path analysis also found that global/local distribution of attention had a moderate predictive power on categorization in both of the tested models, i.e., analytic perceivers (defined by the CFT global precedence score) used analytic categorization in maps, whereas holistic perceivers used holistic categorization. This finding is consistent with the research theory (Chiu, 1972; Ji et al., 2004; Norenzayan et al., 2002) and the empirical research (Kubíček et al., 2016; Šašinka et al., 2018; Stachoň et al., 2019). Consequently, the cognitive style that is characterized as a perceptual process is presumably manifested in higher cognitive processes, such as map reading and categorization.

Conclusions

The article describes cross-cultural differences in western and eastern cultures, between Czech and Chinese/Taiwanese university students, respectively. The theoretical background of the research was based on the theory of analytic and holistic cognitive styles and the dimensions of individualism and collectivism. Two main objectives were defined: first, to identify the possible cross-cultural differences and similarities between Czechs and Chinese/Taiwanese, and second, to verify the entire research model and the relationships between A/H cognitive style and I/C at individual levels. For this purpose, we also developed a new method (CMMS) in order to study how A/H cognitive style was manifested during categorization in map reading. The results suggest that cross-cultural differences exist between both cultures, especially at the level of collectivism (Czechs were less collectivist than the Chinese/Taiwanese) and categorization in map reading (Czechs used more analytic and less holistic categorization). Neither individual differences (e.g., SES, gender, age) nor differences in cognitive style measured by the CFT between Czech and East Asians were found. The findings also indicate that I/C is a weak predictor of A/H cognitive style and that A/H cognitive style moderately predicts categorization in map reading.

These results contradict the East-West dichotomy and suggest that the culture of Central Europe (specifically Czechia) is much more similar to the East than expected from the literature. However, more cross-cultural research of typically Western, typically Eastern and Central European cultures is needed for an improved understanding of the real influence of culture on human perception and cognition in regions outside the East-West dichotomy. Based on the presented results, future research should focus on verification of Nisbett's (2001) vs. Kozhevnikov's (2014) models of cognitive styles. Above all, specify the number of cognitive style families, investigate the stability/flexibility of cognitive styles, and inspect the developmental aspects (e.g., children of different age) of cognitive style and its adaptive nature (e.g., research on expatriates during the process of cultural adaptation) is also suggested.

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Identification of altitude profiles in 3D geovisualizations: the role of interaction and spatial abilities

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ABSTRACT
Three-dimensional geovisualizations are currently pushed both by technological development and by the demands of experts in various applied areas. In the presented empirical study, we compared the features of real 3D (stereoscopic) versus pseudo 3D (monoscopic) geovisualizations in static and interactive digital elevation models. We tested 39 high-school students in their ability to identify the correct terrain profile from digital elevation models. Students' performance was recorded and further analysed with respect to their spatial abilities, which were measured by a psychological mental rotation test and think aloud protocol. The results of the study indicated that the influence of the type of 3D visualization (monoscopic/stereoscopic) on the performance of the users is not clear, the level of navigational interactivity has significant influence on the usability of a particular 3D visualization, and finally no influences of the spatial abilities on the performance of the user within the 3D environment were identified.

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1. Introduction

The use of 3D technology in applied fields has increased rapidly in the last decades. Starting with the vision of Digital Earth (DE; Gore 1998) and later with the advent of virtual globes (e.g. Google Earth), 3D geovisualizations became very popular in practical use under various labels and names. The original idea of DE has developed, and in their vision for the next decade, Craglia et al. (2012, p. 18) described DE as a 'dynamic framework to share information globally', targeting the improvement of 'the complex relationships between society and the environment we live in'. Such a shift of the original paradigm emphasizes not only the technological aspects but also the user''s ability to understand and effectively harness the presented information.

However, the usability of 3D geovisualization as a tool in practical tasks still remains quite unclear. 3D technologies are deployed in many geo-related areas such as teaching geography, geology, urban planning, and emergency and crisis management (Hunter et al. 2016; Lin et al. 2015; Herman and Řezník 2015; Herbert and Chen 2015; Hirmas et al. 2014; Popelka and Dědková 2014; Řezník, Horáková, and Szturc 2013; Konečný 2011). Many applied areas usually emphasize the precision of the human operator''s situational judgement and decision-making, so the ways of

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representing information in the virtual environment (VE) play an important role in the cognitive processing during tasks. Compared to two-dimensional cartographic visualizations, there are still no clear standards or design principles for the creation of 3D cartographic visualizations (Pegg 2011; Haeberling, Bär, and Hurni 2008; MacEachren 1995). The cartographic principles for 3D cartographic visualization are a current issue discussed in several studies (Lokka and Cöltekin 2017; Hájek, Jedlička, and Čada 2016; Sieber et al. 2016; Semmo et al. 2015). Also, most of the research on 3D maps was done only on participants who were highly skilled in map reading (Pegg 2011). Moreover, the results of many studies indicate ambiguity in 3D cartographic visualization usability and the need for extended research (e.g. Bleisch and Dykes 2015; Seipel 2013; Pegg 2011).

The particular factors influencing the effective and efficient design of virtual 3D environments have been analysed from different viewpoints. Regarding this, Lokka and Cöltekin (2016) presented an analytical study identifying three distinctive groups of key factors: (1) users (spatial abilities, age, gender – both on the general and individual levels), (2) type of stimuli (including the visualization, level of realism, type of interactivity, and other factors), and (3) tasks (particular context of use, specific scenario). Earlier Šašinka (2012) introduced a similar triarchic model where they emphasized the importance and interaction of all three of the above-mentioned categories when working with a map. In their triarchic structural model, they suggested that, e.g. the cognitive strategy used when dealing with particular task depends on the level of map literacy (user group factor), on visualization type (type of stimuli group factor) and also on the nature of the problem which is solved (task group factor).

The focus of this article is a synthesis of two selected stimuli aspects (level of interaction and visualization type) influencing the usefulness of 3D visualization. Based on the previous findings (Špriňarová et al. 2015; Herman and Stachoň 2016; Klippel, Weaver, and Robinson 2011), in our study we explored perception of 3D terrain geovisualizations displayed in real 3D (stereoscopic) and pseudo 3D (monoscopic), in both static and interactive forms. General research questions were defined as follows:

- Does the type of 3D visualization (monoscopic/stereoscopic) influence the performance of the users?
- Does the level of navigational interactivity influence the usability of 3D visualization?
- What is the role of personal spatial abilities in the process of solving 3D visualization tasks?

For the purpose of the study, we developed a special computer testing interface. In this study, we tested participants with low levels of map-reading experience.

2. Related work

2.1. Principles of 3D vision

3D visualizations contain a number of visual cues. Some static monocular depth cues are embedded in the 3D visualizations (e.g. lighting and shading cues, occlusion/interposition, relative size of objects, linear perspective, texture gradients, and aerial perspective). Dynamic monocular depth cues, which are considered extremely effective for depth information recognition (Loomis and Eby 1988), include motion parallax, i.e. movement of objects, the viewer, or both in the scene; in cartography also referred to as kinetic depth (Willett et al. 2015). Such mutual movement can indicate depth information in the viewer"s visual field through the perception of different distance changes between the viewer and the objects. In some specific visualization environments, we can also use binocular depth cues, which are represented by binocular disparity, in which case we can see a slightly different view of the scene with each eye separately. The result is synthesized in our brain, creating a 3D perception of the scene. Binocular disparity and convergence are usually provided by 3D glasses or another stereoscopic technology such as head-mounted displays.

Based on the number of visual cues used in the visualization, we can distinguish between real and pseudo 3D visualization (Bowman et al. 2005). Pseudo 3D (monoscopic) visualizations use only monocular cues, whereas real 3D (stereoscopic) visualizations include both binocular and monocular depth cues (Buchroithner and Knust 2013). The added value for real 3D visualization is stereoscopy, provided by binocular depth cues (namely binocular disparity). Stereoscopy is ensured by the use of computer graphics and specific peripheral devices for 3D vision such as 3D glasses. Pseudo 3D (monoscopic) visualization is displayed perspective-monoscopically on flat media or on the computer screen (Buchroithner and Knust 2013).

These two types of visualizations can be considered informationally equivalent, i.e. they can present exactly the same amount of spatial information (Larkin and Simon 1987). However, they are not computationally equivalent, because each of them uses different cognitive processing of the perceived information. When perceiving binocular depth cues in a real 3D VE, the user is expected to better estimate spatial placement/distribution in the scene (Qian 1997; Landy et al. 1995). Nevertheless, previous studies dealing with real 3D visualization (e.g. Ware and Franck 1996; Zanola, Fabrikant, and Cöltekin 2009; Torres et al. 2013; Špriňarová et al. 2015) reported inconclusive implications for practical use of real 3D technology.

2.2. Interactivity in three-dimensional visualizations

Interactivity in 3D geovisualizations presents the possibility of manipulating the geovisualization. In this article, we focus only on navigational interactivity. Navigational or viewpoint interactivity is defined for example by Roth (2012) and it is the core functionality of applications like Google Earth. Navigational interactivity in 3D space usually includes functions like rotation, panning, and zooming. Interactive (movable, navigable) 3D environments provide then the above-mentioned kinetic depth cues (motion parallax), emphasizing the user"s 3D perception. From a distributed cognition theory point-of-view (Hutchins 1995), we can see the interaction process as the behaviour where both internal (inner mind) and external (in the world, within some external medium) cognitive processes occur. Regarding this, in applied areas, the user interface should always be designed with maximal attention to provide optimal information reach, securing the user"s situational awareness. Only a few experiments regarding interactive 3D environments (their features and usability) have been published, and navigational interactivity in 3D environments was not necessarily found to be advantageous (Keehner et al. 2008). For example, Wilkening and Fabrikant (2013) used Google Earth to help participants solve practical tasks, and measured and analysed movement types applied by the user. Bleisch, Dykes, and Nebiker (2008) assessed a potential combination of a 3D environment and abstract data, when comparing differences between reading the height of 2D bar charts and reading bar charts placed in an interactive 3D environment. Herman and Stachoň (2016) published a pilot test comparing static and interactive 3D visualization, and brought enriching methodology for data analysis.

Interactive visualization (i.e. with navigational interactivity) offers more ways to retrieve information than static visualization (i.e. without navigational interactivity). From this point-of-view, the navigational interactivity can be understood as the next frontier of visualization. In Figure 1, we can see the different ways 3D geovisualization offers a different number and variety of visual cues for four different settings: static pseudo 3D, static real 3D, interactive pseudo 3D, and interactive real 3D geovisualization. The above-mentioned monocular depth cues are ensured by the use of computer graphics and represent the base in all four settings. In the interactive setting, kinetic depth is added, and the real 3D setting includes a cue of binocular disparity. In interactive real 3D environments, it is especially the cues of binocular disparity and navigational options (i.e. panning, zooming, and rotating the geovisualization) allowing the user to acquire more information about the terrain (e.g. kinetic depth effect). Although both mentioned types of visual cues promote effective depth perception when used separately, they can be mutually redundant. We presume that the use of both these visual cues simultaneously don"t further improve task performance.

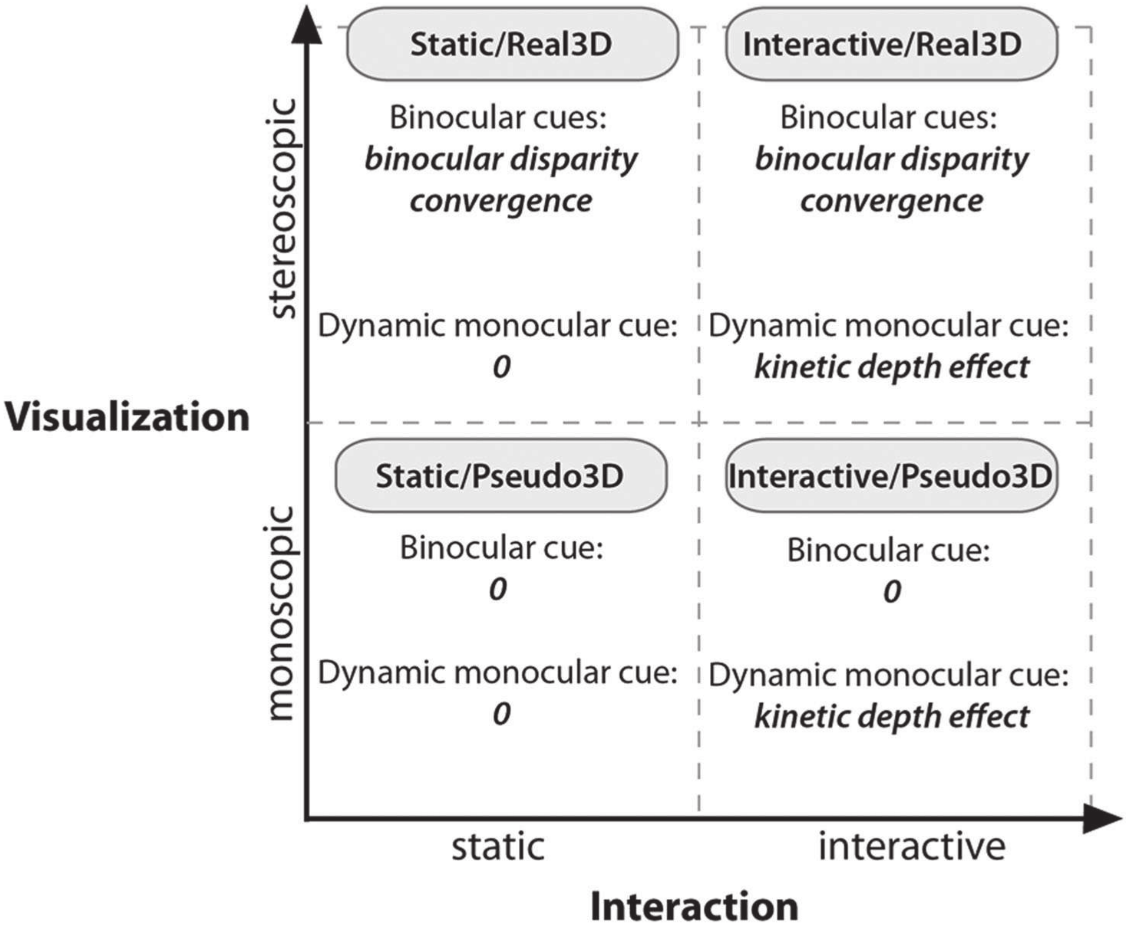

Figure 1. Additional depth cues available in different kinds of environments.

2.3. Spatial abilities of users

The role of individual differences in the context of 2D geovisualization use was explored in several studies (e.g. Kubíček et al. 2017; Stachoň et al. 2013; Griffin et al. 2006; Allen, Cowan, and Power 2006). Individuals vary not only with respect to the level of map literacy (Rautenbach, Coetzee, and Cöltekin 2017), domain-specific expertise (Svatoňová 2016), or cognitive style (Kozhevnikov 2007), but also with respect to their cognitive abilities – for instance, their working memory capacity (Daneman and Carpenter 1980) or spatial ability (Tartre 1990). The role of individual differences among users increasingly shifts in focus, leading us to seek to understand whether or not all users profit equally from visualizations and if they do not, how different users can be supported. Klippel, Weaver, and Robinson (2011) substantiated the role of individual differences for cognitive concepts and proposed a methodology to measure them, stressing both the research methodology aspect and the technological push towards the individualization of visual representations. Höffler (2010) developed a meta-analytical review comparing spatial abilities and learning with visualizations. His results, based on 27 different experiments from 19 independent studies, supported a slight advantage of high spatial ability learners in working with visual stimuli, but also demonstrated that this advantage disappears if users with low spatial abilities work with a dynamic environment and 3D visualization.

3. Research aim

In this study, we took into account the above-mentioned models (Šašinka 2012; Lokka and Cöltekin 2016) and explored human navigational interaction with the 3D environments, investigating all of the previously mentioned key factors. We designed an experiment where we measured the individual participants' spatial abilities (user issue) before they solved altitude identification tasks in different types of 3D visualizations (real and pseudo 3D) and with different types of control/manipulation possibilities (static and interactive – see Figure 1). We expected that in a real (stereoscopic) 3D visualization participants (1) would more accurately estimate the altitude features of the scene (i.e. altitude profiles) when they solve tasks in static (non-moveable) virtual 3D environments. The binocular depth cues included in the real 3D visualization were expected to help 'real 3D' users make more precise estimations. In the interactive (moveable) 3D environments, on the other hand, (2) the performance of the real 3D group and the pseudo 3D group was expected to be similar due to the possibility of manipulating the geovisualization. When moving the scene, kinetic depth cues are available for users to correctly judge altitude features in the scene, and in the case of the pseudo 3D participants, the kinetic depth cues are expected to fully compensate for missing binocular cues. Furthermore, users were expected to differ in terms of their individual spatial abilities, which could influence their performance in particular tasks. We measured participants' spatial abilities with the use of a mental rotation test (MRT), and (3) expected a close correlation between individuals' spatial abilities and their performance in the virtual geographical model.

4. Methods

4.1. Participants

Thirty-nine volunteers (18 females and 21 males; aged 16–18) were recruited from two high schools in Brno (the Czech Republic). The data were collected during October and November 2016. Before the testing, all the participants and their parents were introduced to the research proposal and study design, which was previously approved by the ethics commission of Masaryk University. All but four participants had some previous basic or intermediate experience with 3D visualization applications, such as watching 3D movies or playing interactive games on a computer, but none of them had experience in interacting with 3D geographical data as used in this study. The participants were randomly divided into two groups with an equal proportion of males and females, in order to balance out the suggested differences between males and females in mental rotation tasks. The experimental conditions (including lighting conditions and other external factors) were identical for both groups. All participants had normal or corrected-to-normal vision, and had no motor/movement limitations. We did not perform an objective visual impairment testing, but no participants reported colour vision impairment during the initial test questionnaire or post-test individual interviews. All participants agreed with the experimental procedure and participated voluntarily, with the open opportunity to withdraw from the testing at any time.

4.2. Materials and geographical data

The test was administered with the testing platform hypothesis (Štěrba et al. 2015; Popelka et al. 2016). For the main experiment, a new testing application was developed based on the Unity® game engine.[1] The application supports real-time rendering of large 3D geographical models using both monoscopic and stereoscopic displays, and also automates data collection for further analysis. For each task, the user''s answers and task performance time were logged. After the testing session, data were exported to a structured text file and processed using the R statistical software package.

All 39 participants were tested individually using the same hardware setup: a desktop PC and 27″ display compatible with NVIDIA 3D Vision technology. Users were instructed to put on/off shutter glasses before each section of real 3D/pseudo 3D tasks. A generic PC mouse was used as an input device. In order to keep interaction straightforward for users, we chose an interaction scheme consisting of only three types of actions: orbiting, dragging, and zooming. These actions were controlled by the left button, right button, and mouse wheel, respectively. The range of rotation, panning, and zooming was limited to prevent participants from accidentally moving the terrain completely out of sight or moving a virtual camera below the terrain. Digital terrain models (DTMs) were used for generating 3D models of terrain. A fourth-generation Digital Terrain Model of the Czech Republic (DTM 4G) was acquired by airborne laser scanning and processed to a ground resolution of 5 × 5 m. DTM 4G is now being distributed by ČÚZK (Czech Office for Surveying, Mapping and Cadastre). Six randomly chosen DTMs from various parts of the Czech Republic were used as an input for the experiment. Surfaces with textures were computed from the input DTM and corresponding orthophoto data. 3D models were vertically scaled by variable *Z* factors (one 3D model had a *Z* of factor 1, one model a *Z* of factor 2, three models had a *Z* factor of 3, and one model had a *Z* factor of 4), in order to highlight relatively small variation in altitude in the landscapes.

4.3. Procedure design

The experimental procedure consisted of three main parts. In the first part, we measured the mental rotation skills of all participants. The second part was the main experiment and included tasks where participants were asked to work with 3D geovisualizations to estimate altitude profiles. In this second part, we measured participants' abilities to estimate profiles of geographical models in two stages. In the first stage, both static 3D geovisualizations were presented and participants' estimation of altitude profiles was based only on visual stimuli, with no possibility to interact with the visualizations. The second stage presented interactive environments where participants could manipulate the 3D geovisualizations to estimate the altitude profile. The experiment finished with a third part, which followed immediately after the altitude profile estimation. Using rating scales, participants were briefly interviewed by the experiment operator about their general feelings, previous experience with 3D interactive environments, potential subjective task-solving improvements, and subjective preferences about the task-solving environment.

Participants were randomly divided into two groups, which both used the same geographical models, but in a different task order. Tasks were partially counterbalanced by swapping the order of pseudo 3D (monoscopic) and real 3D (stereoscopic) tasks. See Figure 2 for an overview of the experimental design, and see the supplementary video for a detailed understanding of both tests (the supplementary video is available online at https://youtu.be/ddL6gInQFh4). We used a within-subjects 2 × 2 factorial controlled experiment examining stereoscopic versus monoscopic displays (Factor 1: Visualization) and static versus interactive displays (Factor 2: Interaction). All participants experienced all four combinations (static pseudo 3D, static real 3D, interactive pseudo 3D, and interactive real 3D).

4.3.1. Pilot study

We initially conducted a pilot study in order to validate our research tools. At a public scientific event (Researchers' Night 2016, Brno), 17 participants (11–45 years) tested the application we developed

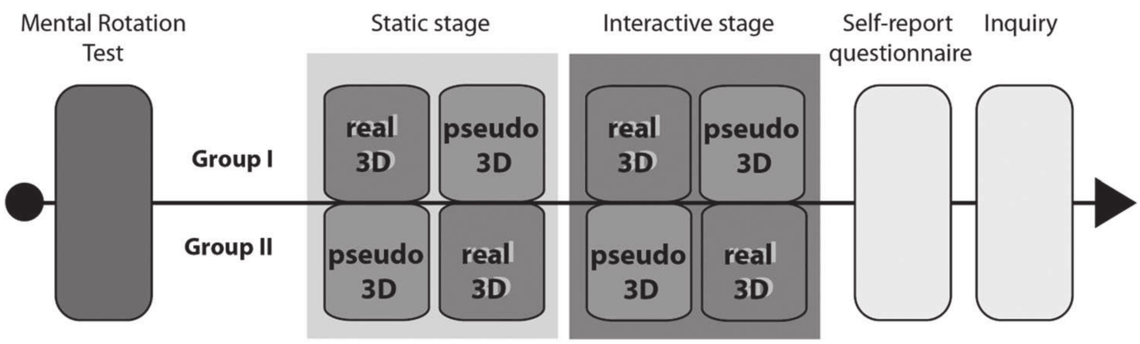

Figure 2. Design of the experiment.

for testing purposes. We observed users' interactions with the application and we also interviewed participants about the usability of the application and level of subjectively experienced difficulty. Based on this experience, participants found the developed application very user-friendly, stating that even 11-year-old children were able to go through the entire procedure without difficulty. The overall accuracy of the answers throughout the pilot testing was 72%, which indicated an appropriate difficulty level of items and applicability of the research design. After the pilot study, we made some minor adjustments to the instructions and examples (grammar revision, graphic resolution of figures, simplifying of instructions). The test tasks (stimuli, navigation, etc.) were used without any changes.

4.3.2. Task and stimuli

The test arrangement was designed specifically for the purpose of this study. A MRT was used for the test of spatial abilities. The version of the MRT used in the study was developed by Ivana Žahourová as part of a new test battery focused on object-spatial cognitive style (Vidláková 2010). The MRT consists of two sub-tests (see Figure 3). There are eight tasks in the first visual comparison sub-test. In each task, two objects are displayed simultaneously, and the participant should judge whether the objects are identical or not (see Figure 4). In the second sub-test, the memory recall sub-test, the model figure is presented for a given time, and then four other figures are presented individually. Participants should again judge whether the figures that follow are identical to the model figure or not (see Figure 5). The total number of correct answers is an indicator of spatial orientation ability (Ekstrom et al. 1976). The MRT developed by Žahourová was inspired by and based on concepts from two other psychological tests (Vandenberg-Kuse MRT – Vandenberg and Kuse 1978; and the Measure of the Ability to Rotate Mental Images – Campos 2012), both of which are very well-grounded in the psychological literature and theories (e.g. Ganis and Kievit 2015).

The second part of the testing battery included a non-interactive (static) stage and an interactive stage. In the interactive stage, participants were asked to estimate the profiles of digital elevation models displayed in static real 3D (stereoscopic), and static pseudo 3D (monoscopic) visualizations. In order to avoid the learning effect, the order of the real 3D and pseudo3D sessions was swapped for group 1 and group 2 (see Figure 2). As seen in Figure 6, each session consisted first of two training tasks, followed by six experimental tasks.

All tasks included the 3D geographical model with a given task and an answer sheet in one screen, as seen in Figure 7. Two types of tasks, which we labelled '1:3' and '3:1', were alternated in the testing battery. '1:3' tasks displayed a set of two interconnected coloured marks in the geographical terrain on the left part of the screen (Figure 7). On the right side of the screen, there were three figures with different profiles. Participants were asked to determine which of the profiles matched the real profile between the marks in the terrain.

'3:1' tasks displayed three pairs of interconnected coloured marks set in the geographical terrain in the left part of the screen (Figure 8). On the right side, there was a single profile, and participants

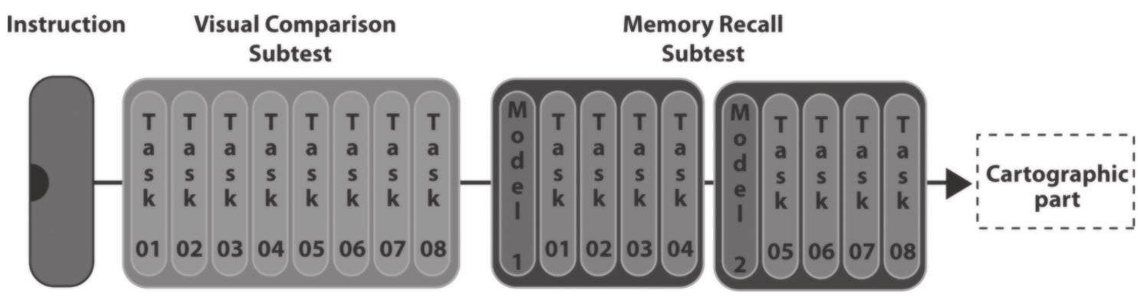

Figure 3. The first part of the experiment, the MRT.

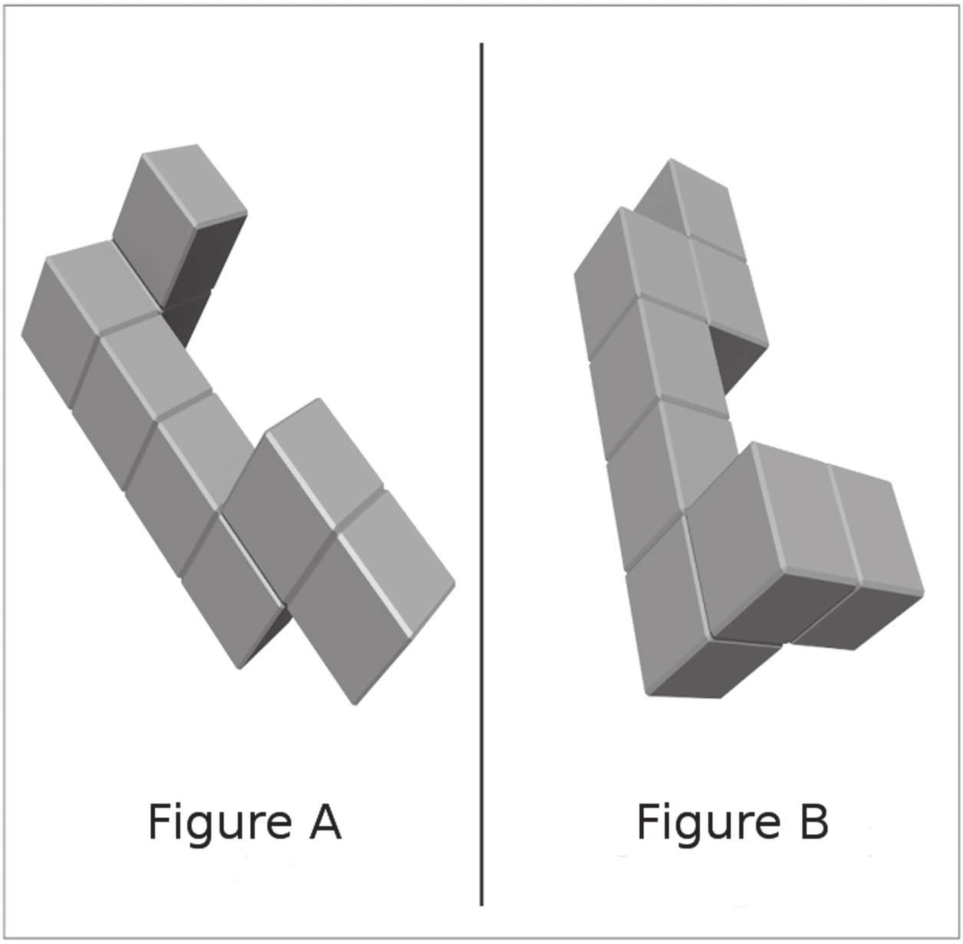

Figure 4. An example of the task from the visual comparison sub-test.

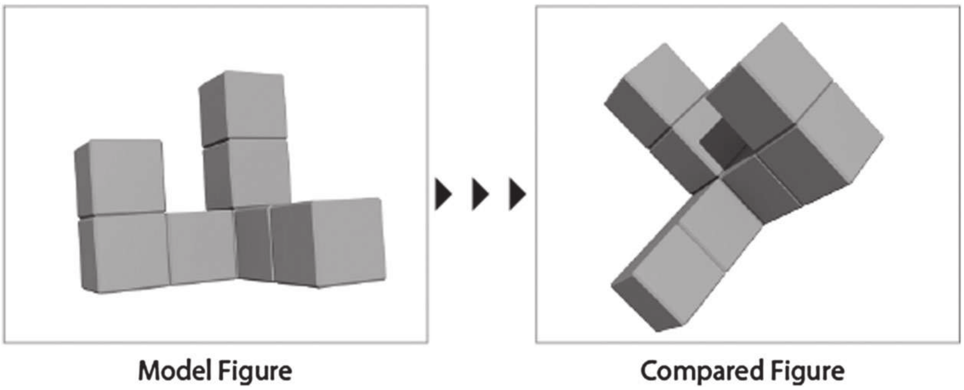

Figure 5. An example of the model figure and figure that follows it from the memory recall sub-test.

were asked to determine which one of the three pairs of displayed interconnected coloured marks shown in the terrain in the left part of the screen matched the given profile.

After the end of the testing battery, we asked participants a series of questions focused on their subjective opinions about the different types of interactive 3D visualizations.

5. Results

The recorded information about the users' performance was statistically analysed. Repeated-measures (within-subjects) ANOVA was used for the evaluation of correct answer rates for the

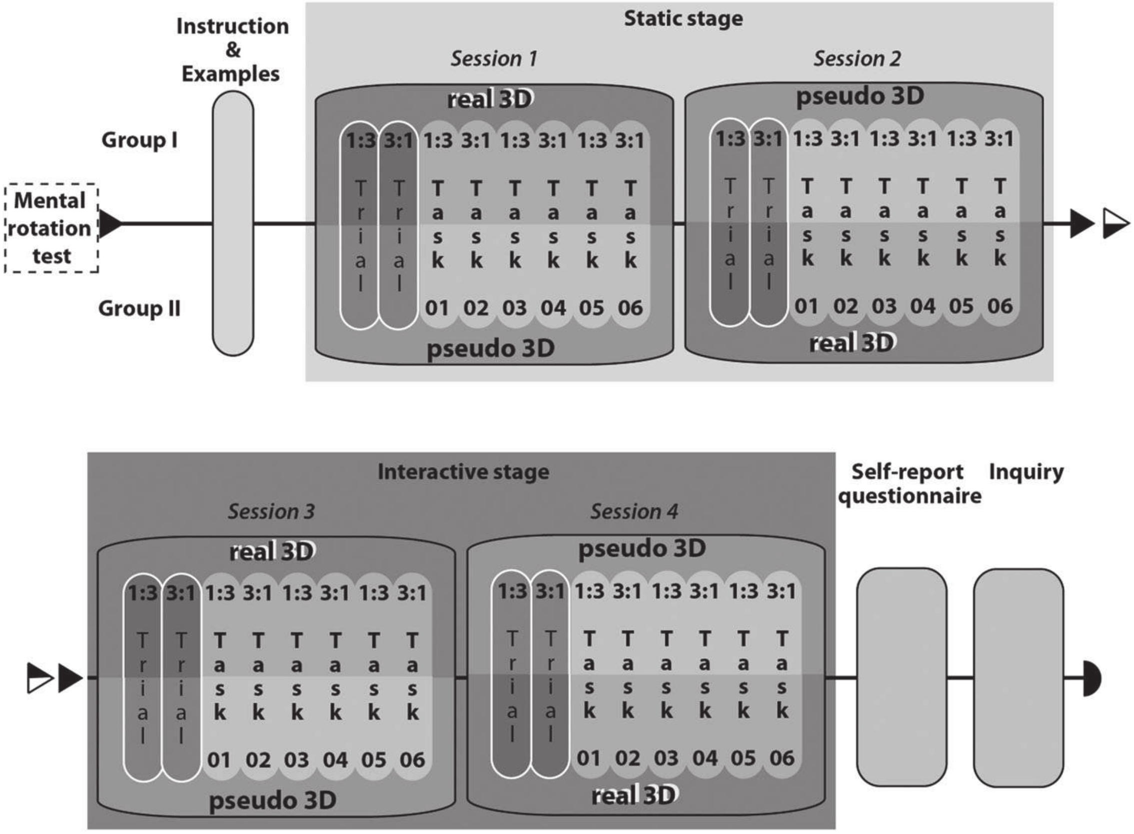

Figure 6. Detailed schema of the second part of the experiment.

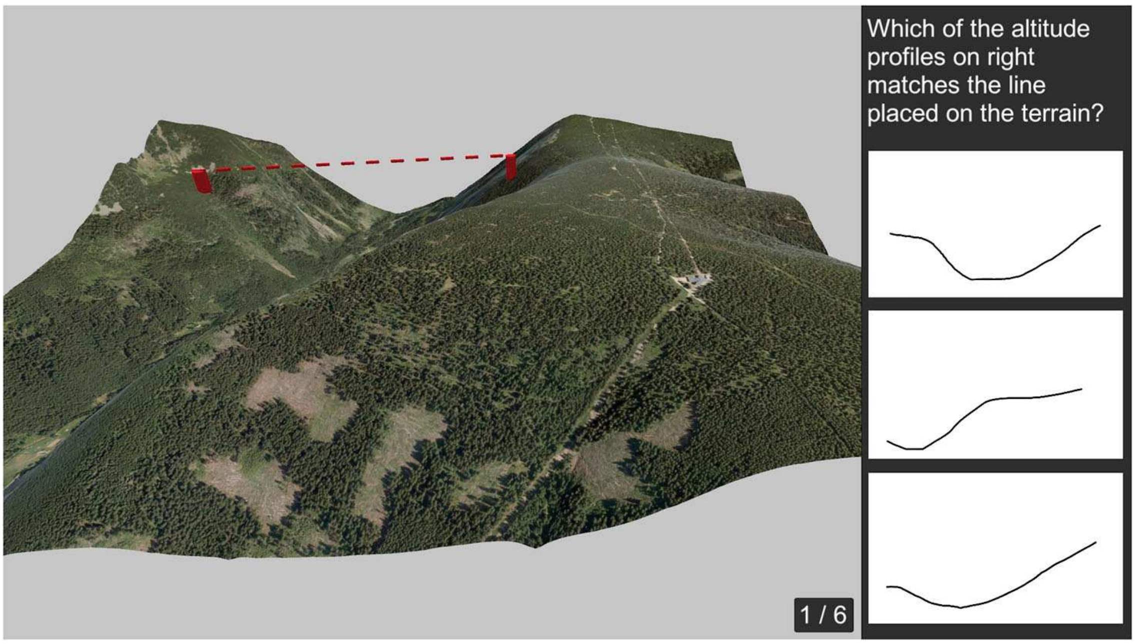

Figure 7. An example of a '1:3' task. The terrain model with a single pair of connected points is rendered on the left side of the screen. Three different altitude profiles are displayed on the right side – one of them corresponds to the terrain in the model. Screenshot from the testing application.

altitude profile identification with factors of static–interactive, pseudo 3D–real 3D, and their combinations (Figure 9). The effects of the order of the pseudo 3D–real 3D conditions were not significant in any of the task combinations (four *t*-tests brought non-significant results), so that we could analyse the two groups together. Only the difference between the static and interactive tasks was

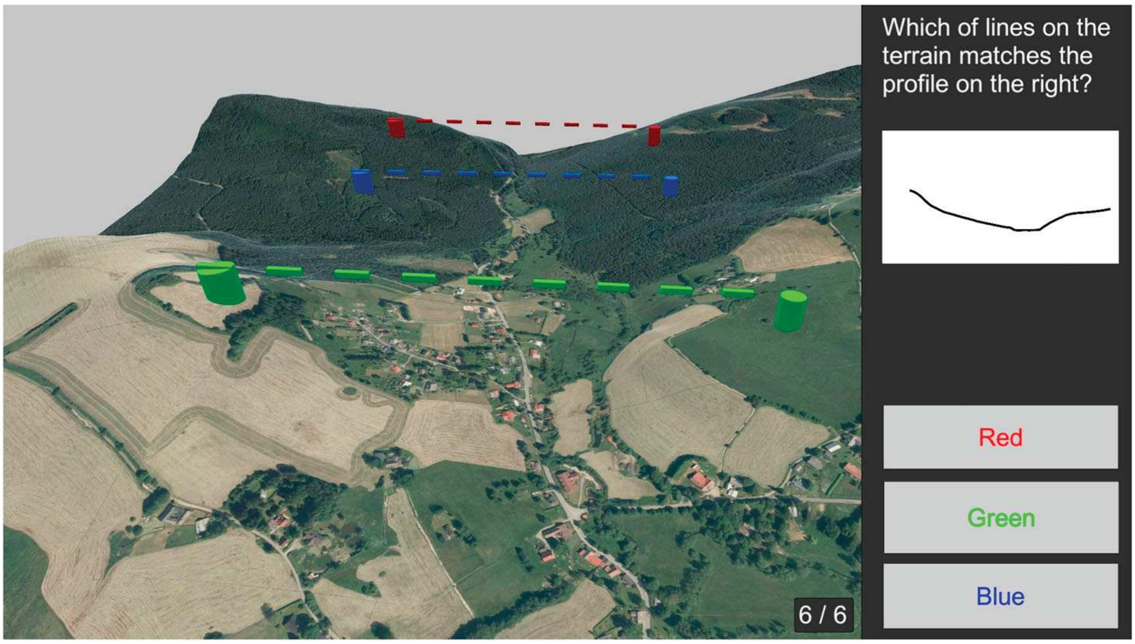

Figure 8. Example of a '3:1' task. The terrain model with three pairs of connected points is rendered on the left side of the screen. A single altitude profile is displayed on the right side. One of the three terrain profiles between the connected points corresponds to the altitude profile. Screenshot was taken from the testing application.

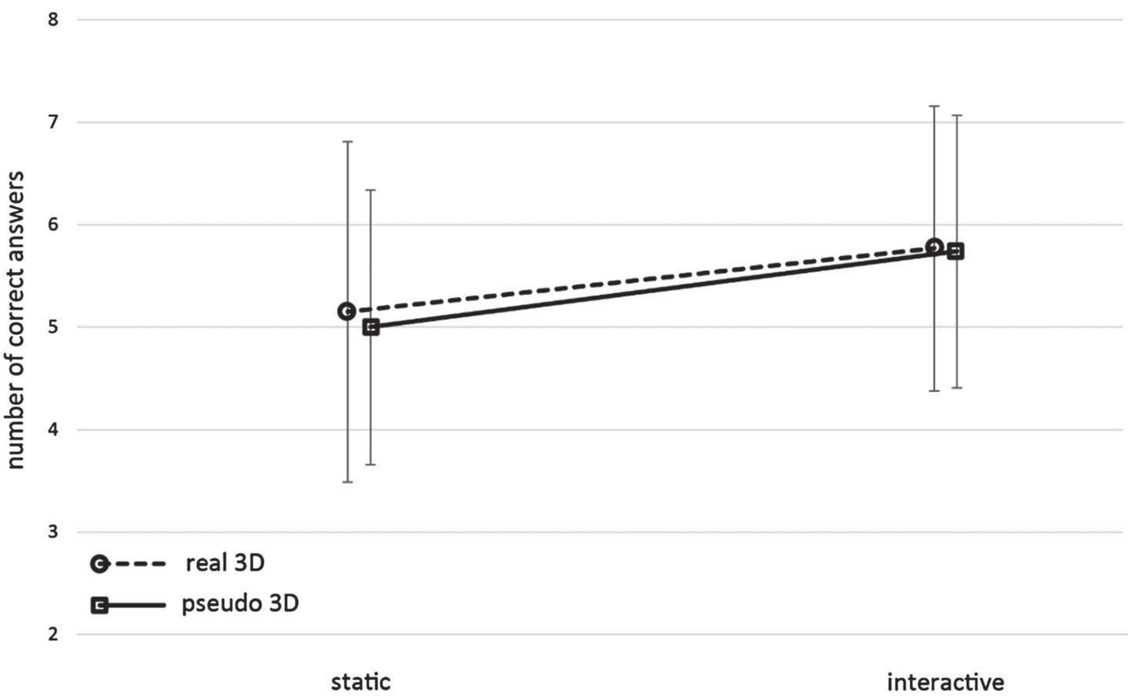

Figure 9. Number of correct answers in the altitude profile estimation. $N = 39$ in all conditions. Pseudo 3D (static $M = 5.00$, SD = 1.34; interactive = 5.74, SD = 1.33) and real 3D (static $M = 5.15$, SD = 1.66; interactive = 5.77, SD = 1.39).

found to be statistically significant ($F = 17.068$; df = 1; $p < .001$; $\eta^2 = 0.130$). Neither the difference between pseudo and real 3D ($F = 0.298$; df = 1, $p = .586$; $\eta^2 = 0.003$) nor the interaction of the two factors (3D cue type and interactivity) was significant ($F = 0.152$; df = 1; $p = .697$; $\eta^2 = 0.001$). We repeated the analyses of the main effects with t-tests with the same results both for static and interactive tasks ($t = 2.972$, df = 152.3, p-value = .003) and for the pseudo and real 3D conditions ($t = -0.382$, df = 151.9, p-value = .703).

Repeated-measures ANOVA was also used to analyse response times in the altitude profile task (Figure 10). Again, only the difference between the static and interactive tasks was found to be statistically significant ($F = 21{,}393$; df = 1; $p < .001$; $\eta^2 = 0.158$). Neither the difference between pseudo 3D and real 3D ($F = 0.061$; df = 1, $p = .805$; $\eta^2 = 0.001$) nor the interaction of the two factors ($F = 0.547$; df = 1; $p = .461$; $\eta^2 = 0.005$) were statistically significant. We repeated the analyses of the main effects with t-tests with the same results both for static and interactive tasks ($t = 3.267$, df = 132.8, p-value = .001) and for the pseudo and real 3D conditions ($t = 0.169$, df = 153.9, p-value = .866).

We also performed additional analyses to explore the dataset and look for some potential trends or patterns. Among others, we compared alternative types of tasks (e.g. 1:3 and 3:1) in order to determine whether there were differences in difficulty. We didn"t find any significant differences in the response time (1:3 m = 18.72 s; 3:1 m = 20.04 s) or accuracy (1:3, 71.7%; 3:1, 79.7%). It seems that the variability in the performance depends above all on the concrete scenes and landscape profiles. We also analysed the data to check for potential learning effects. We addressed this question by means of comparing the results (response time and correctness) for the first and the second sessions of each stage. The differences were not statistically significant for either the static or the interactive stage (see Figure 6). Neither was there a recognizable trend in the response time nor in the accuracy between sessions, thus we assumed no learning effect was caused by the order of static and interactive stages.

In order to identify potential gender differences, the Welch Two Sample t-test was used for a comparison of correct answers in altitude profile task between males and females (Table 1).

The Welch Two Sample t-test was also used for the comparison of performance in the MRT between males and females (Table 2).

The Pearson correlation coefficient was used to assess the relationship between the total score in the MRT and performance in geographical tasks. Males ($n = 21$) and females ($n = 18$) were tested separately. Among female participants, no correlation was found between their total scores on the MRT and geographical tasks. A low, positive but insignificant correlation was found in males (Table 3).

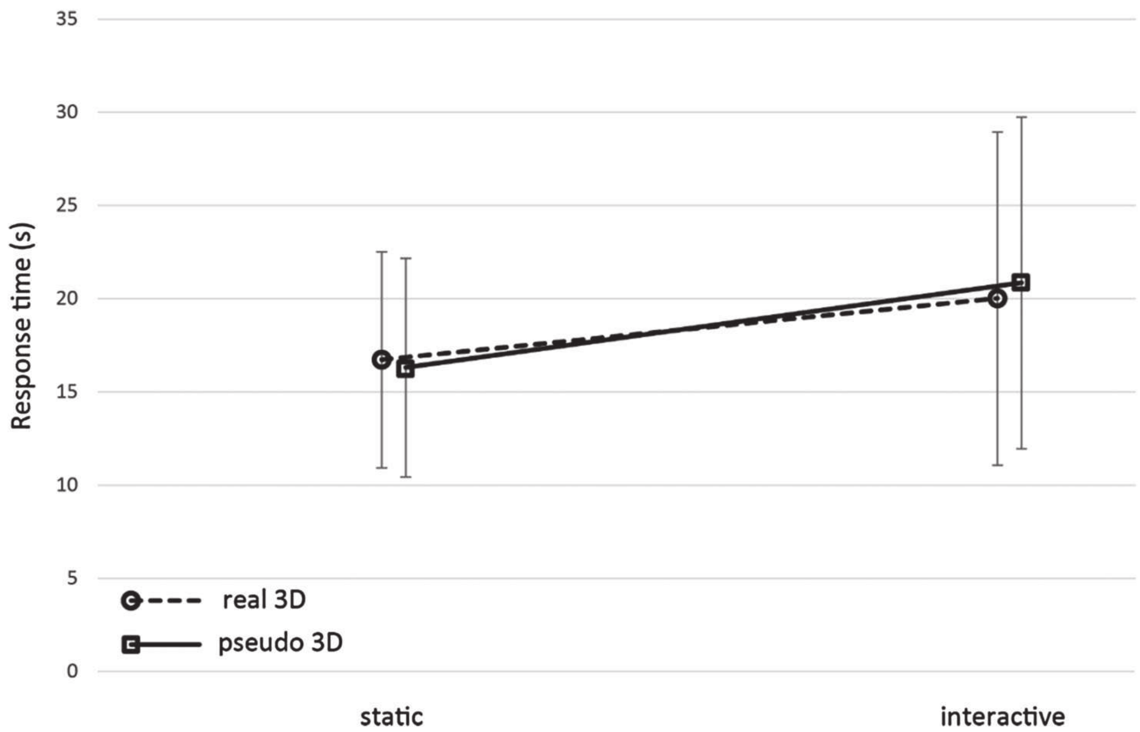

Figure 10. Response time (s) in the altitude profile task. $N = 39$ in all conditions. Pseudo 3D (static $M = 16.30$, SD = 5.86; interactive = 20.85, SD = 8.89) and real 3D (static $M = 16.72$, SD = 5.79; interactive = 20.01, SD = 8.94).

Table 1. Comparison of males ($N = 21$) and females ($N = 18$) in the number of correct answers in the altitude profile task.

	M Males	*M* Females	SD Males	SD Females	*t*	df	*p*
Static pseudo 3D	5.33	4.61	1.24	1.38	1.709	34.59	.096
Static real 3D	5.43	4.83	1.57	1.76	1.108	34.47	.276
Interactive pseudo 3D	5.71	5.78	1.45	1.22	−0.149	36.98	.883
Interactive real 3D	6.14	5.33	1.56	1.03	1.938	34.90	.061
Total number of correct answers	22.62	20.56	4.57	4.30	1.452	36.64	.155

Table 2. Comparison of males ($N = 21$) and females ($N = 18$) in the number of correct answers in the MRT.

	M Males	*M* Females	SD Males	SD Females	*t*	df	*p*
Visual comparison sub-test	5.95	4.94	1.43	1.86	1.871	31.67	.071
Memory recall sub-test	5.38	4.17	1.63	1.62	2.330	36.16	.025
Total number of correct answers	11.33	9.11	2.56	2.63	2.664	35.74	.012

Table 3. Correlation between MRT (total score) and performance in altitude estimation tasks (correct answers).

	MRT total score (males)		MRT total score (females)	
	r	*p*	*r*	*p*
Pseudo 3D and Static	0.06	.8	0.05	.86
Real 3D and Static	0.10	.67	−0.12	.63
Pseudo 3D Interactive	0.27	.24	0.14	.59
Real 3D and Interactive	0.29	.2	−0.10	.69
Total number of correct answers	0.23	.31	−0.02	.93

Table 4. Rating of subjectively experienced difficulty for all conditions in the geographical tasks.

	Static		Interactive	
	Mean	Median	Mean	Median
Pseudo 3D	2.74	3	2.08	2
Real 3D	2.13	2	1.49	1

Note: A 5-point Likert scale (1 = very easy, 5 = very difficult) was used.

Table 5. Preference of participants ($N = 39$) for 1:3 and 3:1 task types, respectively.

Preference of	1:3 type of task	No preference	3:1 type of task
Frequency	17	10	12

In the third part of the experiment, with the help of Likert scales, participants rated which type of environment (visualization and interaction) was most difficult for them (see Table 4). Subsequently, they chose which type of task – '1:3' or '3:1' – seemed to be easier (see Table 5). The experiment finished with a short discussion led by the experiment facilitator. Participants gave verbal feedback about the experiment procedure. They mostly reported that the most difficult part of the cartographic experiment was the static pseudo 3D environment. Some participants experienced difficulties with the manipulation (interaction) of the 3D geographical models, while others reported discomfort using the shutter glasses. They perceived irritating flickering or they experienced a slight headache. However, nobody reported more extreme physiological states that might have led to premature interruption of experiments or the failure of specific parts of the experiment.

6. Discussion

This experiment focused on user performance with different types of 3D visualizations within VEs with different levels of navigational interactivity. The research followed outcomes from recently published articles, e.g. Špriňarová et al. (2015), Herman and Stachoň (2016), and Klippel, Weaver, and Robinson (2011), and was performed using the Hypothesis software and on a custom-built platform based on the Unity® game engine.

The results presented in the previous section provide the following answers to the established research questions.

Our main interest was the level of navigational interactivity. The results showed that even low levels of interface complexity (pan, zoom, rotate) strongly influence the ability of a particular 3D visualization to support good performance on an altitude profile task. The evaluation of correct answers and the response times showed statistically significant differences only between the static and interactive factors, contrary to the conclusions of previously published papers (e.g. Keehner et al. 2008). The main implication of Keehner et al.''s study was the finding that more interactivity may not help to solve the tasks more effectively because users need not be able to use it an effective way. The authors also pointed out the individual differences between people and their particular ability to use interactive visualization. However, we have also found several differences between both studies which are worth mentioning. First, the level of navigational interactivity and available tools is different. While Keehner et al. (2008) provided only rotation, we incorporated zoom in and out, move, and both horizontal and vertical rotation in our study. Second, our interface was also positively constrained and did not allow the vertical rotation of more than 90° (to avoid the upside down view on the terrain). This type of 'hard constraint' could also allow individual user to easily disclose the appropriate view and accomplish the task effectively. Moreover, the user group consisted of teenagers using digital technology on a day-to-day basis and experienced in 3D gaming and other applications. Taking into account the aforementioned differences, the users were more likely to use the interactivity in a more effective way on a general level. Other interaction primitives (Roth 2012) used for exploratory geovisualization, such as layer switching, transparency setting, brushing, or displaying detail-on-demand can be also used in the interactive 3D environment of spatial data (Herman and Řezník 2015; Sieber et al. 2016).

In addition to the influence of navigational interactivity, we focused on the influences of spatial abilities on user performance within the 3D environment. The results from the MRT showed a low but insignificant correlation only in the case of male participants. In case of female participants, no correlation was found. It might indicate that men and women use different cognitive strategies when solving spatially oriented tasks within 3D environments. This interpretation is consistent with the theory of spatial and object imagery, where Blazhenkova and Kozhevnikov (2009) mention that males are relatively more frequent 'spatial imagers' and vice-versa, such that females could be described relatively more frequently as 'object imagers'. The MRT is an indicator of the level of 'spatial imagery'.

Another issue was devoted to the differences between the two task types. We expected the 1:3 tasks and the 3:1 tasks (compare Figures 7 and 8) to produce different levels of cognitive load. We assumed that the 3:1 task would require higher cognitive load because of the necessity to mentally create three different 3D lines on the terrain and compare them with the suggested altitude profiles. Therefore, we hypothesized that we would observe longer response times in the case of 3:1 tasks. The results showed that there were no significant differences in the response time and correctness between the task types.

Finally, an influence of the type of 3D visualization (pseudo (monoscopic)/real (stereoscopic)) on the performance of users was observed. The differences in the use of real 3D visualizations show slightly better, but not significantly different, results as measured by rate of correct answers. Therefore, the influence of the type of 3D visualization is still unclear, with neither method clearly performing better. This finding is consistent with those of Ware and Franck (1996), Zanola, Fabrikant, and Cöltekin (2009), Torres et al. (2013), or Špriňarová et al. (2015).

The comparison of objective results with subjective user preferences was also interesting. The pseudo 3D (monoscopic) static task had the worst subjective evaluation. However, the differences between real and pseudo 3D tasks were insignificant based on objective results. On the other hand, the real 3D static and pseudo 3D interactive environments obtained similar subjective evaluations (2.13 and 2.08 on the Likert scale, Table 4), but the objective results demonstrated considerable differences in users' performance (Figure 9). This could indicate that users have a tendency to overestimate the importance of control method compared with visualization type, which can be explained by cognitive biases, e.g. illusion of control (Thompson 1999). Such an effect of incongruence between subjective rating and objective performance stresses the importance of conducting objective empirical user studies.

7. Conclusion

Based on the results interpreted in the discussion, we can conclude that the major influence on correct answers was navigational interactivity, which provides additional depth cues. However, the decisions performed in the static environments were made faster than those made in the interactive environment.

We did not observe any significant positive effect of real 3D (stereoscopic) in either the static or the interactive environment. Contrary to this finding, Juřík et al. (2017) provide evidence of a positive influence of real 3D visualization on relative point altitude evaluation. Both experiments used almost identical environments and spatial data, but the tasks were different. Based on our results, it appears that for certain types of tasks (as in our case, working with terrain profiles), it is better to use an interactive visualization, no matter whether it is real 3D or pseudo 3D. The advantage of pseudo 3D visualization in this case is that it is literally cheaper because it does not require specific hardware. An interactive pseudo 3D visualization can be produced simply by developing appropriate software. It can be easily modified and currently includes a broad spectrum of technologies, ranging from web-based applications to those available on the desktop. Summarizing our findings from the 3D visualization design viewpoint, we can recommend the researchers concentrate on the (navigational) interactivity instead of stereoscopic visualization. Our conclusions are in line with the current report of Roth et al. (2017) mentioning the necessity to investigate the strategies to compare static and interactive maps and also to evaluate the interactivity in map use cases.

The individual differences among users mentioned by Keehner et al. (2008) are one of the open issues to be solved. We were not able to log out the view at our interaction data when the participants found the 'best' angle to see what was needed for the actual judgement. However, we are currently working on tools which enable us to timestamp and measure types of interaction (zoom, move, rotate) (see, e.g. Herman and Stachoň 2016; Herman et al. 2016). This tool will also enable us to reconstruct the view used for the final judgement and describe the users' performance and strategies on the inter-individual level.

Our conclusions are limited to the particular tasks tested in this experiment – a strong influence of task dependency – and are also limited by the relatively specific group of participants tested in this experiment, which consisted of high-school students with limited map-reading expertise. These 'digital natives' have frequent experience with 3D visualizations, at least with pseudo 3D ones. So, it is possible that they had previously learned how to work effectively with 3D applications. We are planning to focus on different user groups and to extend the complexity of tasks solved by the participants in future work. We want to perform further experiments with these factors modified using another two vertices of the previously described triarchic model.

Note

1. The Unity game engine has recently been frequently used for the development of serious games and other research applications, in addition to commercial games. For more details, see: https://unity3d.com/.

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RESEARCH ARTICLE

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Personalized landmark adaptive visualization method for pedestrian navigation maps: Considering user familiarity

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Abstract

Landmark-based pedestrian navigation can assist pedestrians in navigating successfully. Previous studies have investigated the factors affecting the cognitive efficiency of landmark visualization in terms of both the visual salience of landmarks and the personal characteristics of users. However, empirical studies and applications that consider the influence of spatial familiarity on landmark representation are limited. In this article, we propose a personalized landmark adaptive visualization method for pedestrian navigation maps considering user familiarity. We first explore the influence of spatial familiarity on landmark salience and symbols using cognitive experiments. The results showed that unfamiliar people preferred strong visual salience landmarks and image-based symbols, while familiar people preferred strong semantic salience landmarks and text-based symbols. Based on these results, a mathematical model of landmark salience for selecting personalized landmarks is proposed, and association rules between landmark salience and symbols are mined. Finally, the framework of a landmark visualization method is proposed based on the rules. To verify the effectiveness of the proposed method, a prototype system is developed, and a comparative experiment is conducted with a Baidu map. Experimental results showed that the proposed method has direct practical implications for the development of pedestrian navigation systems, depending on different target users.

1 | INTRODUCTION

In recent years, pedestrian navigation systems have brought convenience to the public and have become increasingly popular (Speake, 2015). Landmarks are essential elements in cognitive maps that can aid pedestrian navigation and provide cues to enhance spatial orientation and route guidance (May, Ross, Bayer, & Tarkiainen, 2003; Millonig & Schechtner, 2007). As salient objects to communicate and organize spatial knowledge during navigation, landmarks have attracted the attention of many researchers in the field of spatial cognition and geoinformation science, especially research on landmark-based pedestrian navigation (Delikostidis, van Elzakker, & Kraak, 2016; Fang, Yang, Guan, Feng, & Jiang, 2020; Filomena & Verstegen, 2021). Landmark visualization is an important factor affecting the efficiency of guidance in landmark-based pedestrian navigation, but current research is limited in considering the personalized preferences of pedestrians.

Developing a personalized landmark model and an adaptive visualization method can improve the efficiency and performance of navigation. Empirical studies show that people with different levels of familiarity have different preferences for landmark selection (Nuhn & Timpf, 2020; Quesnot & Roche, 2015) and representation (Schmid, 2008). Spatial familiarity can be an important variable related to personalized navigation but is often ignored. This article summarizes the following challenges for research on landmark-based navigation maps that consider user familiarity: (1) How to select personalized landmarks for target users?; and (2) How to realize the adaptive visualization of landmarks in pedestrian navigation maps?

However, previous studies of landmark visualization methods in pedestrian navigation maps ignore the preferences of pedestrians with different levels of familiarity for landmark selection and visualization. On the one hand, the selection of landmarks is related to user attributes, such as spatial knowledge, interests, background, and emotions (Balaban, Karimpur, Röser, & Hamburger, 2017; Palmiero & Piccardi, 2017; Ruotolo, Claessen, & van der Ham, 2019; Yesiltepe, Dalton, & Torun, 2021). The selection process has been strongly personalized (Richter, 2017). To explain why something can be considered a landmark, some mathematical models of salience can be used to select personalized landmarks (Götze & Boye, 2016; Nuhn & Timpf, 2017). The weighted sum can also easily be expanded and adjusted to provide personalized settings. On the other hand, the factors influencing the cognitive efficiency of landmark visualization involve the visual characteristics of landmarks (Keil, Edler, Dickmann, & Kuchinke, 2019) and the personal characteristics of users (Nivala & Sarjakoski, 2004). Since spatial familiarity is one of the user attribute characteristics, it can be an essential basis for adjusting the weights of landmark salience indicators and adaptive visualization.

The motivation of this article is to investigate the landmark selection and visualization preferences of pedestrians with different levels of familiarity using cognitive experiments, with the aim of applying the experimental results to personalized landmark visualization in a landmark-based pedestrian navigation system for adaptive map generation to improve navigation efficiency. This study proposes a personalized landmark adaptive visualization method for pedestrian navigation maps considering user familiarity. More specifically, based on the literature (Elias & Paelke, 2008; Quesnot & Roche, 2014), the following hypothesis was tested using cognitive experiments: *People who are familiar with the environment and those who are unfamiliar with the environment have different preferences for landmarks and symbols during navigation*. In addition, to apply the experimental results to a landmark-based pedestrian navigation system, a mathematical model of landmark salience considering user familiarity for automatically selecting landmarks is proposed, and association rules between landmark salience and symbols are mined.

The remainder of this article is organized as follows. Section 2 includes a review of the literature on landmark selection and visualization in pedestrian navigation maps to summarize the differences between previous studies and our work. In Section 3, the personalized landmark adaptive visualization method is described in detail. The results of the verification experiments and discussions are presented in Section 4. Conclusions and future work are presented in Section 5.

2 | RELATED WORK

2.1 | Landmark selection considering spatial familiarity

Individual differences may affect wayfinding, such as gender (Schmitz, 1999), age (Muffato, Meneghetti, Doria, & De Beni, 2020), or spatial familiarity (Iachini, Ruotolo, & Ruggiero, 2009; Xia, Arrowsmith, Jackson, & Cartwright, 2008). Females recalled more landmarks than males, and younger people recalled more landmarks than adults (Galea & Kimura, 1993). Abu-Obeid (1998) found a significant wayfinding advantage for males in new environments but no gender differences in familiar environments. As people become more familiar with their environment, their wayfinding performance improves (Piccardi et al., 2011).

Spatial familiarity is one of the important factors that affects users' preferences for landmark selection (Gale et al., 1990). People with different levels of familiarity build different wayfinding models and use different landmarks during navigation (Ishikawa & Montello, 2006; Xia et al., 2008). People who are familiar or unfamiliar with an environment select different landmarks (Hamburger & Röser, 2014; Lovelace, Hegarty, & Montello, 1999; Quesnot & Roche, 2014). Quesnot and Roche (2014) demonstrated that people who are local to an environment focus more on strong semantic landmarks. Furthermore, familiar landmarks tend to receive the highest priority in human wayfinding (Hamburger & Röser, 2014). Spatial familiarity is also an essential factor that affects wayfinding behavior in the environment and the weight of landmark indicators. Moreover, existing studies have investigated the effects of environmental familiarity on wayfinding (Kim, Choi, Han, & Kim, 2021; Meneghetti, Muffato, Toffalini, & Altoè, 2017; Muffato & Meneghetti, 2020), but few studies have applied user spatial familiarity preferences to practical pedestrian navigation systems.

2.2 | Landmark visualization for pedestrian navigation maps

Using landmarks in maps helps users identify their location (Delikostidis et al., 2013; Hile et al., 2008). Landmarks are the essential elements of a map. Landmark visualization research covers various topics involving cartography, navigation, psychology, and spatial cognition. For example, Li, Korda, Radtke, and Schwering (2014) proposed landmarks displayed on a mobile map for distinguishing between off- and on-screen landmarks. Franke and Schweikart (2016) examined the differences in users viewing three types of landmark symbols. Keil et al. (2019) explored the visual salience of OSM landmark pictograms using eye fixation measures.

In addition, following a user-centered design (UCD) can improve the usability of pedestrian navigation systems (Delikostidis et al., 2016; Perebner, Huang, & Gartner, 2019). The concept of adaptive visualization is similar to that of UCD. An adaptive visualization method refers to extracting and representing geospatial elements relevant to user profiles, such as the current location, preferences, and requirements (Zhou, Bookwala, & Wang, 2011). In terms of personalized landmark visualization research, Elias and Paelke (2008) proposed a design concept of user-centered visualization for landmarks. Moreover, Han and Lee (2015) proposed an adaptive landmark recommendation method for travel planning using geo-tagged social media. Qiao et al. (2018) proposed a familiarity-based and preference-aware location recommendation approach named SocialMix.

2.3 | Discussion of the differences between our work and previous studies

Our work is conducted using a complex university campus as the study area. The issue of wayfinding on university campuses has attracted the interest of several researchers due to its complexity and excessive roaming (Afrooz, White, & Parolin, 2018; Iftikhar, Shah, & Luximon, 2020). There are many studies on spatial familiarity whose areas are selected on the university campus (Brunyé, Burte, Houck, & Taylor, 2015; Meneghetti et al., 2017; Muffato & Meneghetti, 2020; Muffato, Toffalini, Meneghetti, Carbone, & De Beni, 2017). The university campus not only has new students and visitors with a negligible level of familiarity, but also has senior students with a high level of familiarity. Existing studies measure subjects' familiarity with the environment in terms of time lived or frequented, such as years (Brunyé et al., 2015; De Goede & Postma, 2015) and months (Gärling, Lindberg, Carreiras, & Anders, 1986).

The differences between our work and previous studies are illustrated as follows. (1) Our work extends user familiarity as a variable that affects the weight of landmark salience indicators to a mathematical model of personalized landmark salience. In contrast, previous mathematical models of landmark salience have rarely considered user preferences with different levels of familiarity. (2) Previous studies of personalized maps mainly collected behavioral data through user–map interaction systems and then used data mining methods to obtain user preference rules. However, there is a lack of a personalized map representation method that considers user familiarity. In contrast, our work is first based on a hypothesis tested using cognitive experiments, then uses association rule mining to extract user preference rules and applies the rules to a landmark-based pedestrian navigation system.

3 | PERSONALIZED LANDMARK ADAPTIVE VISUALIZATION METHOD

The framework of the methodology is illustrated in Figure 1, which is divided into three steps: (1) The influence of spatial familiarity on landmark salience and symbols based on cognitive experiments is explored; (2) Association rules between landmark salience and symbols are mined; and (3) A personalized landmark adaptive visualization method based on these rules is proposed. In this method, we focus on personalized landmark extraction and adaptive visualization for the pedestrian navigation map. The details of the methodology are discussed in the following sections.

3.1 | Influence of spatial familiarity on landmark salience and symbols

3.1.1 | Cognitive experimental design

Study area and experimental route

A campus in Nanjing, China is selected as the study area, as shown in Figure 2. The university campus contains many salient entities that are significant in terms of visual, semantic, and structural features and host

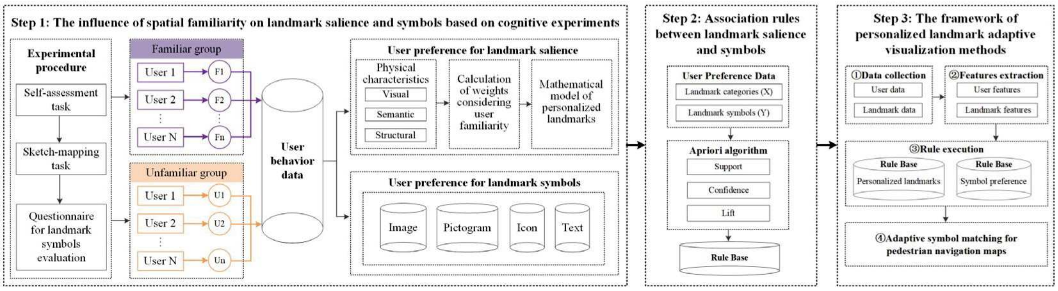

FIGURE 1 The framework of the methodology

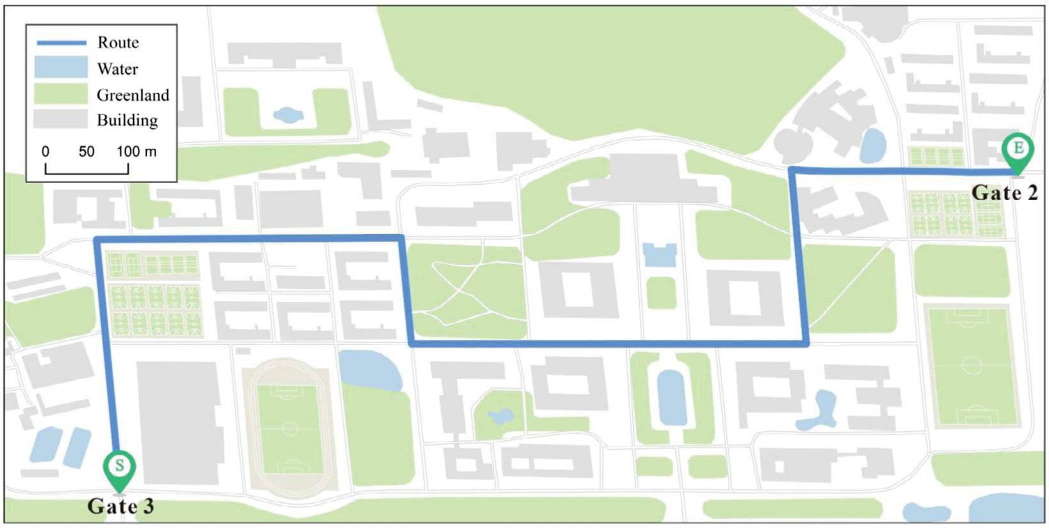

FIGURE 2 Study area and experimental route

activities to provide both education and entertainment for students. The experimental route has a total length of 1,650 m and passes various buildings and facilities. The starting point and destination are Gates 3 and 2, respectively, and there are many intersections along the route, including crossroads and Y-shaped or T-shaped paths.

Participants

The experiment was conducted with 51 participants recruited from campus flyers. All participants were volunteers and signed an informed consent form. The number of visits has been used to explore how familiar individuals are with the study area (Savage, Chun, Chavez, & Höllerer, 2013). Therefore, all participants were divided into two groups (familiar vs. unfamiliar) based on a statistical survey of the number of visits in the study area. Twenty-seven participants (14 females and 13 males) were familiar with the study area, as they had lived within the study area for over 2 years and had visited the area over 30 times. In contrast, the remaining 24 participants (8 females and 16 males) were unfamiliar with the study area, as they had visited the area less than three times.

Materials and procedure

Self-assessment task. The Santa Barbara Sense-of-Direction Scale (SBSOD) questionnaire was used to investigate the subjects' spatial ability (Hegarty, Richardson, Montello, Lovelace, & Subbiah, 2002). The SBSOD questionnaire contains 15 statements, and we reversed the negative statements to positive statements so that a higher score indicates better spatial ability. Participants had to score all the statements using a seven-point Likert scale (from 1 = "least" to 7 = "most"). Each participant filled out a self-assessment questionnaire that included a Chinese version of the SBSOD and two additional questions (i.e., about the number of visits to the study area and mapping ability).

Sketch-mapping task. This task was conducted in fine weather during daylight hours. All participants gathered at the starting point (Gate 3). When all participants arrived, the supervisors briefly introduced the experiment as follows: (a) They were asked to walk from the starting point (Gate 3) to the destination (Gate 2) under the guidance of the supervisors; (b) They could not speak or communicate during the walk; (c) They could not use the mobile map during the walk; (d) They could withdraw from the experiment at any time during the walk; and (e) When the walk was complete, they were to gather at the destination and continue to do other tasks. It is worth noting that they were not informed of the specific task at this point. After the introduction, the subjects performed the walking task with their supervisors. When they arrived at the destination, they were asked to draw a sketch map of the study area on a piece of A4 paper and to recall the details of the study area (e.g., roads, objects, buildings) as far as they could.

Questionnaire for landmark symbols evaluation. Four types of landmark symbols, including image, pictogram, icon, and text-based symbols (as illustrated in Figure 3). The pictogram symbols, icon symbols, and text symbols are mainly blue in color ($R = 0$, $G = 160$, $B = 233$). Image-based symbols are objective and realistic descriptions of landmarks. Pictogram-based symbols represent the geometric structure of landmarks based on image symbols. Icon-based symbols are more concise than pictogram symbols (the design idea comes from https://www.iconfont.cn/). Text-based symbols are the most abstract form. They are designed using Chinese characters and have a more definite meaning than other symbols.

Furthermore, we designed the questionnaire for landmark symbol evaluation (as illustrated in Figure 4). Participants had to evaluate which symbol is best for landmark representation in the pedestrian navigation map.

3.1.2 | Results: Preference for landmark salience

Analysis of self-assessment task

The mean value of all statements was calculated between two groups. Since the dependent variable of spatial ability was normally distributed, a parametric t-test was performed to assess the differences in spatial ability between the two groups (as indicated in Table 1). The results did not reveal any significant differences ($t = 1.76$, $p = .08$) between the familiar group ($M = 3.41$, $SD = 0.66$) and the unfamiliar group ($M = 3.05$, $SD = 0.79$) in terms of spatial ability.

Since the dependent variable of mapping ability was a non-normal distribution, a non-parametric Mann–Whitney U-test was performed to assess these differences (as illustrated in Table 2). The results indicated that there was no significant difference ($Z = -0.92$, $p = .36$) between the familiar group ($M = 3.67$, $SD = 0.88$) and the unfamiliar group ($M = 3.46$, $SD = 0.83$) in terms of mapping ability.

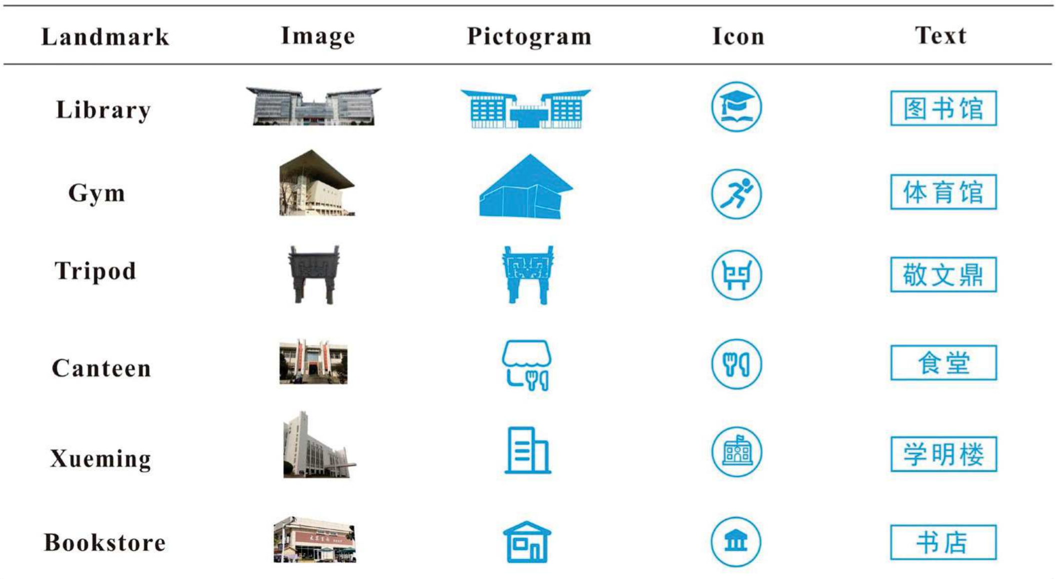

FIGURE 3 Examples of landmark symbols

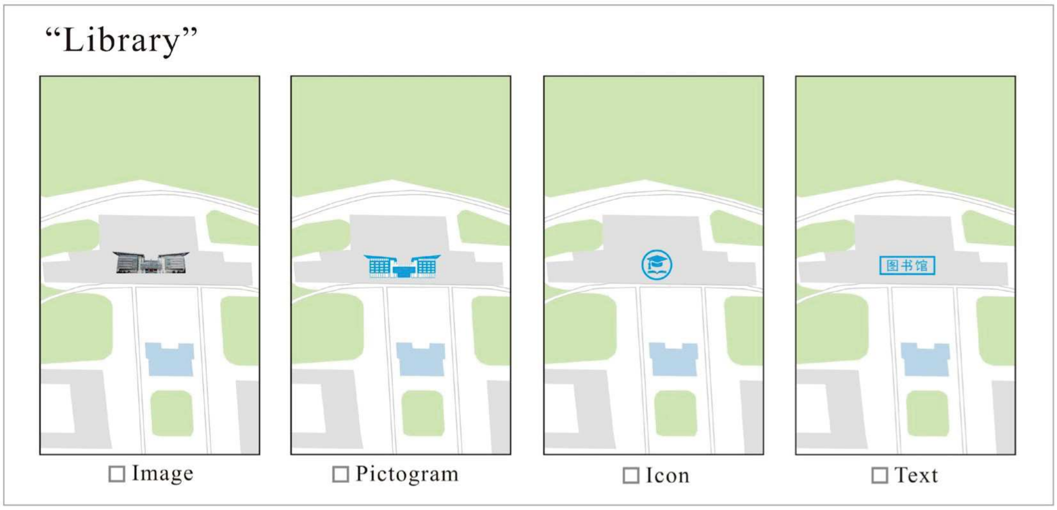

FIGURE 4 Example of a questionnaire for landmark symbol evaluation

TABLE 1 *t*-Test results of subjects' spatial ability

	Familiar (*N* = 27)	Unfamiliar (*N* = 24)	*t*-Test	
	M ± *SD*	*M* ± *SD*	*t*	*p*
Spatial ability	3.41 ± 0.66	3.05 ± 0.79	1.76	.08

Abbreviations: *M*, mean; *SD*, standard deviation.

TABLE 2 Mann–Whitney *U*-test results of subjects' mapping ability

	Familiar (*N* = 27)	Unfamiliar (*N* = 24)	Mann–Whitney *U*-test	
	M ± *SD*	*M* ± *SD*	*Z*	*p*
Mapping ability	3.67 ± 0.88	3.46 ± 0.83	−0.92	.36

Abbreviations: *M*, mean; *SD*, standard deviation.

Analysis of sketch-mapping task

Landmarks are important elements in sketches (Wang & Schwering, 2015). Therefore, we collected landmark data from all sketches and extracted 37 landmarks in the study area. Figure 5 illustrates the results of landmark extraction. The circle size represents the number of times the landmark was included in the sketches. These landmarks have distinct features (e.g., color, size, function, and location) and are easily recognizable. The statistical results showed that buildings account for the largest proportion of landmarks, followed by campus bus stations at important nodes, impressive statues, and large-area stadiums.

Figures 6a,b present examples of sketches drawn by a subject in the familiar group and a subject in the unfamiliar group, respectively. Spatial familiarity was used as an independent variable. The dependent variable was the number of times a landmark was included in the sketches. Since the dependent variable was normally distributed, we used a *t*-test to explore the differences in the number of times a landmark was mentioned between the two groups (as illustrated in Table 3). The *t*-test results indicated a significant difference ($t = 3.70$, $p = .001$) between the familiar group ($M = 16.93$, $SD = 5.14$) and the unfamiliar group ($M = 11.58$, $SD = 5.15$). This result showed that the level of environmental detail provided by familiar and unfamiliar people varied substantially.

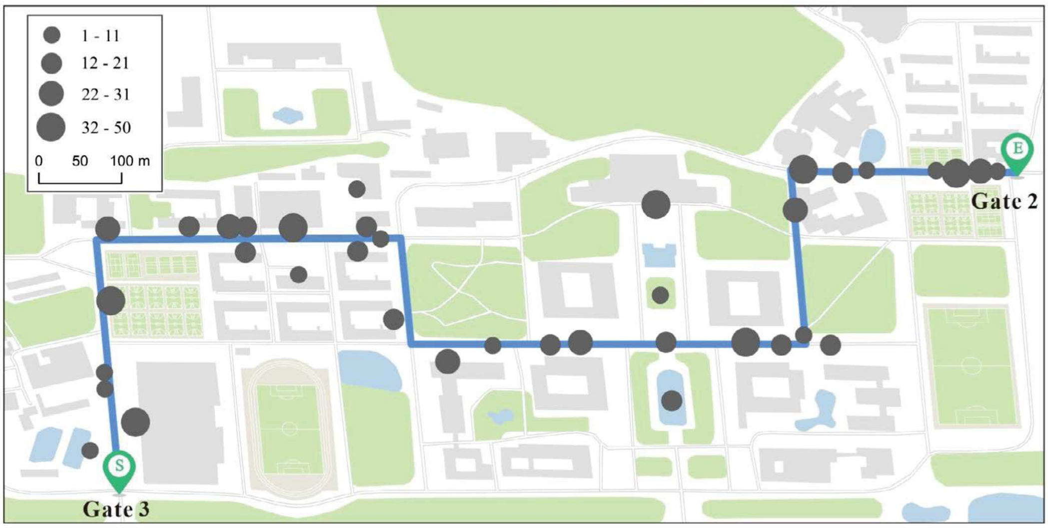

FIGURE 5 The number of times landmarks were included in the sketches

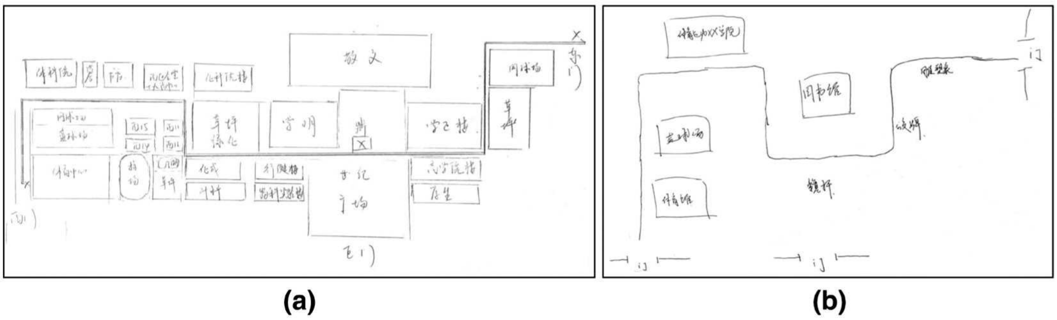

FIGURE 6 Examples of sketch maps: (a) a sketch map drawn by a subject in the familiar group; (b) a sketch map drawn by a subject in the unfamiliar group

TABLE 3 *t*-Test of the number of times the landmarks were included in sketches

	Familiar ($N = 27$)	Unfamiliar ($N = 24$)	*t*-Test	
	$M \pm SD$	$M \pm SD$	t	p
Number of mentioned landmarks	16.93 ± 5.14	11.58 ± 5.15	3.70	.001**

Abbreviations: *M*, mean; *SD*, standard deviation.

**$p < .01$.

People with different spatial familiarity preferred to use different landmarks, and the familiar group had higher landmark memory ability than the unfamiliar group. The reason is that the cognitive maps of people familiar with the environment contain more detail than those who are unfamiliar with the environment (Carlson, Hölscher, Shipley, & Dalton, 2010).

Mathematical model of landmark salience

In this section, a mathematical model of landmark salience was developed for the automatic extraction of personalized landmarks. Thirty-seven landmarks in the study area were divided into landmarks with strong visual salience, with strong semantic salience, and with strong structural salience by analyzing their features. Table 4 presents the indicators of landmark salience measurements.

Visual salience (S_{vis}) refers to the visual attractiveness of landmarks that have certain visual characteristics, such as facade area (α), shape (β), color (γ), and visibility (δ) (Raubal & Winter, 2002). Semantic salience (S_{sem}) represents cultural and historical importance (ε) and explicit markings (ζ) (Fang, Li, Zhang, & Shaw, 2012). Structural salience (S_{str}) refers to the significant location features of landmark candidates (Klippel & Winter, 2005).

In addition, the values of the indicators are normalized with feature scaling because indicators are calculated using different scoring methods. The value of all indicators is brought into the range [0, 1], with x' the normalized value and x the actual value. Finally, the equation for the overall salience (S_L) is as follows:

$$S_L = W_{vis}S_{vis} + W_{sem}S_{sem} + W_{str}S_{str} \quad (1)$$

where S_L is the overall salience and W_{vis}, W_{sem}, and W_{str} are the weights of visual salience, semantic salience, and structural salience, respectively. In addition, the weights satisfy $W_{vis} + W_{sem} + W_{str} = 1$. The literature found that people unfamiliar with the environment prefer to use landmarks with high visual salience, followed by high structural salience. In contrast, landmarks with high semantic salience are not suitable for those unfamiliar with the environment (Quesnot & Roche, 2015). Therefore, based on the above findings, we assigned the following weights for people with different spatial familiarity: $W_{vis}: W_{sem}: W_{str} = 5:2:3$ for unfamiliar people and $W_{vis}: W_{sem}: W_{str} = 3:5:2$ for familiar people. These weight parameters can be adjusted in the pedestrian navigation system according to the user's spatial familiarity.

3.1.3 | Results: Preference for landmark symbols

Crosstab analysis was used to analyze the landmark symbol choices of subjects with different spatial familiarity because it can be used to evaluate the relationship between two nominal variables. Fifty-one questionnaires were analyzed. The results showed significantly different proportions of landmark symbol selection between the familiar group and unfamiliar group ($\chi^2 = 172.3$, $p = .000$). Table 5 presents the descriptive statistics of the preference rates of the familiar group and the unfamiliar group for different landmarks.

The unfamiliar group's preference for landmark symbols from high to low was 63.31% (image), 17.27% (text), 10.43% (icon), and 8.99% (pictogram). People unfamiliar with the environment prefer image-based symbols that directly reflect the physical characteristics of the landmarks because image symbols provide a sense of reality and more details of landmarks, so strangers can quickly find the landmarks in the environment and associate them with cognitive maps. In contrast, the familiar group's preference for landmark symbols from high to low was 41.36% (text), 30.41% (icon), 16.63% (image), and 11.60% (pictogram). People familiar with the environment use more text-based symbols, which are the most abstract form of displaying an object.

3.2 | Association rules between landmark salience and symbols

3.2.1 | Association rule mining method

Data mining is used to discover and analyze personalized patterns from user behavior data automatically. Association rule mining is a popular data mining method for finding patterns, relationships, or associations that are not explicitly stored in a database. Compared with other techniques, association rule mining algorithms have been widely used in the study of preference rule extraction during user–map interactions (Wilson, Bertolotto, &

TABLE 4 The indicators of landmark salience measurements

Category	Indicator	Measurement	Value of salience
Visual	Façade area (α)	$\alpha = \int x \mid x \in$ facade	$S_{vis} = \frac{\alpha' + \beta_1' + \beta_2' + \gamma' + \delta'}{5}$
	Shape factor (β_1)	β_1 = height/width	
	Shape deviation from rectangle (β_2)	β_2 = (area of minimum rectangle $-\ \alpha$)/area of minimum rectangle	
	Color (γ)	γ = med([H, S, B])	
	Visibility (δ)	$\delta = \sum x \mid y$ visible	
Semantic	Cultural and historical importance (ε)	Using the scoring system and the weight assigned (ω_ε) is 0.7	$S_{sem} = \omega_\varepsilon \frac{\varepsilon}{\max(\varepsilon')} + \omega_\zeta \frac{\zeta}{\max(\zeta')}$
	Explicit markings (ζ)	Using the scoring system and the weight assigned (ω_ζ) is 0.3	
Structural	Structural salience (S_{str})	Landmark is not located on the route and visible	$S_{str} = [0, 0.2]$
		Landmark is located on the route	$S_{str} = [0.2, 0.5]$
		Landmark is a decision landmark near a junction	$S_{str} = [0.5, 1]$

TABLE 5 Summary of landmark symbol evaluation

Group	Image (n, %)	Pictogram (n, %)	Icon (n, %)	Text (n, %)	χ^2
Familiar (N = 27)	76 (16.63)	53 (11.60)	139 (30.41)	189 (41.36)	172.3***
Unfamiliar (N = 24)	176 (63.31)	25 (8.99)	29 (10.43)	48 (17.27)	

Note: χ^2 refers to a chi-square test.
***$p < .001$.

TABLE 6 Examples of the preferences for landmark categories and symbols (1 = prefer, 0 = none) considering user familiarity (1 = familiar, 0 = unfamiliar)

		Landmark categories			Landmark symbols			
User ID	Spatial familiarity	Visual	Semantic	Structural	Image	Pictogram	Icon	Text
1	1	1	0	0	0	0	0	1
1	1	1	0	0	0	0	0	1
1	1	0	1	0	1	0	0	0
1	1	0	1	0	0	0	0	1

Weakliam, 2010). This study aims to identify the personalized mode of user interactions with pedestrian navigation maps based on user familiarity. Therefore, association rule mining can explicitly generate preference rules for users to interact with different landmarks and symbols.

Association rules are mined from datasets based on frequent and infrequent item set analysis. The basic form of an association rule can be defined as $X \Rightarrow Y$ (IF X THEN Y), where X is the antecedent and Y is the consequent (Agrawal, Imieliński, & Swami, 1993). The item sets X and Y are the antecedent and consequent, respectively. In this study, the item sets X represent "Landmark categories": $X = \{C_{vis}, C_{sem}, C_{str}\}$ and the item sets Y represent "Landmark symbols": $Y = \{Image, Pictogram, Icon, Text\}$. To further clarify these concepts, Table 6 presents examples of the preferences for the categories and symbols of recalled landmarks considering spatial familiarity. The rules are generated by the Apriori algorithm, which uses support-based pruning to mitigate the effects of exponential growth of the candidate item set (Agrawal & Srikant, 1994). Three metrics are used to compare rules: support, confidence, and lift.

Support refers to the probability of X and Y occurring together. $S(X \cup Y)$ is the probability of the occurrence of all item sets. The support is given as follows:

$$S(X \Rightarrow Y) = S(X \cup Y) \quad (2)$$

Confidence refers to the probability of Y occurring when the precondition X occurs, given by Equation (3):

$$C(X \Rightarrow Y) = S(X \cup Y) / S(X) \quad (3)$$

Lift is a measure of its support compared with the support that can be expected if X and Y are independent. The lift is given as follows:

$$L(X \Rightarrow Y) = S(X \cup Y) / S(X) S(Y) \quad (4)$$

3.2.2 | Association rule analysis

To explore the symbol preferences corresponding to landmark categories for users with different levels of familiarity, we take the maximum value of confidence in different landmark categories (visual, semantic, structural) to construct rules. Table 7 illustrates the association rules generated by the Apriori algorithm. The association rules are denoted by $R = \{R_1, R_2, R_3, \ldots, R_6\}$ .R_1, having frequent items "Landmark categories = Semantic" and "Landmark symbols = Text," indicates that 46% of familiar users prefer text symbols when they use semantic landmarks. R_2, containing frequent items "Landmark categories = Visual" and "Landmark symbols = Text," indicates that 38% of familiar users prefer text symbols when they use visual landmarks. Similarly, R_3, having frequent items "Landmark categories = Structural" and "Landmark symbols = Icon," indicates that 36% of familiar users prefer icon symbols when they use structural landmarks. In addition, R_4, having frequent items "Landmark categories = Visual" and "Landmark symbols =Image," indicates that 62% of unfamiliar users prefer image symbols when they use visual landmarks. R_5, containing frequent items "Landmark categories = Semantic" and "Landmark symbols = Image," indicates that 67% of unfamiliar users prefer image symbols when they use semantic landmarks. R_6, having frequent items "Landmark categories = Structural" and "Landmark symbols = Image," indicates that 58% of unfamiliar users prefer image symbols when they use structural landmarks.

3.3 | The framework of the personalized landmark adaptive visualization method

To facilitate the discussion, Table 8 presents the notation used in this article. We propose an adaptive landmark visualization method based on the rules to improve the performance and user experience of the pedestrian navigation system. The proposed method comprises the following steps: data collection, features extraction, and rule execution (as illustrated in Figure 1). The details of the proposed method are as follows.

3.3.1 | Data collection

The data included user data (e.g., familiarity), landmark data (e.g., image, location), and the range of the pedestrian navigation map. This step aims to collect and add new data to the system database. The user fills in a simple form to register through the pedestrian navigation login interface. The familiarity of the subjects was measured using a study area familiarity scale from 1 (very unfamiliar) to 10 (very familiar). Thus, the collected datasets are U and L. Let $U = \{u_1, u_2, \ldots, u_i\}$ be the set of users and $L = \{l_1, l_2, \ldots, l_j\}$ be the set of landmarks, where each landmark has a unique identifier and geographical coordinates.

3.3.2 | Features extraction

The key step of the adaptive landmark visualization method is to extract features from the dataset. We extract user features (familiar vs. unfamiliar) and landmark features (i.e., salience features) in this step.

TABLE 7 Association rules between landmark salience and symbols

Rule	Semantic association rule	Sup.	Conf.	Lift
Rules related to familiar user				
R_1	*Semantic* ⇒ *Text*	0.21	0.46	1.12
R_2	*Visual* ⇒ *Text*	0.15	0.38	0.92
R_3	*Structural* ⇒ *Icon*	0.06	0.36	1.20
Rules related to unfamiliar user				
R_4	*Visual* ⇒ *Image*	0.29	0.62	0.97
R_5	*Semantic* ⇒ *Image*	0.27	0.67	1.06
R_6	*Structural* ⇒ *Image*	0.08	0.58	0.92

TABLE 8 Notation in this article

Symbol	Definition
U	Set of all users
u_i	A user; $u_i \in U$
L	Set of all landmarks
l_j	A landmark; $l_j \in L$
S_{ij}	Salience value of a landmark
S	Set of all landmark symbols
S_v	A landmark symbol; $S_v \in S$
n	Number of users
m	Number of landmarks
C	Set of categories of landmarks
c_g	Category of a landmark; $c_g \in C$
F_u	Familiarity of user u

User features

Users have different levels of familiarity with the environment. Some users live in the area and visit it frequently, but others do not. We define visit frequency as a user familiarity feature (F_u). For $u_i \in U$, the familiarity of users (F_u) is a binary value. If user u_i visits the study area frequently, $F_u = 1$; otherwise, $F_u = 0$.

Landmark features

Landmark features are extracted from the images and information input by the system. Landmark features include three aspects: visual, semantic, and structural. Visual features comprise facade area, shape, color, and visibility. Semantic features include the function and meaning of the landmark. Structural features refer to the location features of landmarks. According to Equation (1), the salience values of all landmarks (S_L) are obtained. Let $S_L = \{S_{l1}, S_{l2}, \ldots, S_{lj}\}$ be the set of salience values. Landmarks (L) are ranked in descending order of landmark salience value (S_L), and the top-ranked landmarks are extracted.

3.3.3 | Rule execution

We constructed two types of rule base as follows. (1) A mathematical model of salience is constructed for selecting personalized landmarks (as illustrated in Section 3.1.2). Based on the calculation of the overall landmark salience, landmarks with higher scores are selected and recommended to users. In addition, landmarks are classified into different landmark categories based on their features. (2) Association rules between landmark salience and symbols are mining (as illustrated in Section 3.2). The purpose of association rule mining is to generalize useful patterns in pedestrian navigation systems for people with different levels of familiarity, thereby creating a knowledge base of user-specific rules.

4 | VERIFICATION EXPERIMENTS AND DISCUSSION

4.1 | Prototype system design and development

The prototype system architecture is illustrated in Figure 7. It comprises five components: information collection, data storage, recommendation engine, navigation services, and user interface. These components are organized in a three-tier client/server design.

In the data-based server, information collection refers to the acquisition of information by the user inputting data in the login interface. It provides parameters for the personalized landmark visualization method by analyzing the input information. The user data, landmark data, and symbol data are recorded through the storage function.

In the application service, the recommendation engine includes user preference rules and user profiles. Navigation services include symbol, location, and map modules. A symbol module is used to complete the rule matching of personalized landmark symbol visualization for users with different levels of familiarity. It comprises logical judgment of symbol type and symbol rendering. The location module is developed using Mapbox Navigation SDK for Android, including geolocation and GPS tracking. The module uses the starting and destination coordinates provided by the GPS tracker to calculate two routes based on time and distance. The map module is a visual platform used to design personalized pedestrian navigation maps and landmarks. The customization of the map is implemented using Mapbox Maps SDK for Android. In addition, user interaction with the map is developed using the JavaScript language and the open source "Mapbox GL JS" library, such as zoom in/out and pan.

In the client layer, the user interface represents the entry point for the recommended landmark-based pedestrian navigation map implemented through the software architecture.

4.2 | User experiments

4.2.1 | Participants

We recruited 28 subjects to participate in the user experiment. None had participated in any cognitive experiments previously. All subjects were volunteers and signed an informed consent form that stated the experiment content and the right to withdraw from the experiment at any time. Subjects were divided into the familiar group and the unfamiliar group according to the statistical analysis of the number of visits to the study area. The familiar group had 14 participants (8 females and 6 males, mean age: 28 years) who had lived in the study area for at least 3 years and had visited the specific location over 30 times. The unfamiliar group had 14 participants (5 female and

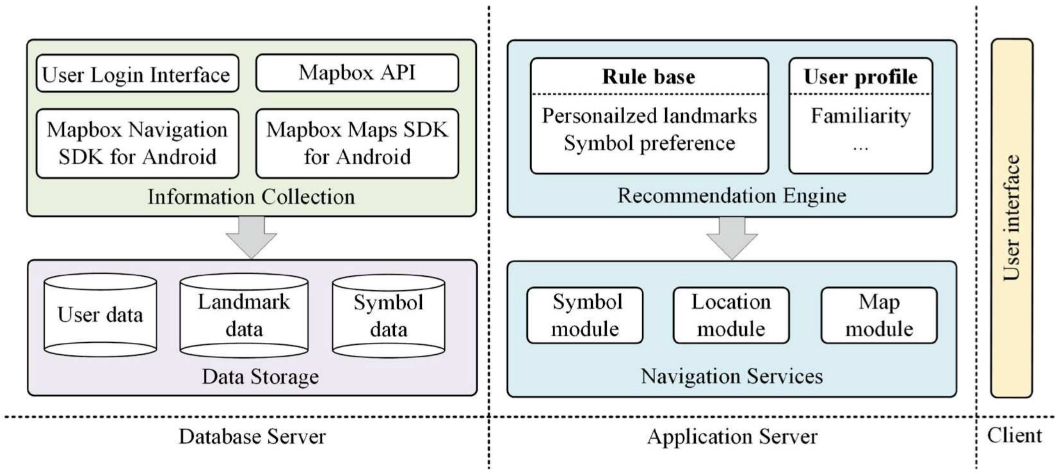

FIGURE 7 Prototype system architecture

9 males, mean age: 24 years) who had never visited the study area. All participants had an Android smartphone and experience with mobile maps.

All subjects assessed their experience with mobile maps and spatial ability before the experiment. They had to rate their experience with mobile maps using a seven-point Likert scale (from 1 = "least" to 7 = "most"). Due to the distribution of the data, a parametric *t*-test was performed to assess the difference. The results did not reveal any significant difference between the familiar group ($M = 4.21$, $SD = 1.25$) and the unfamiliar group ($M = 4.50$, $SD = 1.02$) in terms of experience with mobile navigation maps ($t = -0.66$, $p = .51$).

In addition, subjects had to fill out a self-assessment questionnaire using the SBSOD. A parametric *t*-test indicated that there was no significant difference ($t = 0.65$, $p = .52$) in the spatial ability of the familiar group ($M = 3.90$, $SD = 0.65$) and the unfamiliar group ($M = 3.69$, $SD = 1.01$).

4.2.2 | Materials

In the experiment, subjects with different spatial familiarity used two types of mobile maps to complete the navigation task: (1) the prototype; and (2) Baidu map for mobile (BMM). The prototype focused on the personalized representation of landmarks and adaptive symbols. Figure 8a illustrates the user login interface of the prototype. BMM focused on point of interest (POI) representation, and used a combination of icons and text as the symbol form. In addition, the color of the symbols was gray ($R = 205$, $G = 205$, $B = 205$) in BMM. We randomly divided the familiar participants into two groups: 7 subjects (4 females and 3 males) used the prototype (Figure 8b) and the other 7 subjects (4 females and 3 males) used BMM (Figure 8d). Similarly, the familiar participants were randomly divided into two groups: 7 subjects (2 females and 5 males) used the prototype (Figure 8c) and the other 7 subjects (3 females and 4 males) used BMM (Figure 8d).

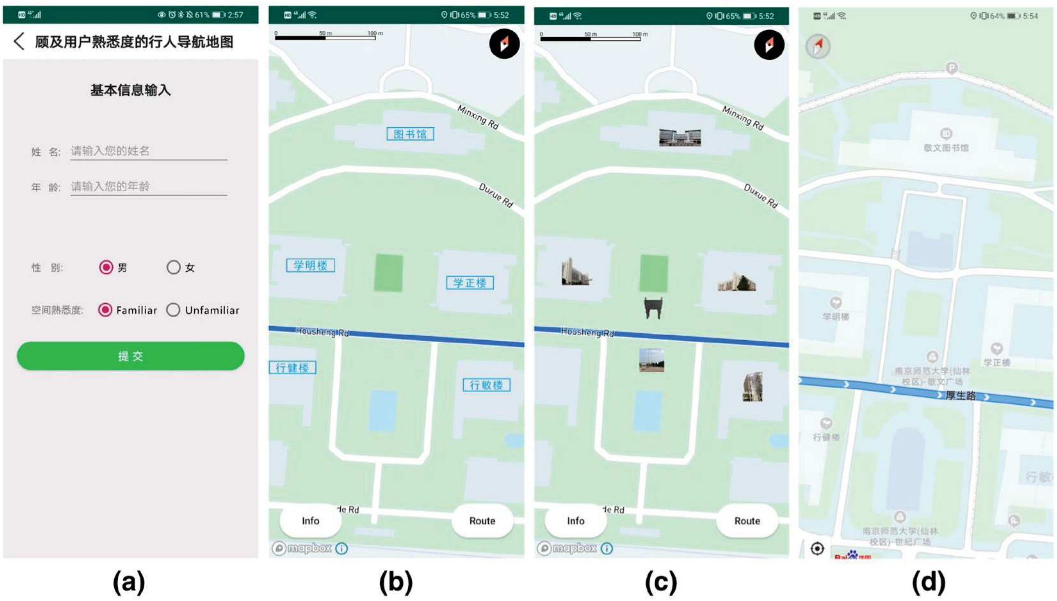

FIGURE 8 Interface of the pedestrian navigation system: (a) user login interface of the prototype; (b) pedestrian navigation maps of the prototype for familiar users; (c) pedestrian navigation maps of the prototype for unfamiliar users; and (d) Baidu map for mobile

4.2.3 | Procedure: Pedestrian navigation task

The experimental area and route are the same as those used in the cognitive experiments in Section 3.1.1. All subjects had to walk along the experimental route using the mobile map as navigation aid. Subjects had to walk as accurately as possible at normal speed, and the supervisors followed a few steps behind. Each participant performed the task under only one display condition. We used an on-screen recording function to record all subjects' operations on the mobile device throughout the whole process, including zooming in/out, moving the map up/down/left/right, the current zoom level, and time (accurate to seconds).

4.2.4 | System usability scale questionnaire

When the pedestrian navigation task was completed, all subjects were asked to fill out the system usability scale (SUS) questionnaire to assess the usability of the displayed map they used. The SUS has a 10-item scale that provides a global perspective of subjective assessments (Brooke, 1996). A five-point Likert scale was used to indicate the degree of agreement or disagreement with the various statements.

4.3 | Results

4.3.1 | Time efficiency

Time efficiency refers to the total time spent by each participant to complete the pedestrian navigation task. Completion time refers to the time spent by the subject from the starting point to the destination. A shorter completion time indicates better navigation performance of the displayed map. Figure 9 shows the average completion time for participants with different spatial familiarity (familiar vs. unfamiliar) who used the prototype or BMM during navigation.

Subjects who used the prototype (M = 1,648.71 s, SD = 212.11) spent less time than those who used BMM (M = 1,835.14 s, SD = 225.53). Due to the distribution of the data, a parametric t-test was performed to assess these differences. A significant difference ($t = -2.25$, $p = .03$) in completion time was observed between participants who used the prototype and BMM during navigation.

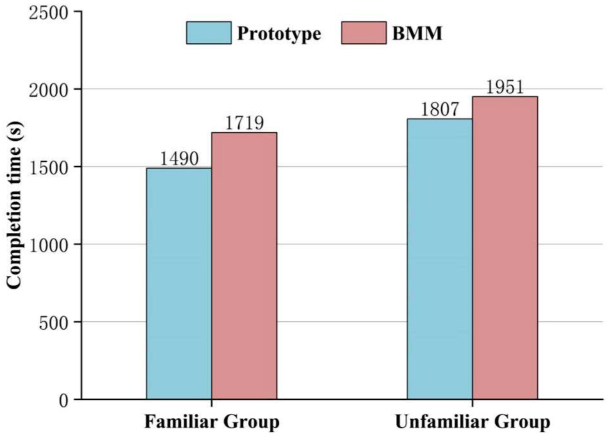

FIGURE 9 The average completion time for participants who used the prototype or BMM during navigation

Familiar participants who used the BMM (*M* = 1,718.86 s, *SD* = 166.43) had a longer completion time than those who used the prototype (*M* = 1,490.29 s, *SD* = 127.60). A parametric *t*-test showed that there was a significant difference ($t = -2.88$, $p = .01$) in completion time between familiar participants who used the prototype and BMM during navigation. Unfamiliar participants who used BMM (*M* = 1,951.43 s, *SD* = 225.72) had a longer completion time than those who used the prototype (*M* = 1,807.14 s, *SD* = 150.45). A parametric *t*-test showed that there was no significant difference ($t = -1.41$, $p = .19$) in completion time between unfamiliar participants who used the prototype and BMM.

4.3.2 | The number of map views

The number of map views refers to the number of zooms the subjects use during navigation. The zooming process takes time and requires the subjects' attention. In addition, the interactive operation of map zooms shows that the subject needs additional information during navigation. Therefore, fewer map zooms indicate higher navigation efficiency of the displayed map for users who have the same degree of familiarity with the environment. Figure 10 shows the average number of map views for participants with different spatial familiarity (familiar vs. unfamiliar) who used the prototype or BMM during navigation.

Subjects who used the prototype (*M* = 10.79, *SD* = 4.99) spent less time than those who used BMM (*M* = 12.57, *SD* = 5.56). Due to the distribution of the data, a parametric *t*-test was performed to assess the difference. No significant difference ($t = -0.89$, $p = .38$) in the number of map views was observed between participants who used the prototype and BMM during navigation.

Familiar participants who used BMM (*M* = 8.29, *SD* = 2.56) had more map zooms than those who used the prototype (*M* = 6.86, *SD* = 2.80). However, the *t*-test results showed that there was no significant difference ($t = -1.00$, $p = .34 > .05$) in the number of map zooms between familiar participants who used the prototype and BMM during navigation. Unfamiliar participants who used BMM (*M* = 16.86, *SD* = 4.18) had more map zooms than those who used the prototype (*M* = 14.71, *SD* = 3.20). However, the *t*-test results showed that there was no significant difference ($t = -1.08$, $p = .30 > .05$) in the number of map zooms between unfamiliar participants who used the prototype and BMM during navigation.

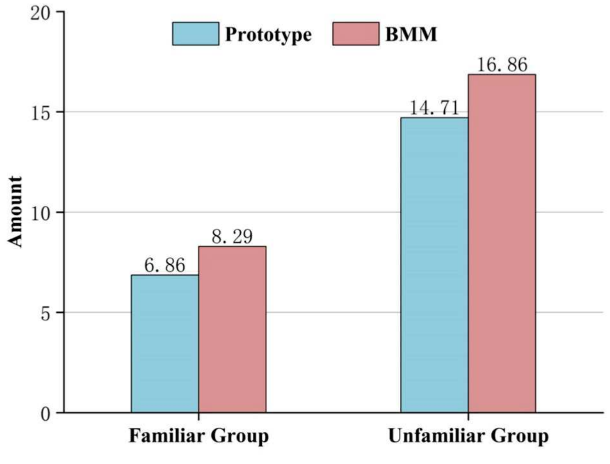

FIGURE 10 The average number of map views for participants who used the prototype or BMM during navigation

4.3.3 | Analysis of the system usability scale

The mean SUS score for the prototype ($M = 84.64$, $SD = 3.65$) was better than that for BMM ($M = 77.86$, $SD = 4.58$). Due to the distribution of the data, a parametric *t*-test was performed to assess these differences. The *t*-test result of the SUS questionnaire revealed a significant difference ($t = 4.33$, $p = .00 < .05$) between participants who used the prototype and BMM during navigation. People who used the prototype scored higher than those who used BMM.

4.4 | Discussion

The results of completion time, the number of map views, and the SUS questionnaire indicated that the prototype has more efficient and better user experience than the BMM. More specifically, although the number of POIs and symbols (combinations of icon and text) in BMM represent more information than in the prototype, users prefer the prototype that represents personalized landmarks and symbols based on their spatial familiarity. It can be explained that using landmarks is one of the main factors affecting map users' satisfaction with the map (Lorenz, Thierbach, Baur, & Kolbe, 2013). People who are unfamiliar with the environment prefer to use image-based symbols. Instead, they have the cognitive burden for the semantic information of text-based symbols. In addition, those who are familiar with the environment perform better than those who are not during navigation tasks. The literature indicates that as spatial familiarity increases, people can develop more refined representations of the environment (Iachini et al., 2009; Prestopnik & Roskos-Ewoldsen, 2000). The results also confirm that people's navigation performance is related to their familiarity.

4.5 | Limitations

The proposed method can meet the personalized needs of users and is of great significance for intelligent travel. However, our work has some limitations. (1) *The formalization of landmarks*. The objects that appear in the pedestrian sketches are used as landmarks in our work. Therefore, most landmarks are buildings or artificial objects. Landmarks can be divided into three categories according to their geometry: point, linear, and area-like landmarks (Hansen, Richter, & Klippel, 2006; Richter, 2007). In this study, we focused on point landmarks, while other types of landmarks were neglected. (2) *The characteristics of the user's spatial familiarity*. We explored the influence of spatial familiarity on landmark salience and symbols; however, familiarity is difficult to quantify. Wayfinding models are divided into three types according to the user's spatial familiarity: familiar, partially familiar, and unfamiliar (Xia et al., 2008). Our work divided spatial familiarity into familiar and unfamiliar, which has certain limitations. (3) *The limitations of the landmark datasets*. The proposed method is suitable for small study areas because it usually relies on detailed landmark datasets.

5 | CONCLUSIONS AND FUTURE WORK

This study explored how spatial familiarity affects users' preference for selecting landmarks and symbols. The aim was to propose a personalized landmark adaptive visualization method for pedestrian navigation maps considering user familiarity. In addition, our work reveals some important findings as follows.

1. Influence of spatial familiarity on landmark salience and symbols. The results showed that familiar people prefer strong semantic salience landmarks and text-based symbols, while unfamiliar people prefer strong visual salience landmarks and image-based symbols.

2. A mathematical model of landmark salience that can be used to automatically extract personalized landmarks is proposed, and the association rules between landmark salience and symbols are mined for users with different levels of familiarity.
3. A personalized landmark adaptive visualization method considering user familiarity is proposed. The results of user experiments verify that the proposed method can significantly improve pedestrian navigation performance. The above findings of this study have implications for the development of personalized landmark-based pedestrian navigation.

Future work can apply personalized landmark adaptive visualization methods for pedestrian navigation maps in different scenarios, such as tourist attractions and indoor scenes. Moreover, individual differences impact landmark selection preferences. The proposed method could be further enhanced to consider individual differences, such as gender, age, the level of education, and spatial knowledge.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available on request from the first author. The data are not publicly available because they contain information that could compromise the privacy of the research participants.

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