MASARYK UNIVERSITY

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Cognitive Processing of Spatial Information with Respect to Various Visualization Methods and Individual Differences

Habilitation thesis

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Acknowledgements

I want to thank my teachers who, during my studies, guided me to understand psychology as a science of man inextricably linked to his environment. Especially prof. Švancara and doc. Kostroň. Many thanks to my colleagues with whom I can develop our interdisciplinary topics together. The greatest thanks go to my beloved wife.

Abstract

The main thematic line of the work is the research of cognitive processes involved in working with various visualization methods that are used to encode and communicate spatiotemporal data. Maps, three-dimensional models, diagrams, etc. are a specific communication channel through which information is conveyed to the receiver in visual analogue form. This communication channel is complementary to the propositional (verbal) channel.

The first chapter, *"**Introduction**"*, presents a broader theoretical introduction with examples of various alternative forms of visualizations and their effect on cognitive processing, as well as the historical perspective of this line of research at the Department of Psychology, Faculty of Arts.

The central theme of the second chapter is the investigation of the influence of the form of visualization on the efficiency of processing and interpretation of the given data. Identical data can be represented in different ways, and the form of the display itself can have a profound effect not only on the recipient's cognitive processing, but also on their own understanding and interpretation. The first section focuses on the ***"Comparison of alternative modes and methods of visualization".***

The third part focuses more on the recipient of the information itself, or more precisely on inter-individual differences. Individuals with different cognitive equipment, organization of cognitive processes, and experience may show different preferences for different forms of representation and may also process the same representation in different ways. Individual differences are explored, among other things, in terms of cognitive styles. The ***"Relationship between individual dispositions and the way visualizations are processed"*** is examined.

In the fourth part, the focus of the investigation of differences in processing visualizations shifts from the individual level to the cross-cultural level. The research studies are based on the theory of the holistic-analytic cognitive style, which postulates the existence of intercultural differences in the organization of cognitive processes and which are determined primarily by the different cultural and historical experience of the ethnic groups being compared. Thus, in the third part, "***Cross-cultural differences in perception as an influence of the cultural-historical experience"*** are studied.

The fifth part presents the research tools, methods and procedures that had to be designed and developed for the field of research on complex forms of visualization.

The specific nature of the researched content, i.e., visualizations and their corresponding task types, does not allow for the use of procedures common in experimental psychology and it was necessary to develop and search for ***"Research methods, procedures and tools for the research of visualizations"***.

The ambition of chapter six is to bring together the conducted research studies under the Theory of Probabilistic Functionalism and to describe the phenomena using the Lens model. This model is also adapted and further developed, especially with regard to the collaborative nature of the usage of visualizations. The last chapter offers ***"Reflection in the perspective of the Theory of Probabilistic Functionalism"***.

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1 Introduction

The thesis stands on the borderland between three worlds and purposefully explores their interrelations. The first world is the actual tangible world in which we are physically present. In this world we meet others, share our ideas and thoughts with them, and discuss our understanding of the phenomena of the material world. One of mankind's unique abilities is to capture this world (objects, phenomena and events) through various media (texts printed on paper, sculptures or images on the phone screens). Through media and external representations, we simultaneously share and pass over intangible social and cultural-historical assets. It is the external representations of objects, events and phenomena of the first world that constitute the second world. The third world is then the internal world of the individual, his or her mental representations and ongoing cognitive operations. The unifying line of my research and this thesis is the attempt to capture how an individual perceives and interprets external graphical representations in order to form on their basis a mental representation of phenomena that are anchored in the real physical world.

In Kirsh's (2010) perspective, external representations enhance the cognitive power of an individual. External representations such as schemes, diagrams, or written statements do not only serve for sharing with others, but they represent an extension of the cognitive system of an individual by which they relate to states, structures, and processes outside their mind (Giere, 2004). External representations serve as a tool for more efficient processing of content when the use of internal cognitive functions and capacities is not sufficient. Visualization is one form of external representations and the aim of this thesis is to investigate to what extent different methods of visualization correspond with the cognitive structure of an individual, how effectively they can operate with them and whether they not create obstacles in the process of understanding.

The presented publication consists of selected research studies of the author which were conducted as part of several research projects and published in journals indexed in the Web of Science database. Since the research was interdisciplinary, the publications were directed to psychology journals (e.g., Behavior Research Methods, Psychological Reports, Studia Psychologica), multidisciplinary journals (e.g., PLOS One, Computational Intelligence and Neuroscience), as well as journals focused on the area of geospatial data visualization (e.g., International Journal of Digital Earth, Cartography and Geographic Information Science). The first chapter, "Introduction", and the last chapter, "Reflection in the Perspective of Probabilistic Functionalist Theory", is an original text that at the beginning introduces the reader to the research of cognitive processes when working with visualizations, and then anchors each research study and research topic as a whole in the Theory of Probabilistic Functionalism. Individual experiments and studies were conducted as part of research projects that either involved the author of the thesis or where he was a principal investigator (e.g., The influence of socio-cultural factors and writing system on perception and cognition of complex visual stimuli – GAČR, Education in Collaborative Immersive Virtual Reality – TAČR, Experimental Practicum: Design and Realization of interdisciplinary researches – MU Intern project, Adaptation of Psychological Tests for Online Computer-based Diagnostic for Psychological Praxes and Personalistic, Adaptation of Psychological Tests for Online Computer-based Diagnostic for Psychological Praxes and Personalistic – TAČR, Employment of Best Young Scientists for International Cooperation Empowerment). The research studies are organized into four thematic chapters, which always begin with a discussion of the main objectives and findings.

1.1 External graphical representation and cognitive processes

The topic of the thesis is elaborated in the perspective of the philosophical tradition of pragmatism (e.g., Peirce, 1878). I work on the practical presumption that if I, based on my incorrect interpretation of an external representation – a map or specifically contour lines – form an improper mental image of the difficulty of the contemplated cross-country skiing trail, and decide to set off alone as a beginner towards evening into unfamiliar steep hilly terrain, then the night return to the mountain hut is more likely to be a matter of a happy coincidence than guided by a sufficient level of knowledge and processing of available information. In another similar situation, the cognitive system is already enriched by previous experience, and fulfills its pragmatic function; it is better at predicting probable scenarios and effects of decisions on the course of events. And a similar plan is likely to be discarded. The thesis is also anchored in psychological approaches and theories that emphasize an ecological perspective (e.g., Gibson, 1979; Michaels and Palatinus, 2014). Egon Brunswik (1943) argues that in order to understand mental processes, it is always necessary to understand the structure of the environment, the habitat of an organism. In this perspective, cognitive functions and processes are seen as a form of adaptation of the individual and the animal species to the environment. The same is true for external representations. Palmer (1978) states that to understand the nature of representations, we must first understand and specify the entity being represented. It is necessary to understand the relationship between the referent (represented world) and the representational medium. Encoding objects and phenomena of the world into external representations is not straightforward. We live in a three-dimensional world in which the passing time represents a fourth dimension. The common visualization medium, on the contrary, is only two-dimensional, and temporal phenomena are often captured in static visualizations or in discrete steps. Examples include air traffic control (ATC) systems and the work of operators who evaluate potential collision trajectories in a 4D world (three spatial and one temporal dimensions, i.e., vertical and horizontal axes, direction and speed of the aircraft) based on a two-dimensional representation (Fields et al., 1998). The individual must have the necessary literacy, e.g., graphical literacy (Shah and Freedman, 2011; Fry, 1981) or map literacy (Clarke, 2003; Xie et al., 2018), and perform cognitive transformations in both the real world-external representation direction (when capturing phenomena in the external world) and the external representation-real world direction (when inferring phenomena in the world from representations). What are the pragmatic reasons for creating external representations in a situation where the necessary transformations require considerable cognitive capacities of the individual? One of the first functions is naturally the use of external representations as a communication channel. Van Ruler (2018) states that there is no consensus on the definition of the term communication (originally from Latin, communicare meant "to share with, to share out, to make generally accessible") and presents the conceptions of several authors. According to van Ruler, Rosengren (2000) emphasizes the process of meaning creation in psychological, social and cultural terms, how people understand communicated messages, what ambiguities arise and how they are resolved. Also, Littlejohn (1992), according to van Ruler, deals with the genesis and understanding of meaning in the communication process. External representations, including graphical representations (e.g., maps), must always be seen and therefore examined as a graphical product carrying meaning. Drápela (1983) states that one of the basic properties of maps is their communicability, i.e., the ability to transmit and convey information. Among other properties, the author includes illustrative nature (the ability to quickly and efficiently initiate thought processes), interpretability (the ability to evoke comprehensibility in the interpreter) and compressibility (the ability to increase the density of information reception per unit of time). The approach towards maps as a communication channel has been developed by Robinson and Petchenik (1977) or Koláčný (1977), whose works are inspired by the information theory of communication by Shannon and Weaver (1949). The communicative function of external representations is also examined, for example, in the approach of Star and Griesemer (1989), who introduce the term boundary objects. Boundary objects, which also include graphical representations or maps (Huvila et al, 2014), represent a borderline between groups or institutions and enable communication and cooperation.

External graphical representations not only facilitate comprehension (Kirk, 2016), but according to Kirsch (2010), they also serve as a tool for increasing the cognitive potential of an individual. In theoretical work, we can come across terms, such as embodied (Shapiro, 2007), situated (O'Connor and Glenberg, 2003), distributed (Hutchins, 1995a, 1995b), and extended (Clark, 2008, Rupert, 2004) cognition. Although the content of each term varies by individual authors, these conceptions are interlinked by the thesis that the way of human cognition needs to be understood and examined in extension to the extraorganismic environment. External graphical representations account for one form of extension, enabling the achievement of performances and outputs that the human mind would not be capable of in purely internal cognitive operations. Kirsh (2010) includes among the mechanisms enhancing cognitive performance besides other things the fact that external representations often represent the structure of phenomena more naturally than mental representations, enable explicit encoding of information, help coordinate thinking and reduce its cost, create permanent referents, or enable contriving of complex phenomena. The computational potential of the human mind is surprisingly low for certain types of tasks. Drawing a conclusion from a data matrix of two variables both of which can take three values (see chapter 1.2, Fig. 5) is – without external visualizations – a challenging task for an average person. External graphical representations offer an extension of the cognitive apparatus, both in terms of working memory (information storage) and in terms of taking over partial operations. The result of a conjunction operation, for example, can be expressed in color in an external graphical representation (see 2.1, Fig. 1 and 2), and the individual no longer performs additional internal operations by comparing the values of two independent variables. Thus, they can free up cognitive capacity for other necessary operations, e.g., searching for trends or correlations in the processed variables.

The activity associated with external representations is understood as a sensorimotor process and the design of individual research studies has always been considered, among other things, in the perspective of Neisser's perceptual cycle (see Fig. 1). At this point, it is necessary to emphasize the basic methodological premise. Experimental research in the field of external graphical representations (maps) cannot be narrowed down to methods, techniques and task types that measure only partial sections of cognitive processes and isolated cognitive functions. For example, if there is a research design on the comparison of alternative map symbols of a simple "visual search paradigm" type, then this is done with full awareness that potential findings cannot be generalized to other types of map activities, nor do they reflect the quality of the map in its complexity. The findings in this case refer only to the visual quality of the map symbols and may only to a lesser extent relate to other key map functions such as communicating meaning, or not at all. In some cases, an improperly chosen research design may even distort the quality of the external graphical representation. Such an example may be research comparing two alternative symbol sets (Stachoň et al., 2013), in which the more visually distinctive and icon-based designed symbol set A was proven to be more effective in terms of visual search for individual map symbols. A limitation of the study and for the interpretation of the results is that while symbol set A was a simple set of symbols, symbol set B was hierarchically structured. Symbols of the same category carried common graphical attributes, and thus it can be assumed that, for example, in terms of legend memorability, set B might be more effective. Also, regarding the actual usage of the map, the phase of visual search for symbols is rather minority activity; instead, the emphasis is put on operations that involve discovering relationships between map elements and information extraction. Symbol set B could again offer an advantage due to its internal logic. The emphasis on the mere visual quality of the map and the use of simple research techniques clearly loses its relevance if the ambition is to investigate the ability of an external graphical representation to carry and communicate meaning. A typical example is a research design in which partial cut-outs of a map are exposed for a limited period of time and subsequently the effect is measured through the recognition of the presented cut-outs. By analogy, we would then investigate the propositional representation using a design in which the researcher randomly selects every nth page from a book, cuts out three lines of text from that page, then exposes these to the participant for a few seconds, and tries to infer the overall clarity of the book's message based on the results of the recognition of the text cut-outs. Working with a map or another external graphic representation must be seen as a continuous cyclic process in which the sensory phase alternates with the motor phase, and through targeted activity the individual processes the stimulus material, forming partial and temporary hypotheses which they gradually refine. Especially in the case of map products processing, this sensorimotor rhythm is evident on multiple levels. The basic motor activity is eye movements which are guided by a gradually formed internal representation of the phenomenon. In the case of electronic interactive maps, users have a direct access to additional tools and functions (e.g., zoom, pan, layer change) through which they can interact with the map and get gradually additional and more detailed information, which they use to create and modify their current mental schemes.

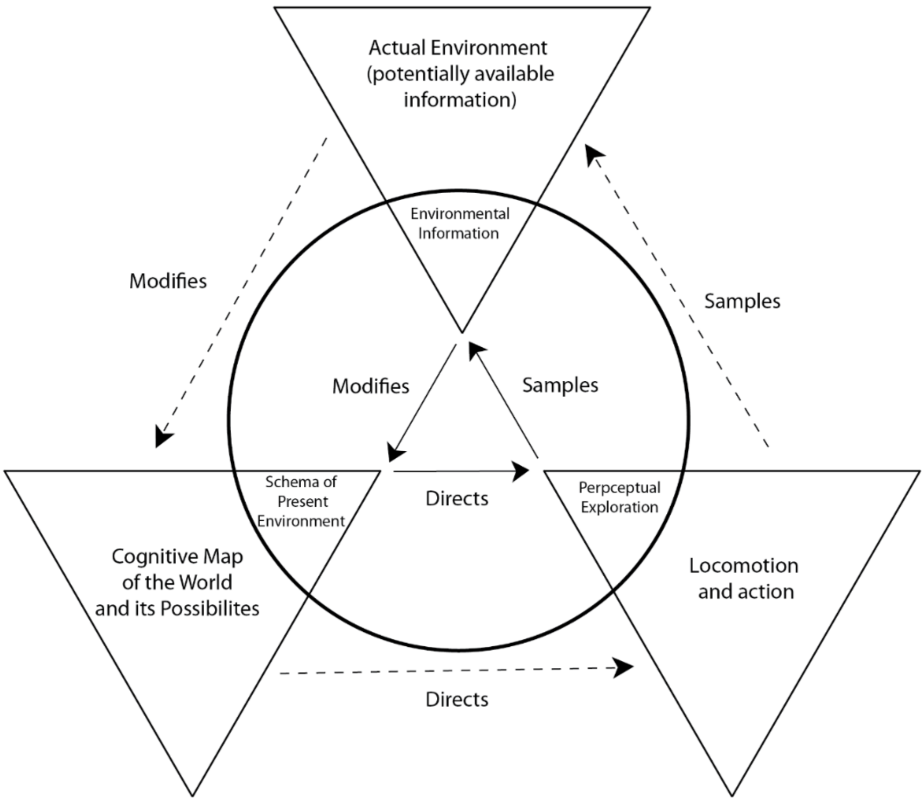

Fig. 1: Neisser's perceptual cycle (adapted according to Salmon et al., 2019)

Representations, internal (mental) or external, can be distinguished by the form of symbolic encoding as propositional or analogue (Eysenck and Keane, 2005). Propositional and analogue representations differ in many aspects. Eysenck and Keane (2005) argue that propositional representations (linguistic descriptions) are arbitrary and feature explicit symbols representing objects, phenomena and relations, are composed of discrete symbols with defined smallest units, organized by precise rules, and the reception is not tied to a particular sensory modality. In contrast, a graphical representation, according to Eysenck and Keane (2005), represents an analogous relationship between a graphical representation and the object being represented, has no natural smallest units (it can be deconstructed into smaller parts or elements for a purpose), does not have symbols for all phenomena, has no precisely defined rules for combining sub-elements, and is tied to a visual modality. The existence of alternative forms of external representations naturally raises questions as to whether there are differences in the ways of processing and their efficiency, and also whether they are anchored in the neural structure in the same way or differently (e.g., Dual coding theory, Paivio, 1986; Clark and Paivio, 1991). Larkin and Simon (1987) focus on differences in the way of processing and the types of processes involved. They state that propositional representations are expressed in logical or temporal sequences. Graphical representations, on the other hand, preserve topological and geometric relations and can be scanned simultaneously, or allow targeted location of a selected element. Larkin and Simon (1987) define three basic categories of operations: 1. search (locating target elements or sets of elements in the data structure), 2. recognition (recognizing a match between a given condition or target and the localized elements), and 3. inference (associating new elements into the data structure). I believe that graphical representations (e.g., different types of schemas) have an advantage over verbal descriptions in terms of the unambiguity of expression. Whereas purely verbal description allows for formulation of relatively vague statements often in contradiction to each other, precisely because of the sequential nature of communication, schemas force the author to be precise. Inconsistencies or errors in the relations between the elements of a schema are relatively easy for the reader to detect. Dexter and Hughes (2013) state that Waller (1981) was the first author to introduce the term visual argument. He uses the term visual argument to explain the way and mechanisms by which information is conveyed through graphical representations. Vekiri (2002) argues that, according to the visual argument hypothesis, cognitive processing of graphical representations requires less working memory because fewer transformations are required compared to propositional representations. Diagrams, maps, and charts preserve visuospatial properties, and thus communicate information through both their individual elements and their relations and arrangements in space. Winn (1991) points out that maps and diagrams have the advantage of engaging pre-attentive processes, which happen in parallel and independently of the top-down cognitive control, and thus do not overload the cognitive capacity. Winn (1991) further states that there is pre-attentive organization of information. Authors who have compared the impact of propositional and graphical representations on the way a defined problem is solved include also Schlender et al. (2000) and Löhner et al. (2003). Löhner et al. (2003) concluded that students' behavior while working at the assigned task, computer modeling in physics, varied significantly depending on the used form of the task assignment – text-based model representation and graphical representation, in which the model is built by qualitatively linking variables.

This thesis focuses in particular on external graphical representations that are intended for the communication of spatiotemporal phenomena. A typical form of representation for this type of data is a map. Maps and other related graphical external representations arouse interest of psychologists because they represent a specific research domain in which various cognitive functions and processes are applied, as well as a valuable stimulus material that allows for a unique way of investigating perception and thinking. Within a psychophysiological paradigm, the influence of visual attributes of symbols has been investigated, for example, by Ekman et al. (1961), or earlier by Williams (1958). Higher cognitive functions and processes in the context of maps and displays have been investigated, for example, by Thorndyke, P. W., and Stasz, C. (1980), Thorndyke and Hayes-Roth (1982), Wiegmann et al. (1992), Richardson et al. (1999), or Hegarty et al. (2010). The potential use of maps in education has been addressed by, e.g., Wiegmann et al. (1992), or Stock et al. (1995). Other types of graphical representations in the field of education, especially graphs and diagrams, have been addressed by, e.g., Winn (1987, 1990, 1991, 1993, 1994). Finally, graphical representations are an integral part of scientific data communication. Harold et al. (2016) points out that the cognitive and psychological sciences dispose of a knowledge base that allows for design adaptations of visualizations that are an integral part of communicating scientific knowledge to both professional and non-professional audiences. Cleveland and McGill (1985) state that graphs, on the one hand, serve for communicating scientific knowledge, and on the other hand represent a powerful tool for analyzing scientific data. However, research data visualizations, which are a natural part of scientific publications, are also undergoing an evolution. Figure 2 shows three ways to present central tendency.

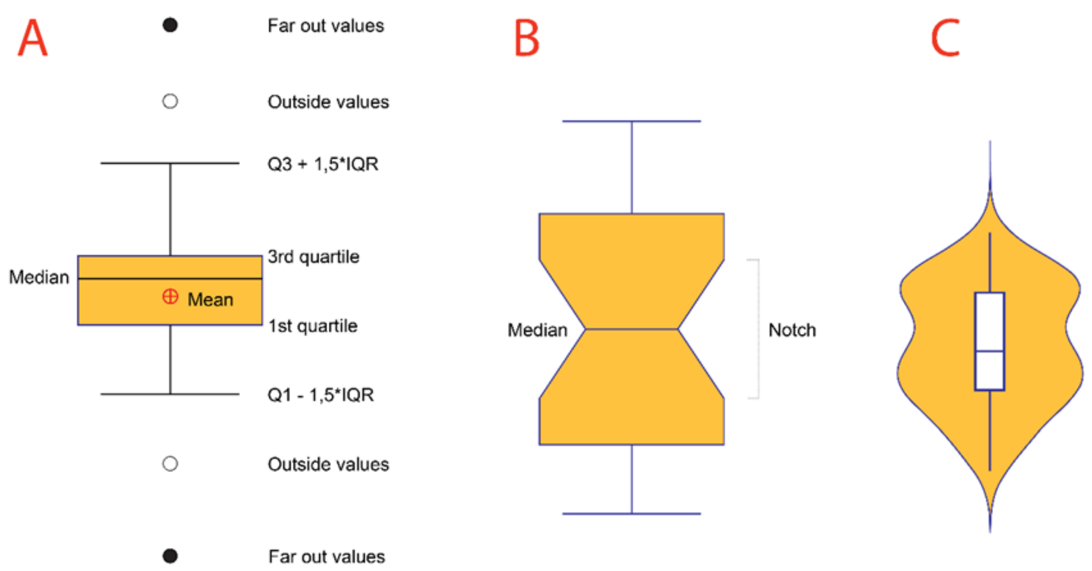

Fig. 2: A) A mean was added to a „traditional" Box-and-Whisker plot (see Tukey, 1977); B) Notched Box-and-Whisker plot – displays a confidence interval which, however, does not represent „95% confidence interval", but "a confidence interval" that enables a comparison of the medians (See McGill et al., 1978); C) Violin plot – presents the probability density of the data and it is often smoothed by a kernel density estimator (e.g., Hintze and Nelson, 1998, Thrun et al., 2020). (figures were adapted from https://www.medcalc.org)

1.2 Visualization as graphically encoded information and storytelling

Visualization is a form of communication and as such it always conveys meaning. Individual elements represent partial data and as a whole they convey a complex message. Even at the elementary level of graphical elements, we can examine visualizations in terms of information or computational equivalence. Larkin and Simon (1987) state that two representations are informationally equivalent if all the information contained in one is also inferable from the other, and vice versa. They further state that two representations are computationally equivalent if they are informationally equivalent and at the same time the condition holds that conclusions can be drawn equally "easily" and "quickly" from the information explicitly expressed in the two representations. Computational equivalence depends on the way individuals cognitively process the information encoded in them. The aforementioned theoretical background is crucial for reasoning about the topic of visualizations and their cognitive processing, as well as in terms of research procedures. The principle of information equivalence tells us that we are able to fully control independent or intervening variables. Using different types of visualizations, identical data are conveyed to the participant, and any observed differences in performance can be exclusively attributed to the form of the visualization. And conversely, alternative forms of visualization can serve as valuable stimulus material, since different modes of cognitive processing can be explored depending on the type of visualization. It should be noted, however, that the principle of information equivalence is in some cases (when using alternative visualizations) only theoretically achievable, or rather full information equivalence is not achieved. We can talk about different types of information non-equivalence (Šašinka, 2012).

Alternative visualizations (different forms of information notation) can be compared from various aspects, namely different parameters can be examined:

- Are the alternative forms of visualization equivalent with respect to the speed of solution?
- Are the alternative forms of visualization equivalent in terms of the correctness of the solution or the tendency to trigger errors in an individual's responses?
- Do the alternative forms of visualization put equal strain on the cognitive apparatus? Do they generate the same cognitive or perceptual load?
- Are the same cognitive processes and functions evoked and engaged when processing alternative forms of visualization? And, alternatively, is the form of visualization reflected in the involvement of different neural structures?
- Are identical data that are encoded by alternative graphical variables interpreted identically and do they evoke identical conclusions?

In particular, the issue of response correctness and the influence of the visualization form on the interpretation of the phenomenon itself have significant practical implications. Will the operator of a fire brigade control center tend to generate more errors depending on the type of visualization? Will policy makers make different decisions based on the same data as a result of using different forms of maps?

The following figures (Fig 3 and 4) present four visualization methods that always represent two variables. The visualization methods chosen are primarily intended for a three-dimensional environment (stereoscopic medium), but can also communicate information in a conventional 2D medium. For illustrative purposes, the graphical elements are displayed on a square grid, i.e., outside the typical context of for example a geographical terrain model. This is a so-called bivariate visualization, since the aim is to display the values of two variables simultaneously for each entity (e.g., a condition or a territorial unit). The typical purpose of such a visualization is to detect correlations and trends depending on the condition or spatial relations. In these four cases, each of the two parameters (variables) can take exactly three values: low – medium – high. The visualizations in pairs are informationally equivalent to each other, i.e., they represent identical input data. Any differences are precisely in the way cognitive processing is performed, what demands they place on the cognitive apparatus and what differences in performance may occur.

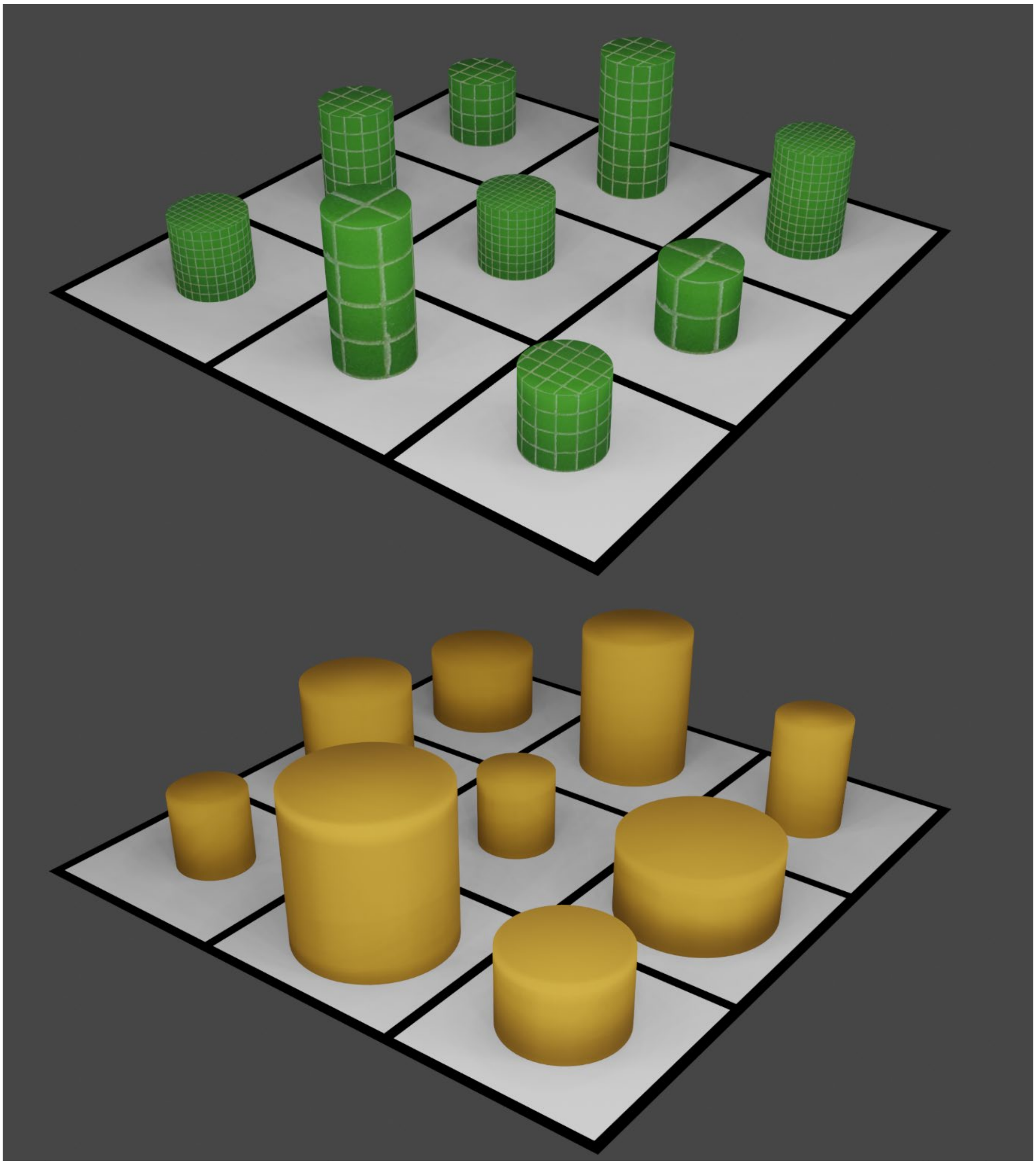

Fig. 3: Alternative informationally equivalent methods of visualization represent two variables which can take exactly three values (low – medium – high); A) An extrinsic visualization (above) uses two separable graphic elements – height and texture of the cylinder – to represent two variables. Height is used to represent the values of one variable. The larger the variable takes on values, the taller the cylinder. The other variable is represented by the texture, namely by the size of the squares. A larger square size represents a larger value. B) Intrinsic visualization (below) uses for representation two non-separable variables, i.e., size. One variable is represented by

the height of the cylinder, the other by its width. (Authors of visualizations are Šašinka and Ugwitz, 2022.)

From the standpoint of cognitive processing, extrinsic and intrinsic bivariate visualizations differ primarily in the necessity of merging or decomposing the communicated variables. If the task objective is to determine the value of one or the other variable separately, then it is preferable to work with the extrinsic option. The visual apparatus of the message recipient is focused on either the height of the column (size) or the texture. The processing of the second variable is suppressed by attentional mechanisms and does not increase neither the perceptual load nor especially the cognitive load. In case of intrinsic visualization for the same task, on the contrary, the message recipient is forced to decompose and separate the symbols only by the selected variable. This necessarily leads to an increase in cognitive load. However, when the assignment is changed, the situation is reversed. If the task is to detect trends or to compare areas in which a specific combination of values of both variables is found (e.g., co-occurrence of high and low values), then intrinsic visualization offers an advantage. The individual is no longer forced to perform cognitive operations and merge separated variables. They can focus their visual attention on a selected shape (e.g., a tall slender cylinder) and explore in which conditions or areas a given conjunction of values is to be found. In case of the extrinsic variant, parallel cognitive processing requires the involvement of divided attention, i.e., simultaneous sensory processing of both graphical symbols (height and texture) and their evaluation. The other option is a serial processing of the task, i.e., detection and visual selection of areas with defined height, and subsequent evaluation of the second variable.

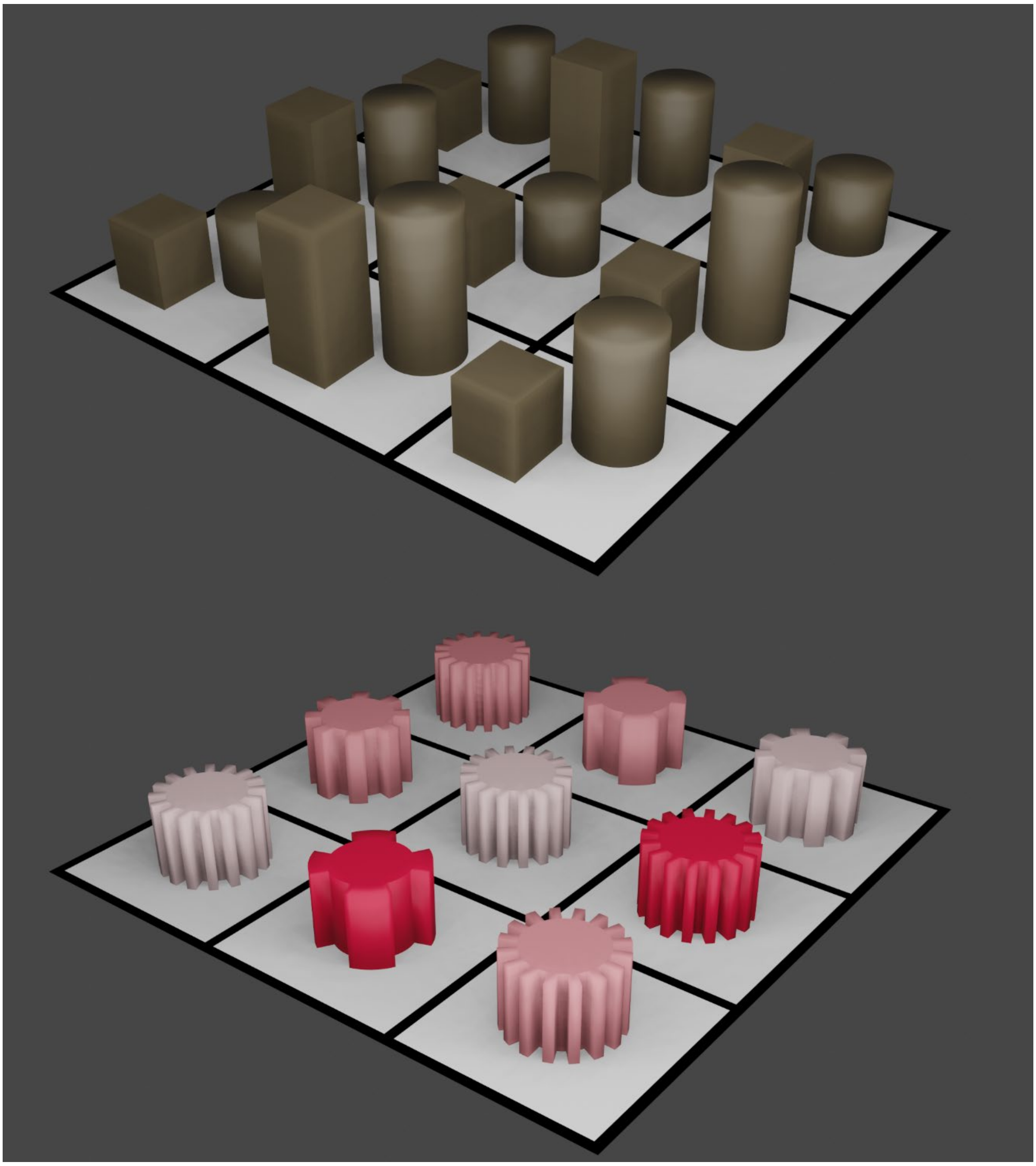

Fig. 4: Two informationally equivalent methods of extrinsic visualization; A) the visualization above represents each variable with separate 3D symbols – a cylinder and a cuboid. The values (low – medium – high) are represented by the height of the 3D symbols; B) the visualization below always uses one 3D symbol (object) to represent two variables – shape and color lightness. Higher intensity of the phenomenon is represented by wider gears; higher value of the phenomenon is represented by lower lightness. (Authors of visualizations are Šašinka and Ugwitz, 2022.)

Both visualizations in Figure 4 (A and B) present another possibility of bivariate representation of two phenomena. Yet in both cases, these are extrinsic methods. In the former case, two separate 3D symbols are used – a cuboid and a cylinder. In the latter case, the phenomena are represented by shape and color lightness. The disadvantage of the first method is a higher level of graphic fullness, which makes the visualization less clear and can lead to a higher perceptual load (Lavie and Tsal, 1994). Also, with a certain constellation of values, two effects may occur. In particular, in the case of static visualizations, the larger 3D symbol in the foreground may completely overshadow the 3D symbol of lower value placed behind it. The impact of this effect is limited by interactive visualizations, yet the recipient of the information may not have all values available at a glance and has to manipulate (e.g., rotate) the visualization. Another important factor is the effect of the distance of the 3D symbol from the observer, which accounts for a different size of the projected image of the object on the retina. A 3D symbol with a lower value (height) placed in the foreground may appear the same or larger compared to a 3D symbol of a higher value placed further away from the observer. The use of shape to represent a value of a phenomenon offers, compared to size (height), a different positioning in the hierarchy of graphical (visual) variables (Bertin, 1967, Roth, 2017). According to Bertin (1967), a visual variable is associative but it is not suitable for quantification.

To have a concrete idea about the cognitive processing difficulty of bivariate visualizations, we can assign a specific content and task type. When a 3x3 matrix is used, the goal may be to explore the effect of two variables, both of which take three values (Type of settlement and Education attained), on life satisfaction and financial income.

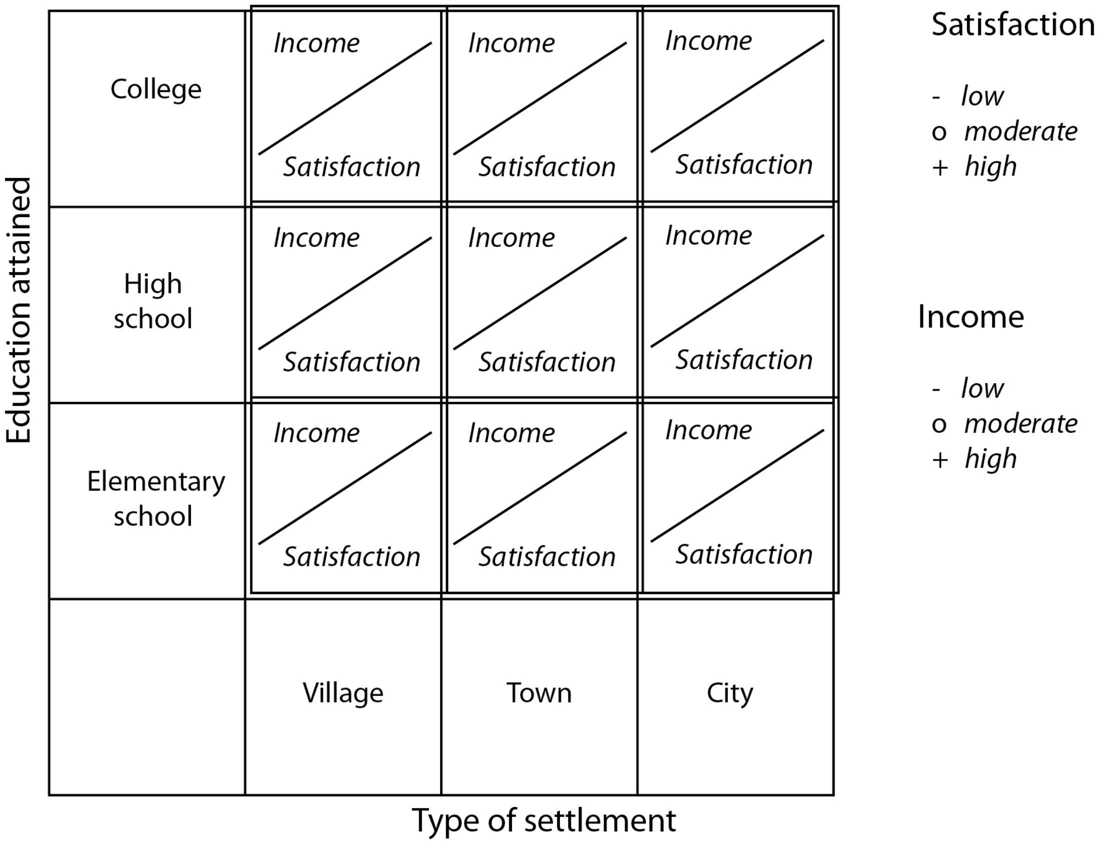

Fig. 5: Matrix representing two variables: life satisfaction and financial income, which are displayed with respect to the type of settlement and education attained.

The alternative visualizations above (Fig 3 and 4) demonstrate how cognitive processing is potentially influenced by the way of notation of one or two variables. However, in most cases, the goal of the visualizations is not simply to determine the value of a given phenomenon, but to understand the relationships between multiple variables. The notation above (Fig. 5) is designed to identify the relationships between the type of settlement and the level of education attained, or in other words between the impact on subjective perceived life satisfaction and objectively attained income. It would be possible to ask different types of questions and use the visualization to seek answers. Is the level of education and income interrelated in a similar way in the village as in a small town or a large city? Is there a close relationship between income and satisfaction, and is it the same for village and city? Comprehensive visualizations do not just provide us with data and offer information. They tell us stories.

One of the big stories of our time is global warming. What story do the two infographics below tell? If we trust the reliability of observed temperature data over time (Fig. 6), then the story cannot be told in any other way than that it will be already our generation that will witness a significant change in the world around us. To what extent the story told can feel like a thriller depends not only on the information communicated, but also on the form of visualization. Would these predictions seem more catastrophic if we used red color for this part and a cooler purple or blue tone for the past?

WORLD TEMPERATURE ANOMALY FOR 22 000 YEARS

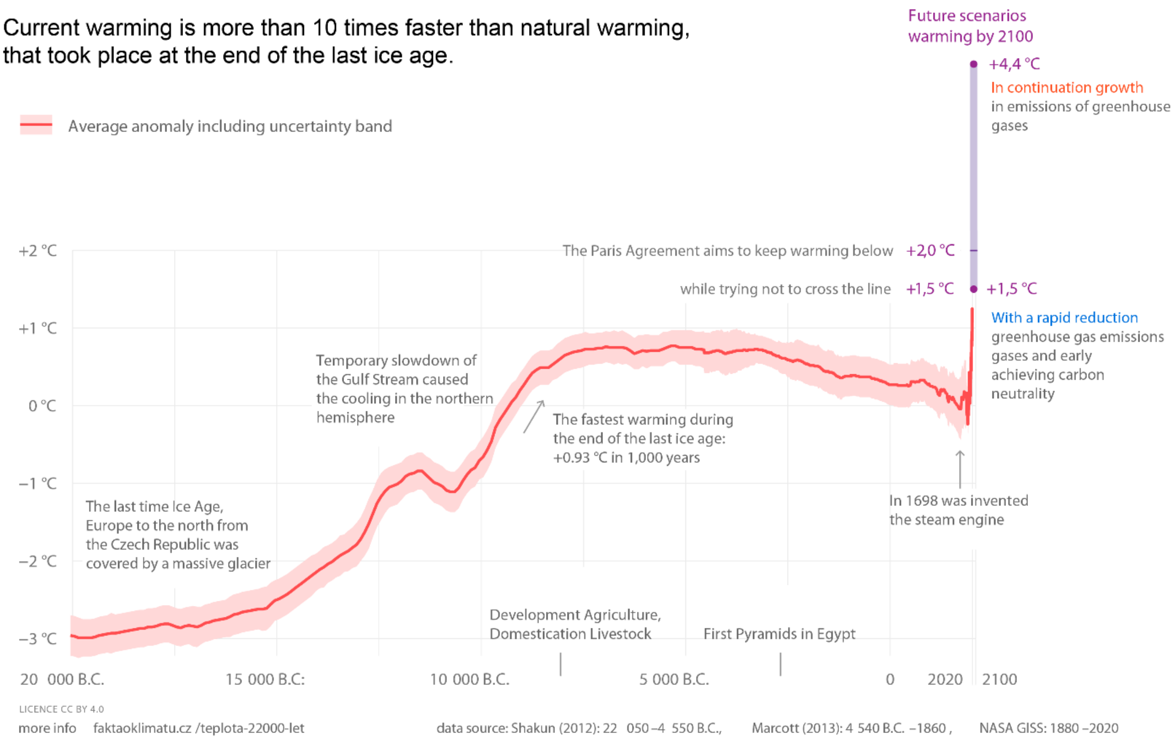

Fig. 6: World temperature anomaly for 22 000 years (adapted from https://faktaoklimatu.cz/infografiky/teplota-22000-let)

The second infographic (Fig.7) rounds out the big story. Where to look for the cause, who is the proverbial "bad guy" in this story? And isn't it all just a natural fluctuation, a natural cycle? How big are the changes, anyway? The diagram offers us, among other things, an important clue to possible interpretations, and that is scale. We can compare cyclical annual changes in element concentrations with their ten-year trends. In order to make the story emotionally charged, we have helped by layering curves of different values in the same space. Crossing them makes a sufficiently dramatic punchline. It must be stressed, however, that it is not visual manipulation in this case. Putting the two variables in absolute values would virtually make the necessary visual inspection impossible.

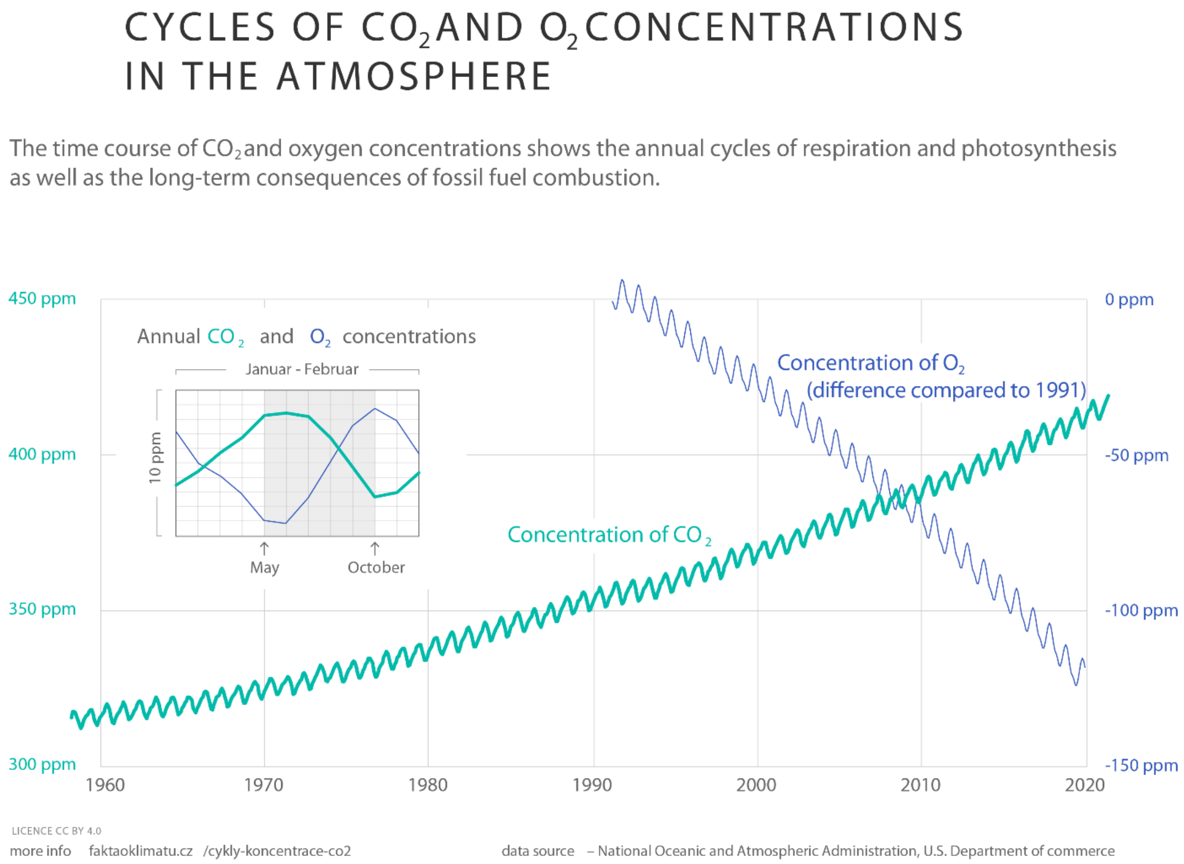

Fig. 7: CO_2 and O_2 concentration cycles in the atmosphere (adapted from https://faktaoklimatu.cz/infografiky/cykly-koncentrace-co2)

The advantage of graphical forms of representation over verbal representations is the preservation and more efficient communication of topological relations. Even though static graphical representations (as opposed to animated ones) do not allow to capture and convey the temporal component in a straightforward way, dynamic, or spatiotemporal phenomena can still be communicated effectively. If the factory staff had a diagram (Fig. 8) at their disposal, they would surely be at least mildly concerned if an aircraft flew over them without bombing them in the process.

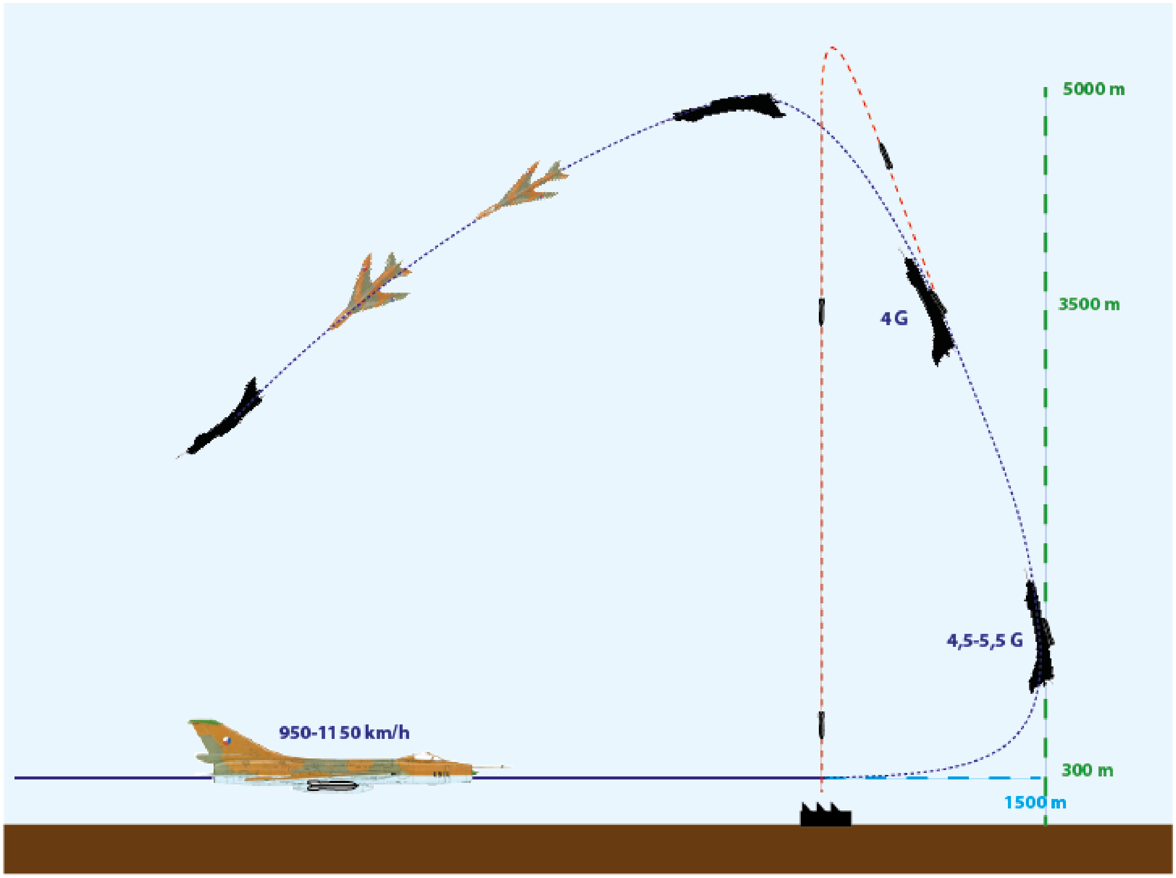

Fig. 8: Flight manoeuvre during the use of a tactical nuclear bomb

In the picture you can see one of the methods of dropping tactical nuclear bombs from SU7 BM or SU7 BKL aircrafts, which were also in the Czechoslovak Air Force's arsenal. In this maneuver, the drop was performed at an angle of 110°, that is on the back, roughly above the target. The maximum desired deviation of the target was up to 600 m. Errors were caused, for example, by inaccurate maneuvering. A 1G overload error during heading upwards resulted in a deviation of approximately 950 m. Incorrect calculation of the wind (the duration of the bomb fall was 40 seconds) led to an error of about 200 m at a wind speed of 5 m/s (Šašinka, Sr., 2022, oral communication). The diagram of the optimal execution of the maneuver can be completed with, among other things, the deviations caused by errors in maneuvers and the degree of inaccuracy of the munition fall.

1.3 Historical perspective of the cognitive research of visualizations at the Department of Psychology

The first rule of geography by Tobler (1970), "everything is related to everything else, but near things are more related than distant things", is also true for the development of the topic of experimental research on cognitive processing of visualizations within a working group that was established at the Department of Psychology and Geography at Masaryk University. This line of research at the Department of Psychology did not emerge suddenly, but rather it was always present, permeating time and space like a persistent theme. From the very beginning, Prof. Rostohar had developed an experimental method of cognition and in his publication Studies in Developmental Psychology [original Studie z vývojové psychologie, 1928], he elaborated on the topic of the genesis of ideas (Gabriel, 2017). Švancara (2006) explains that Rostohar investigated in a laboratory setting how the idea of a complex geometric, multi-coloured figure develops when viewed repeatedly. Subjects captured their ideas in drawings. Švancara also reports (1999, 1995) that Rostohar anticipated the notions of schemes in perception and mental representation in his study of apperception, which were not elaborated until decades later. Professor Švancara further developed the experimental method of cognition and also focused his dissertation on the area of visual perception (Analysis of attention in apperception of homogeneous optical shapes [Analýza pozornosti při apercepci stejnorodých optických tvarů]) (see Svoboda, 2004). The scope and impact of Prof. Švancara's work is undeniable. Crucial for establishing a research line and a working group focused on the research of cognitive processes while working with maps and spatial phenomena, was, however, the beginning of the 90's, when Prof. Švancara and Prof. Konečný from the Institute of Geography at the Faculty of Science of MU started their cooperation. And with the first joint publications (Konečný and Švancara, 1996, Konečný and Švancara, 1997,) they started a close interdisciplinary psychological-cartographic cooperation, which subsequently resulted in the formation of a broader working group thanks to a large research project "dynamic geo-visualization in crisis management" (GEOKRIMA 2005 to 2011). The working group was maintained and more formally developed even after the end of the research project, among other things thanks to follow-up research projects.

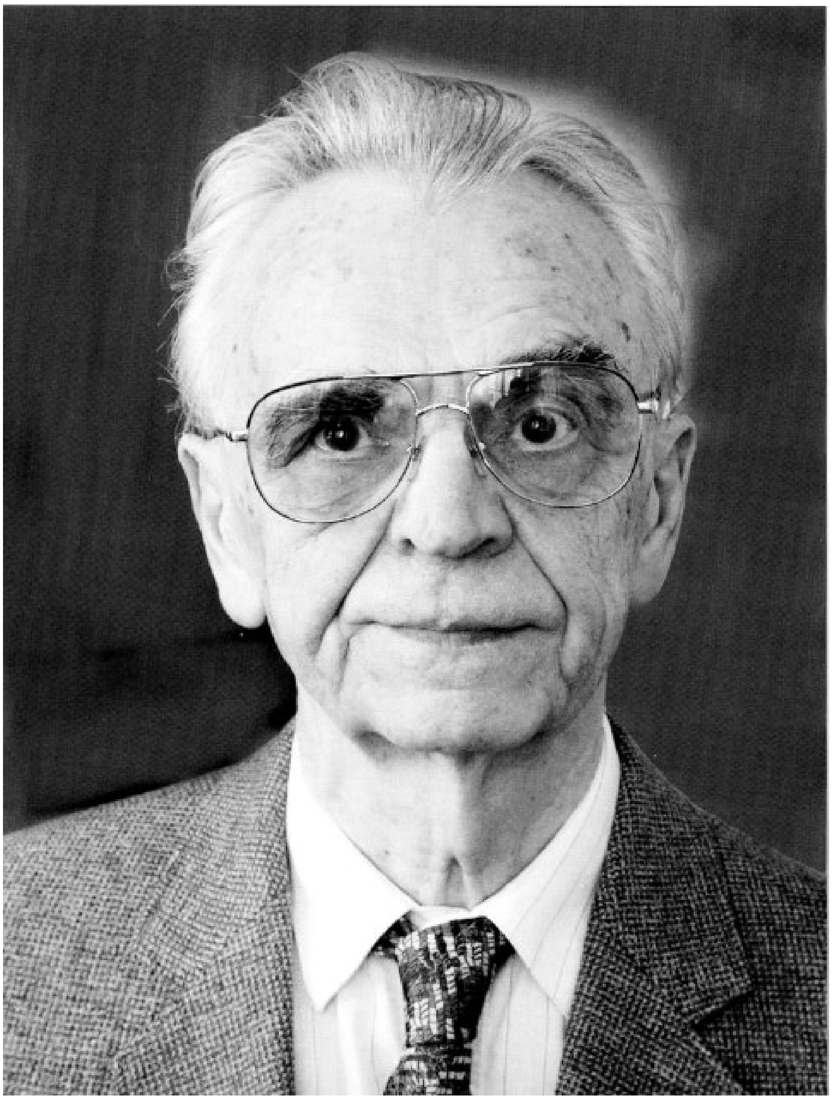

Fig. 9: Prof. Josef Švancara (Svoboda, 2004)

I was invited to the GEOKRIMA project by Prof. Švancara in 2008 and having come from the Psychiatric Hospital to the Department of Geography, I experienced a real culture shock. At the first meeting, map keys by doc. Drápela and Dr. Friedmanová were being discussed for several hours and I was bewildered wondering what was there in the maps to explore. The comparison of alternative map keys in terms of visual search efficiency led to professor Švancara's first publication with new colleagues (see Stachoň et al., 2013), which built on his previous conceptual works in the field (Švancara, 2006, 2007, 2009). At the same time, I started my postgraduate studies after professor Švancara got me to accept visualizations as the topic of my research, although we preliminary agreed on my priority topic at that time – modeling dependencies in system dynamics. In retrospect, I am grateful for this. After a few months into the project, I began to bore my friends in the pub by telling them what a fascinating topic map research was.

It was only with some hindsight that I realized how important was the fact that a psychological topic was a separate work package in the GEOKRIMA research project (WP5 – Perceptual Aspects of Visualization in Crisis Management). Professor Švancara later confirmed to me that he considered the formal embedding of psychology to be a very important moment, and – as it was a relatively small working group – also a kind of a daring feat. In the light of further developments, I repeatedly regretted that he, on the other hand, had failed to push through his other vision – the purchase of an eye-tracking system. What advance could the emerging cognitive team have gained if it had had this research apparatus at its disposal as early as 2005? I did not take over the first eye-tracking systems for the emerging HUME Lab until ten years later. On the other hand, it can be assumed that if an eye-tracking system had been acquired, research topics as well as methods would have been largely directed by the available research instrument. No new ways would have been sought to explore complex visualization and there would have been no demand for new research equipment. This was the software MuTEP (Stachoň et al, 2014) and subsequently Hypothesis (Šašinka et al., 2017), which were designed from the very outset to administer both mapping tasks and psychological tests. The collaboration between the Department of Psychology and the Department of Geography was able to be developed and deepened thanks to follow-up projects (e.g., by applying for and obtaining two postdoctoral positions within the program called "Postdoc II - Employment of Best Young Scientists for International Cooperation Empowerment", considered from the beginning as complementary), to be subsequently expanded by a third player – the Department of Visual Informatics, and specifically doc. Kozlíková and Dr. Chmelík. The strongly interdisciplinary working group has benefited from complementary expertise and mutual cross-overs until now. Thanks to the development of modern technologies, the focus has partly shifted from research on 2D representations to new media and display methods. Some of the most recent applied research projects focus, for example, on the display of information for pilots of ultralight aircraft in augmented reality glasses or the use of collaborative virtual reality for education and, among other things, the representation and mediation of geographical phenomena. Several researchers at the Department of Geography, e.g., Dr. Zbořil (2010), Dr. Štěrba (2012), Dr. Stachoň and the current head of the Department of Geography, prof. Kubíček, have developed their expertise on the GEOKRIMA project and also in the follow-up to WP5. After the completion of the GEOKRIMA project, the aforementioned Postdoc II projects were followed up and the development of the expertise and potential of the research team was further enhanced by two parallel projects. Thanks to the support of the INPSY development project of doc. Burešová, intensive relations to international researchers could have been developed, e.g., prof. Fabrikant (Bartošová, 2014). As part of the CARLA project, a new research infrastructure – HUME Lab – was established, which provided the necessary equipment for the research team. An interdisciplinary research team consisting of psychologists, cartographers and computer scientists was established that had the necessary research infrastructure. At the core of the team, there was particularly intensive cooperation with Dr. Stachoň, which was reflected in the preparation of joint projects, but also, for example, in the mutual supervision of thesis and dissertation works that stood at the boundary between the two disciplines. At the Department of Psychology, it was, for example, the thesis of Mgr. Knedlová (2016), Mgr. Lacko (2018), and on the contrary, methodological supervision was provided, for example, to students of the Department of Geography (Bilíková, 2017). The intense cooperation also allowed for interchange between the two institutes. Mgr. Ugwitz carried out his master thesis at the Department of Psychology, subsequently enrolled for postgraduate studies with Dr. Stachoň and in the meantime successfully completed his studies at the Department of Visual Informatics with Dr. Chmelík. Among the first dissertations, which were written with the support of the interdisciplinary team and in the context of the newly established Center for Experimental Psychology and Cognitive Sciences, are those of Dr. Kukaňová (2017) and Dr. Čeňek (2016). Dr. Juřík (2020) and Dr. Herman (2018) have already fully benefited from the development of the infrastructure and the established interdisciplinary cooperation. Currently, the joint research line is being developed by the next generation of researchers in the field of psychology (Mgr. Jochecová, Mgr. Lacko, Mgr. Šašinková), as well as cartography (Mgr. Ugwitz, Mgr. Kvarda, Mgr. Švédová). The main core of research has shifted to virtual reality research with an emphasis on educational and collaborative aspects (Jochecová et al., 2022). Thus, the research scope has broadened to include social aspects, and research focused on working with complex visualizations in the context of a group is taking the center stage, among others, thanks to the work of A. Bandura (e.g., socio-cognitive theory, of which Prof. Blatný is a leading promoter).

Simultaneously, cross-cultural comparative research has developed, in which maps also serve as specific stimulus material and which is based on the assumption that the environment (physical or cultural) plays a significant role in shaping cognitive processes.

I believe that it was specifically the reflections on the role of the environment in explaining psychological phenomena, that was an important part of the reasoning of academics at the Department of Psychology in Brno, who then passed on this perspective to their students. To be able to understand psychological processes, one needs to understand the structure and processes of the environment. In addition to professor Švancara, who in his wide range of research explored also the relationship between the individual and their environment (Švancara and Švancarová, 1986), these included, among others, doc. Černoušek (1986) and doc. Kostroň (1997, 2011), who investigated the influence of the environment purposefully in their work. Doc. Kostroň had worked closely with and was strongly influenced by professor Hammond, who was a direct student of Egon Brunswik. The work of important personalities in Czech and international psychology permeates time and space, creating a terrain in which their ideas can be applied and further developed.

2 Comparison of alternative methods of visualization

Identical data and phenomena can be displayed and communicated using different methods of visualization. At the same time, different media can be chosen as a communication channel, which can also influence how the conveyed information will be cognitively processed. The main research question here is: How is the way of content processing and interpretation affected by the form used?

At first, chapter two presents a study focused on the comparison of two alternative bivariate visualization methods, so called extrinsic and intrinsic visualization. The other study examines the effect of the medium, in particular comparing conventional Pseudo 3D projection with Real 3D projection using glasses for stereoscopic vision. In terms of applied research and practical impact, the concepts of effectiveness and efficiency are fundamental (ISO 9241-11). It is investigated whether there are differences between various visualizations in terms of correctness, or accuracy of the solution, as well as the speed of solution. Examples of the author's original work investigating user aspects include studies on the comparison of visualization methods of positional uncertainty (Kubíček, Šašinka and Stachoň, 2014, Selected Cognitive Issues of Positional Uncertainty in Geographical Data), base topographic maps (Konečný et al., 2011, The usability of selected base maps for crises management - Users' perspectives) or map legends for crisis management (Stachoň et al., 2013, Influence of Graphic Design of Cartographic Symbols on Perception Structure). Yet, in the perspective of cognitive psychology, the ambition is not only to compare visualization methods in terms of effectiveness and efficiency, but also to explain the mechanisms and cognitive processes behind the observed behavior.

In the first study, "A Comparison of the Performance on Extrinsic and Intrinsic Cartographic Visualizations through Correctness, Response Time and Cognitive Processing", two phenomena are alternatively represented, soil depth and soil moisture, using extrinsic and intrinsic method. Whereas the extrinsic method uses two separable (independent) graphic variables for each phenomenon – size and color lightness, the intrinsic method encodes phenomena only using the non-separable graphic variables, i.e., color hue and lightness. The results of the study clearly demonstrated that the extrinsic method is superior in terms of both effectiveness and efficiency. An exploratory eye-tracking analysis provided a plausible explanation. The intrinsic method is significantly more cognitively demanding in the legend decoding phase; the higher effort can be explained by the pre-attentive visual processing theory (Treisman and Gelade, 1980; Wolfe, Cave, and Franzel, 1989). Visual elements designated as pre-attentive, such as size, can be detected in a single glance, and in map reading, they help in decoding and processing information.

The following study use different types of tasks to compare the effect of the medium itself on the effectiveness and efficiency of information processing. The comparison of Real 3D medium versus conventional Pseudo 3D medium offers stereoscopic depth cues. Research studies in the past have not provided a clear-cut answer and the results of the presented studies are not entirely congruent either. However, the results show that the benefit of the more complicated Real 3D technology lies more in the subjective experience and does not have a positive effect on the performance itself. On the contrary, there is a performance degradation in some types of tasks, both in terms of effectiveness and efficiency. It can be concluded that an individual is able to compensate quite effectively for the lack of stereoscopic depth cues or to make effective use of the available monoscopic cues when working with a Pseudo 3D visualization. Conversely, an increased level of immersion may lead to a loss of the necessary perspective when solving assigned tasks.

The first experimental studies of the interdisciplinary team at Masaryk University comparing REAL and PSEUDO 3D geovisualizations include Špriňarová et al. (2015) and Juřík et al. (2017). In the latter article (Juřík et al. 2017, When the Display Matters: A Multifaceted Perspective on 3D Geovisualizations), the authors found no differences between Real 3D and Pseudo 3D for most conditions and task types that dealt with the altitude identification of objects in the terrain. Only for the task type with no interaction option and no time limit was Real 3D significantly better in terms of correctness. In all other task types and parameters observed, e.g., speed of solution, the effect of the medium was not significant.

In the study, "The 3D hype: Evaluating the potential of real 3D visualization in geo-related applications", more types of stimulus material were included compared to the previous experiment, namely isolated objects – cubes (as in the previous study), flat areas or water bodies and linear terrain elevation profiles. The main effect observed was that with the REAL 3D condition, there is a significant increase in the time needed to solve the task. The completion time increased also for interactive tasks, where participants had the opportunity to actively explore the terrains. Contrary to expectations, however, there was also an increase in error rates in the interactive tasks. If the interaction of independent variables (visualization type – REAL vs. Pseudo 3D; and interface type – interactive vs. static environment) was taken into account, then interactive Pseudo 3D conditions tended to encourage greater accuracy than static Real 3D conditions.

Follow-up study, Herman et al. (2021), A Comparison of Monoscopic and Stereoscopic 3D Visualizations: Effect on Spatial Planning in Digital Twins, which was built on previous experimental designs comparing REAL and PSEUDO 3D and which I contributed to conceptualize and supervised, emphasized more common, realistic, and complex types of tasks that require the involvement of higher cognitive functions and complex spatial analysis. The participants were asked to explore a virtual terrain with located buildings and then place a transmitter that would cover all buildings, or all priority buildings, with a direct signal. The results showed no differences in terms of correctness, but significant differences were found to the disadvantage of REAL 3D in terms of the speed of solution, i.e., efficiency.

Although the findings of the abovementioned studies are not conclusive, the superiority of REAL 3D that would justify its wider use in practice, e.g., in crisis management, has not been proven clearly. More frequently, the results spoke rather against REAL 3D media. Differences between REAL 3D and PSEUDO 3D in terms of effectiveness have not been found even in another research study by the author (see 3.2) either, which focused more on the aspect of individual differences.

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

Šašinka, Č., Stachoň, Z., 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), e0250164.

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.

PLOS ONE

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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Competing interests: The authors have declared that no competing interests exist.

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.

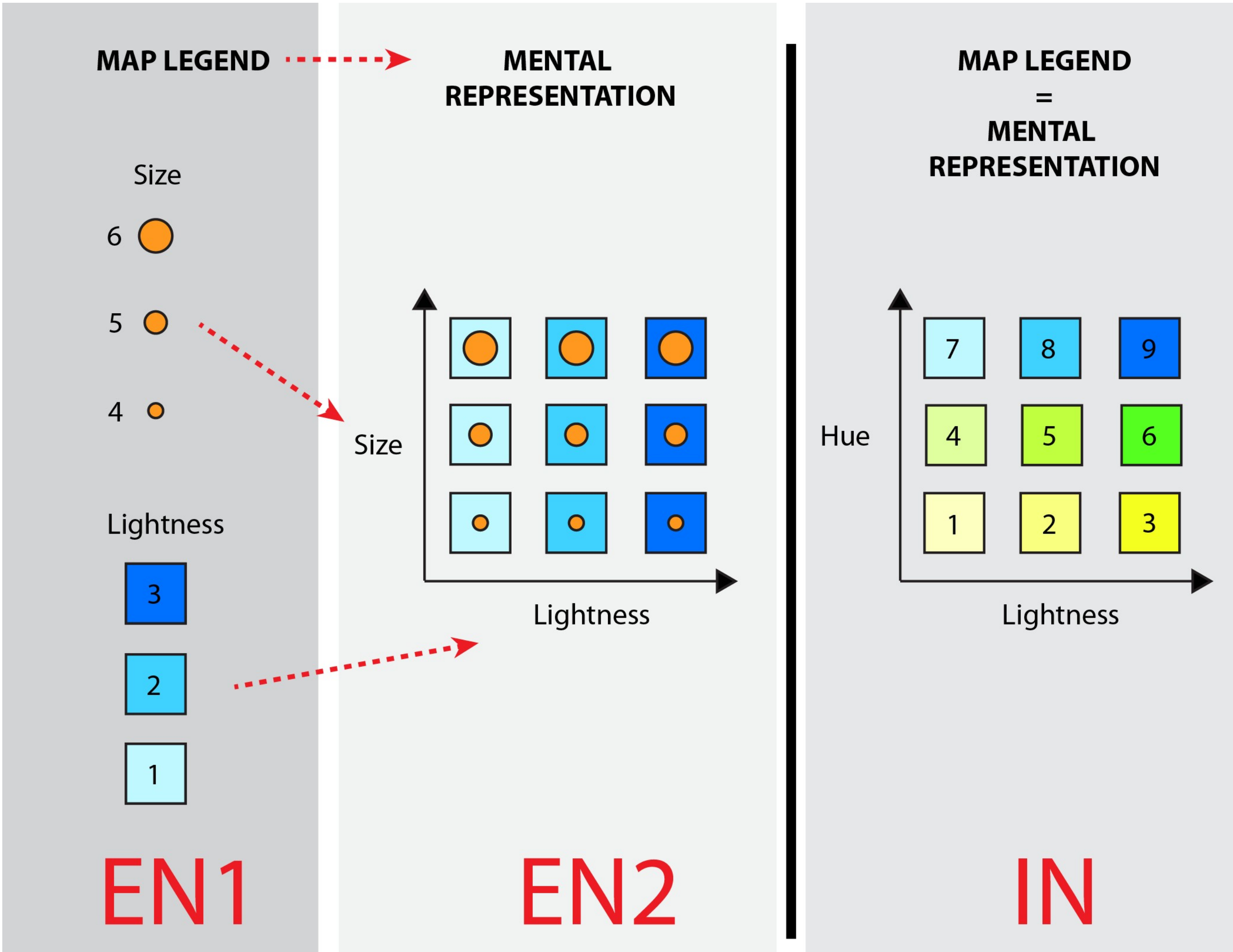

Fig 1. Examples of extrinsic and intrinsic bivariate encoding of geographic variables. EN1: extrinsic (separable) encoding of variables according to size and color lightness; EN2: mental representation of extrinsic visualization (all the possibilities); IN: intrinsic (inseparable) encoding of variables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

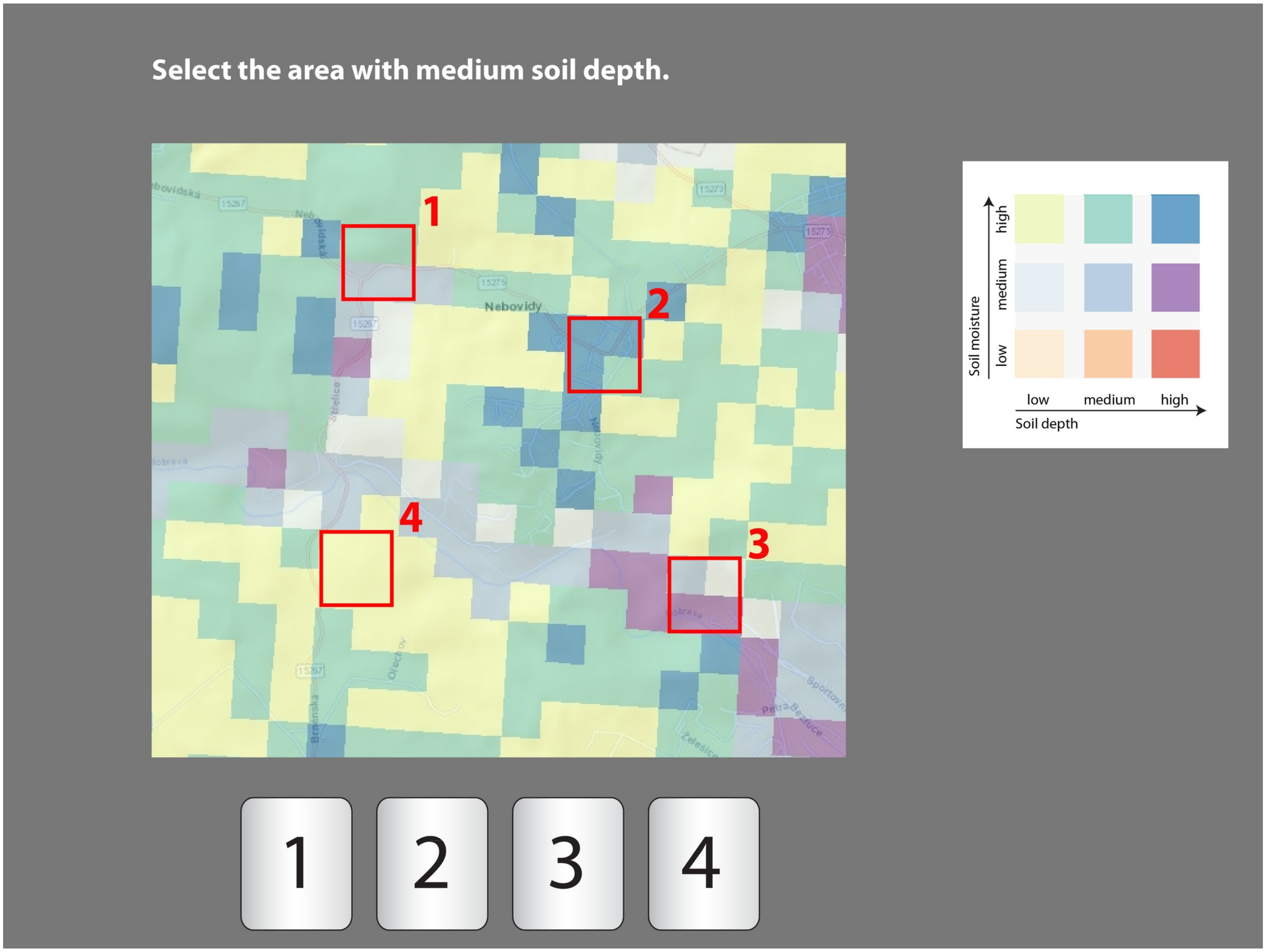

Fig 3. Example of an intrinsic visualization item (subtest A–part A.1.). The task was to select the area which contained "medium soil depth"; the correct answer was area No. 1.

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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

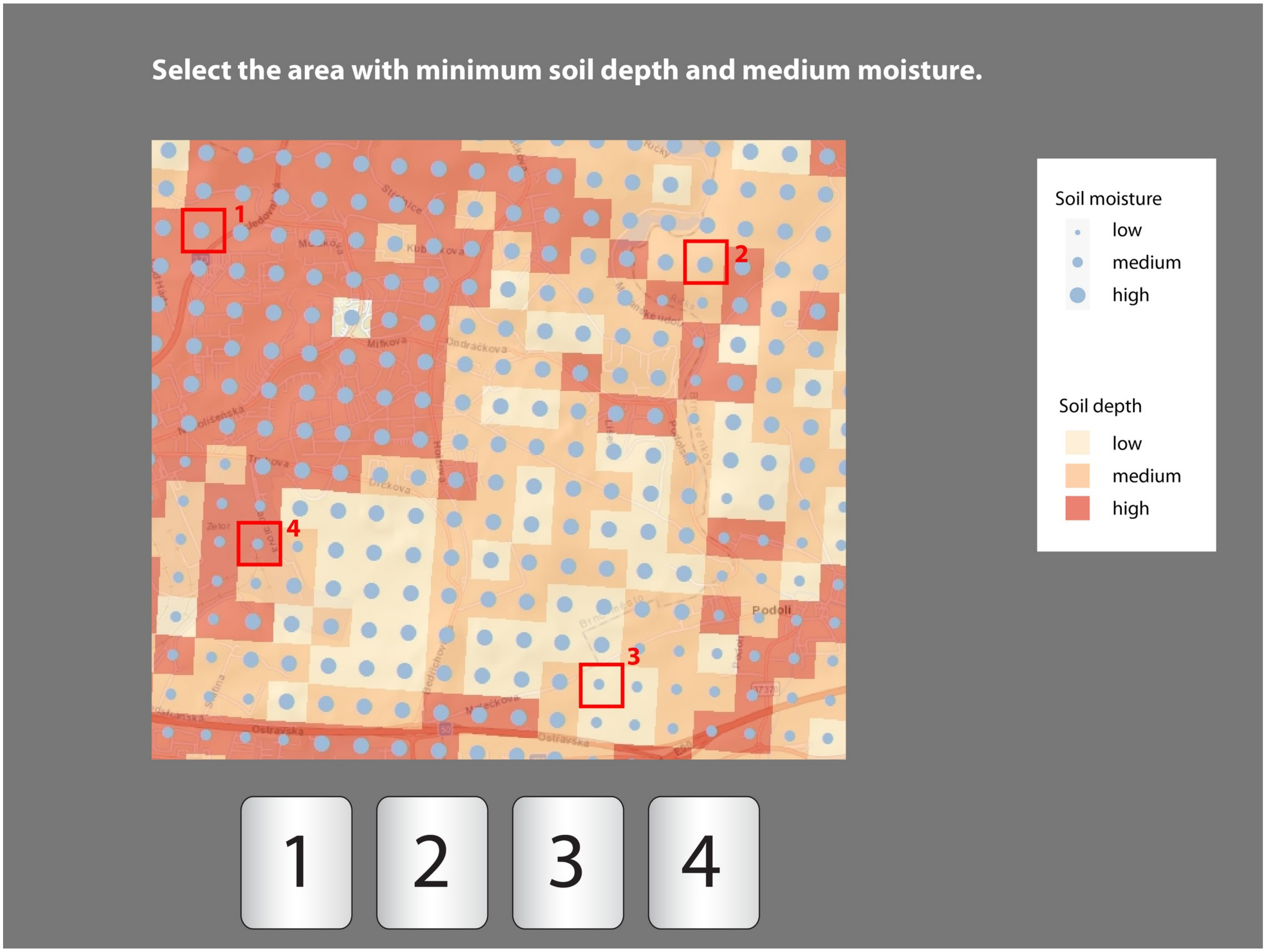

Fig 4. Example of an extrinsic visualization item (subtest B—part B.2). The task was to select the area which best satisfied the conditions of "low soil depth" and "medium soil moisture"; the correct answer was area No. 3.

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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

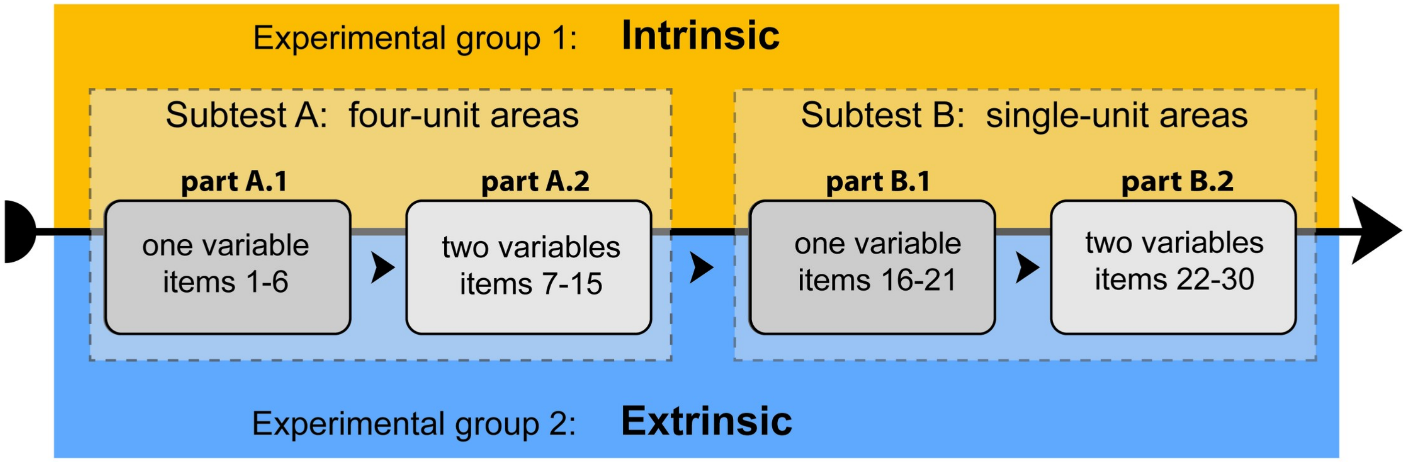

Fig 5. Between-subject experimental design (subtests A and B; parts A.1, A.2, B.1 and B.2). Both independent experimental groups, Intrinsic and Extrinsic, performed the test in exactly the same manner. The order of all items was constant for both groups, and all participants.

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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

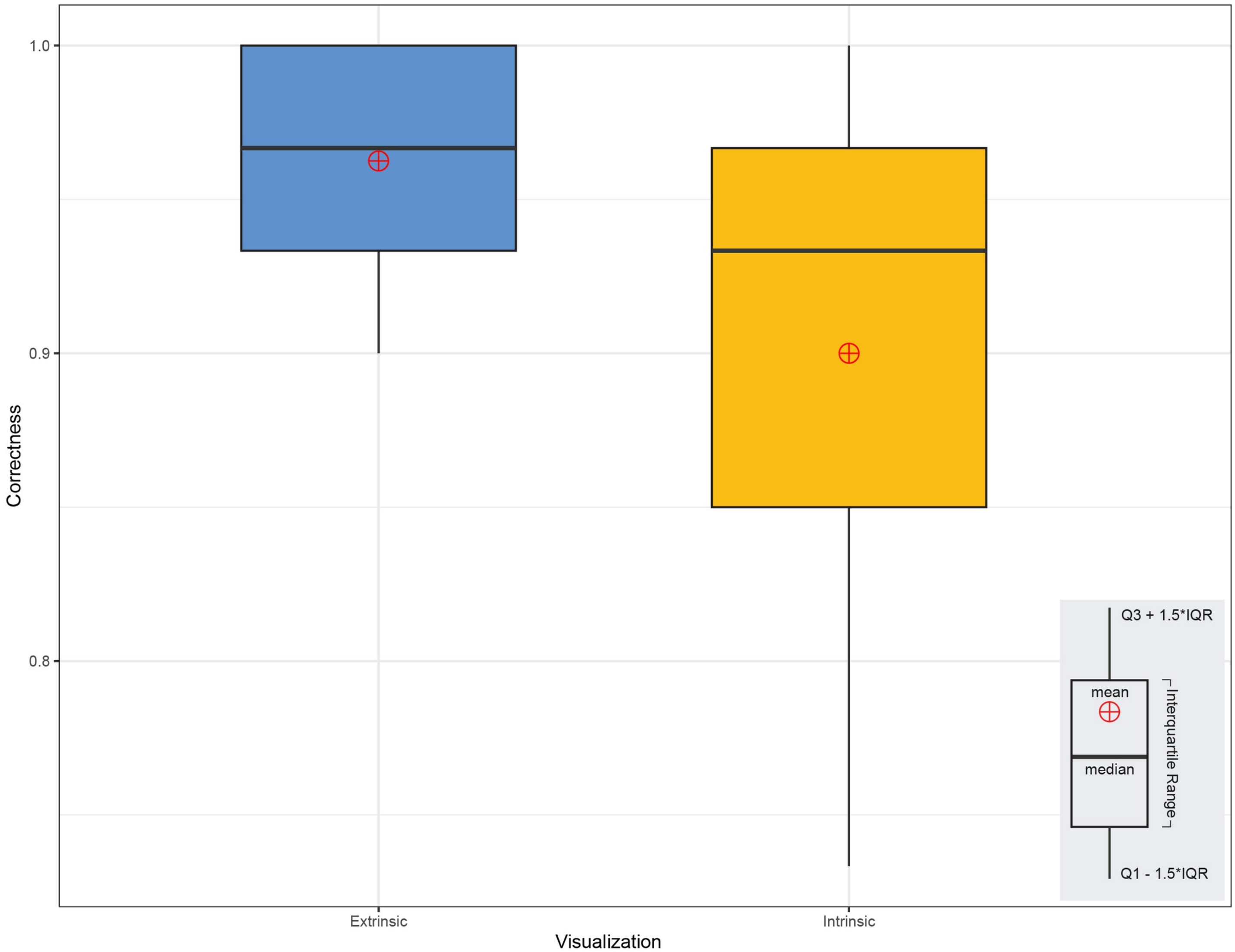

Fig 6. Response correctness for the entire test. Correctness was calculated as a ratio of the number of correct answers to the number of all answers.

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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

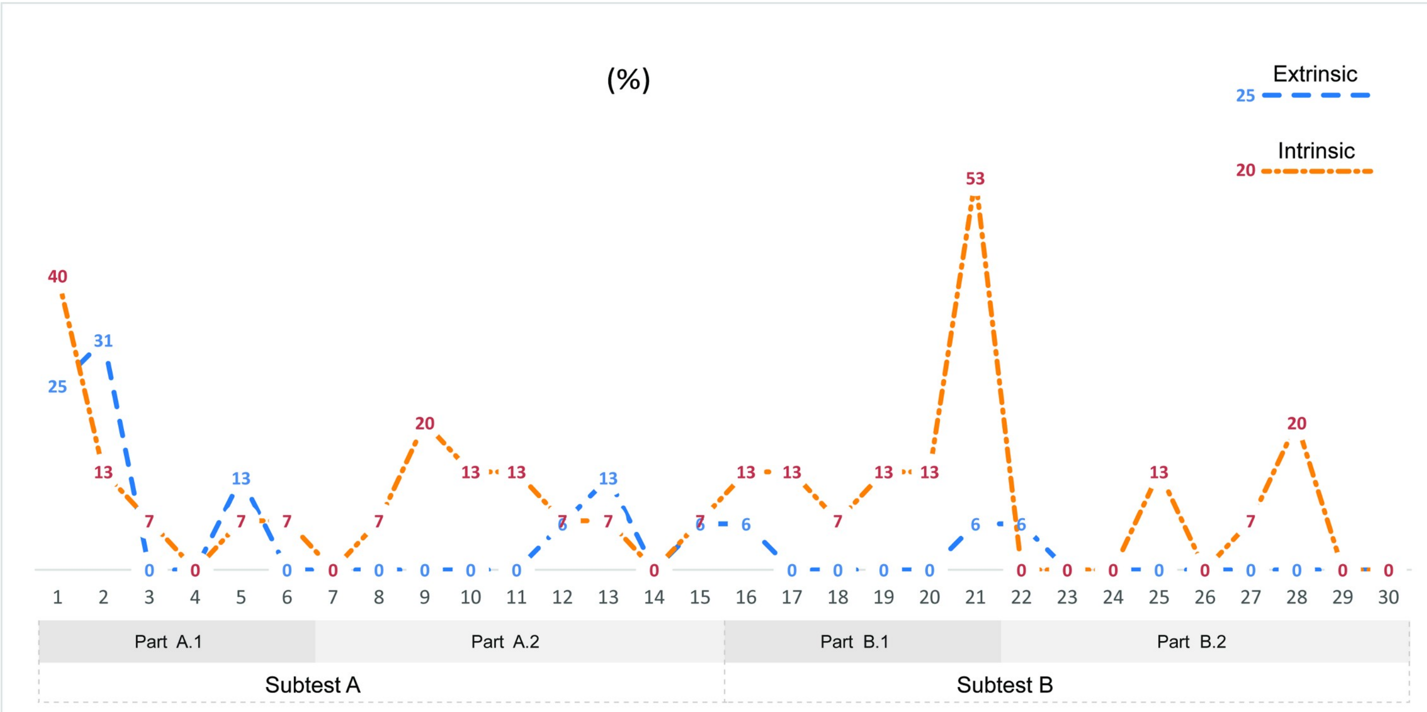

Fig 7. Error rate per item. INT–red/yellow, EXT–blue. Particular attention was given to items with a significant difference between the two visualizations (1, 2, 9, 21, 28). The error rate was calculated as a percentage of incorrect answers of all answers.

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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

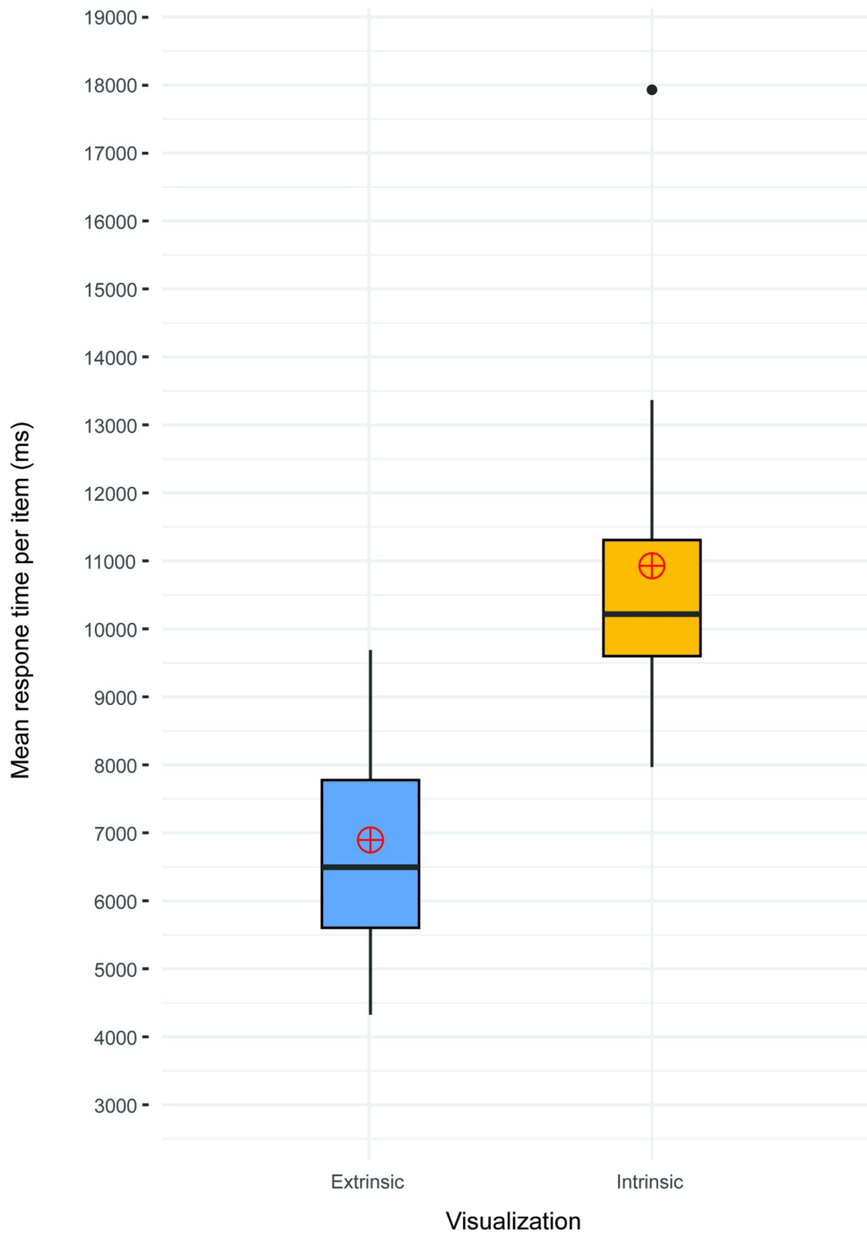

Fig 8. Mean response time per extrinsic/intrinsic visualizations (calculated from the response times to all extrinsic/intrinsic items for all participants).

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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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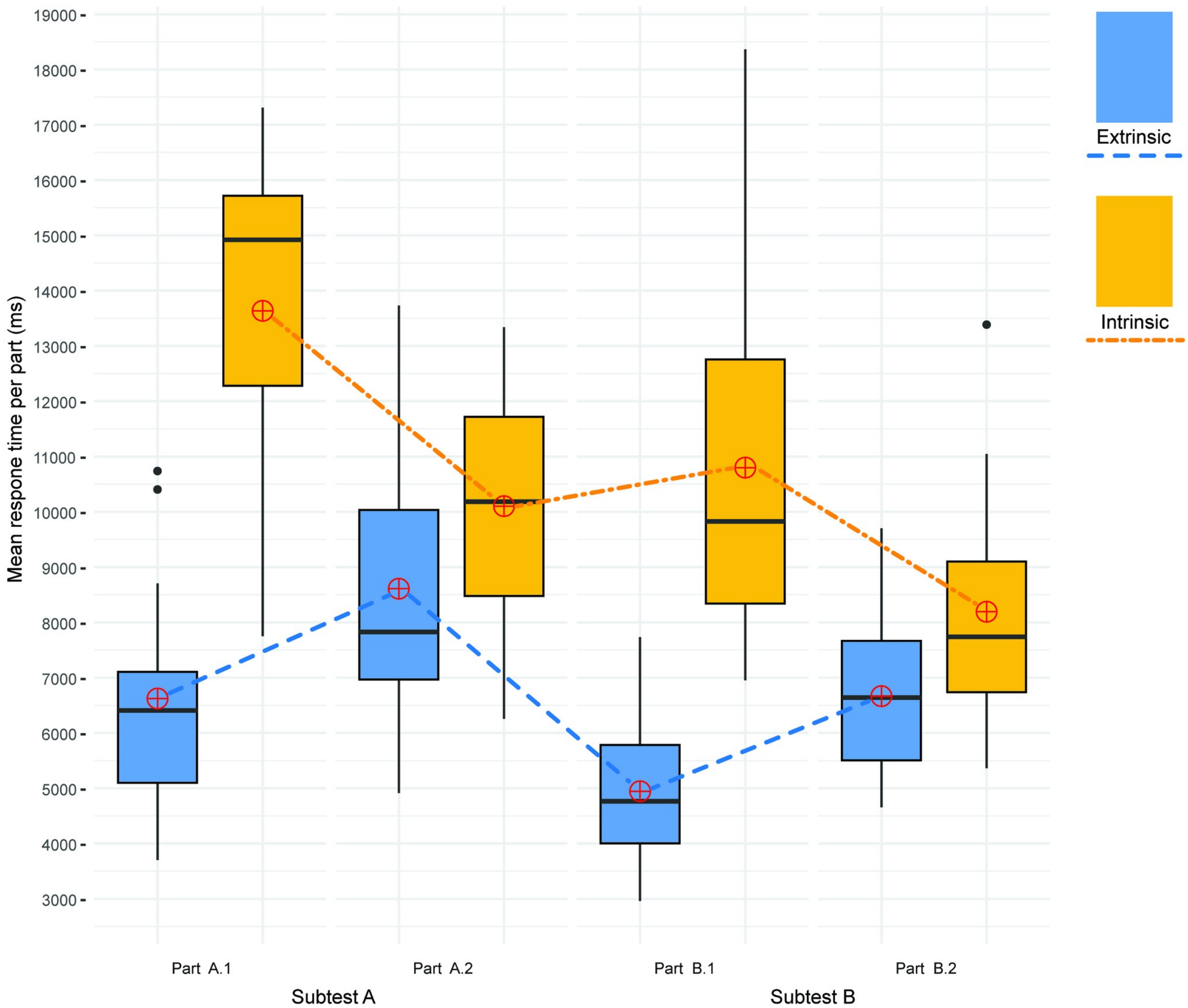

Fig 9. Mean response time (ms) per item (calculated for the individual subtest levels).

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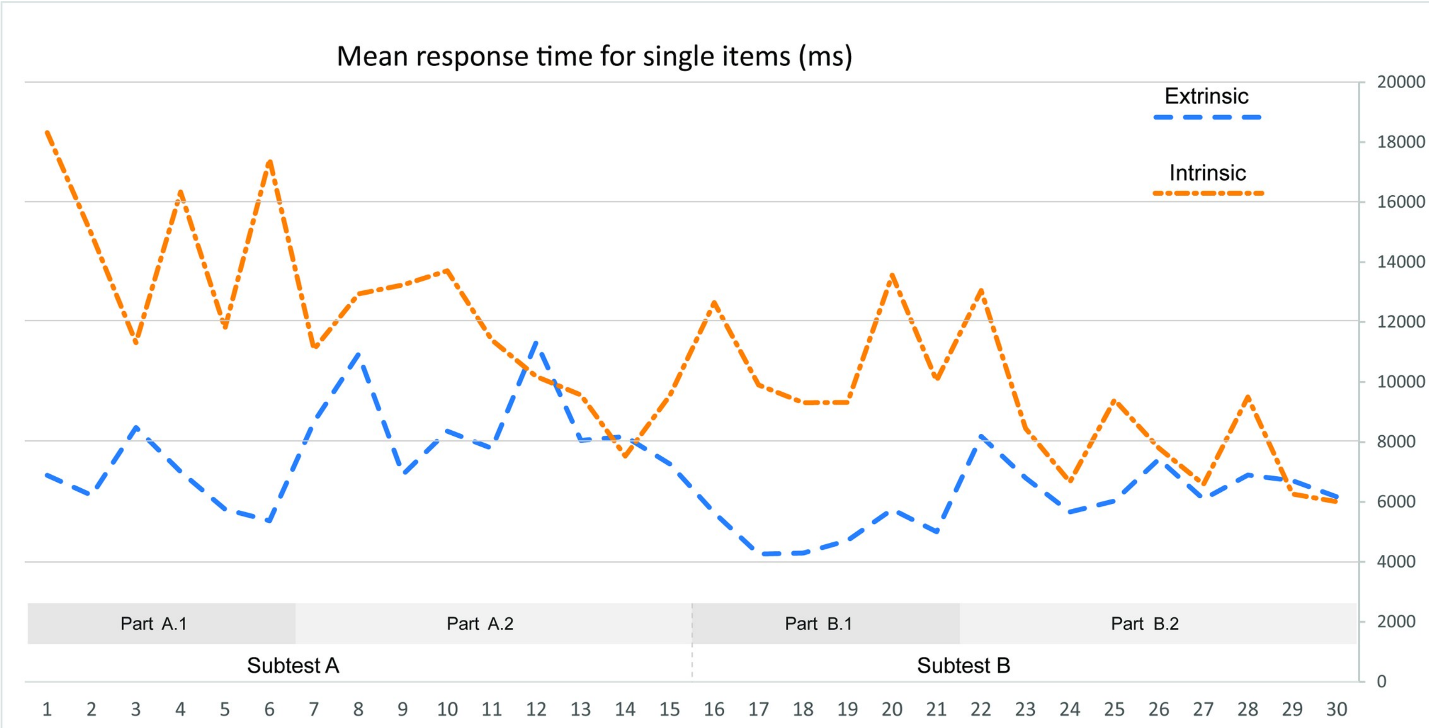

Fig 10. Mean response times (ms) per individual items for extrinsic and intrinsic visualization (all items).

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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]***

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(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

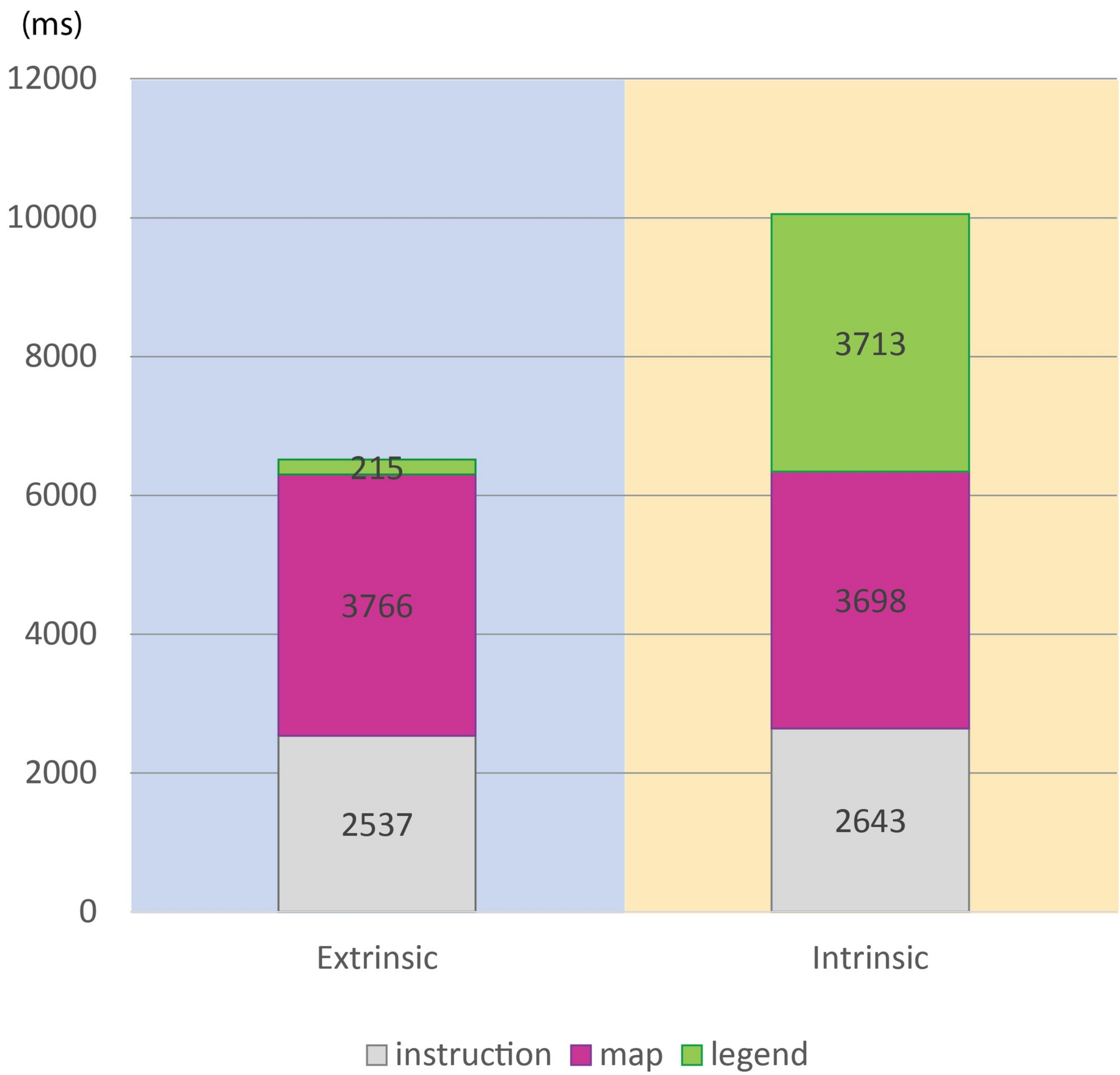

Fig 11. Mean AOI dwell time per extrinsic/intrinsic group (ms).

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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

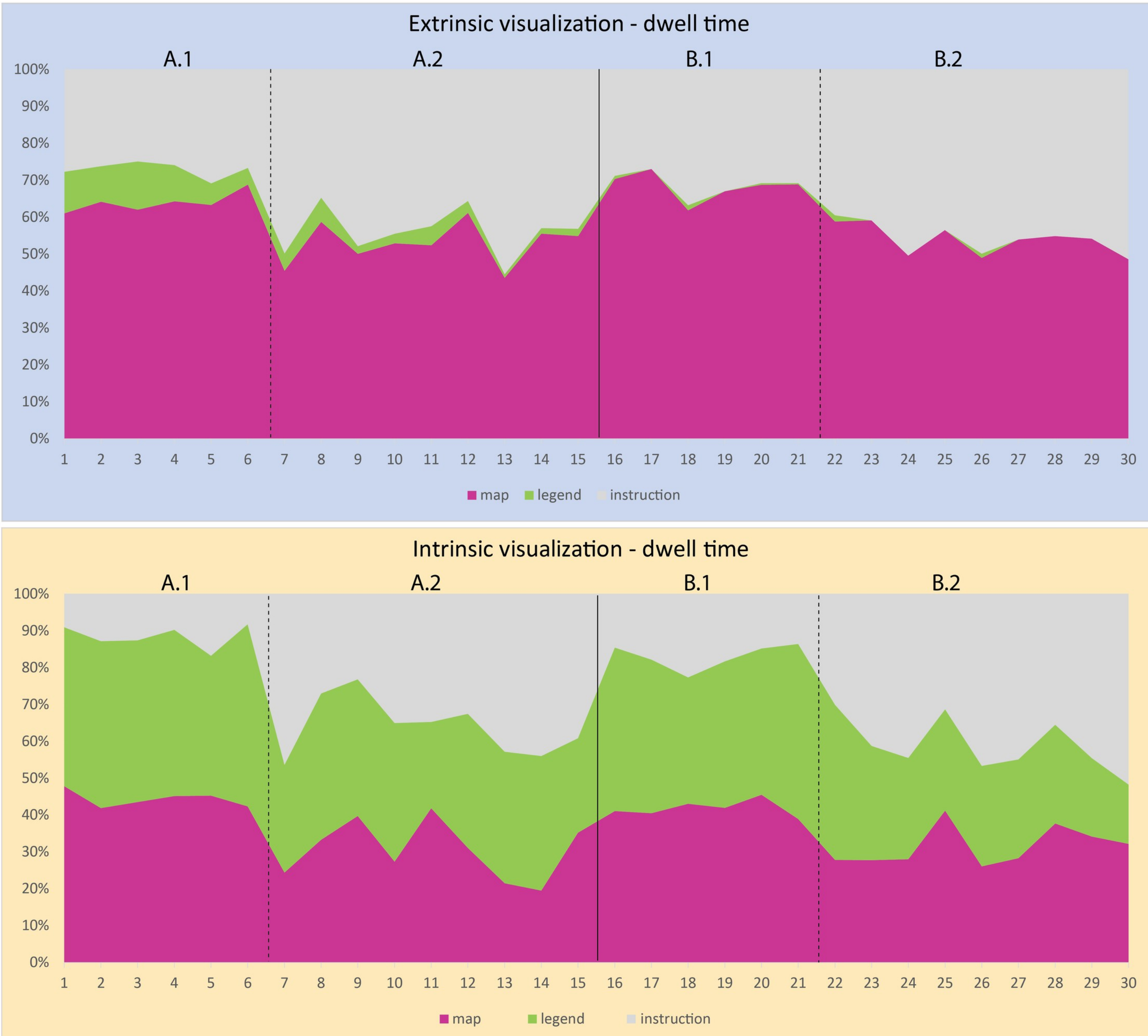

Fig 12. Dwell time on AOI (%) for the extrinsic visualization (top) and intrinsic visualization (bottom). Extrinsic visualization–proportion of dwell time at AOI in single items; (top); Intrinsic visualization–proportion of dwell time at AOI in single items (bottom).

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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.

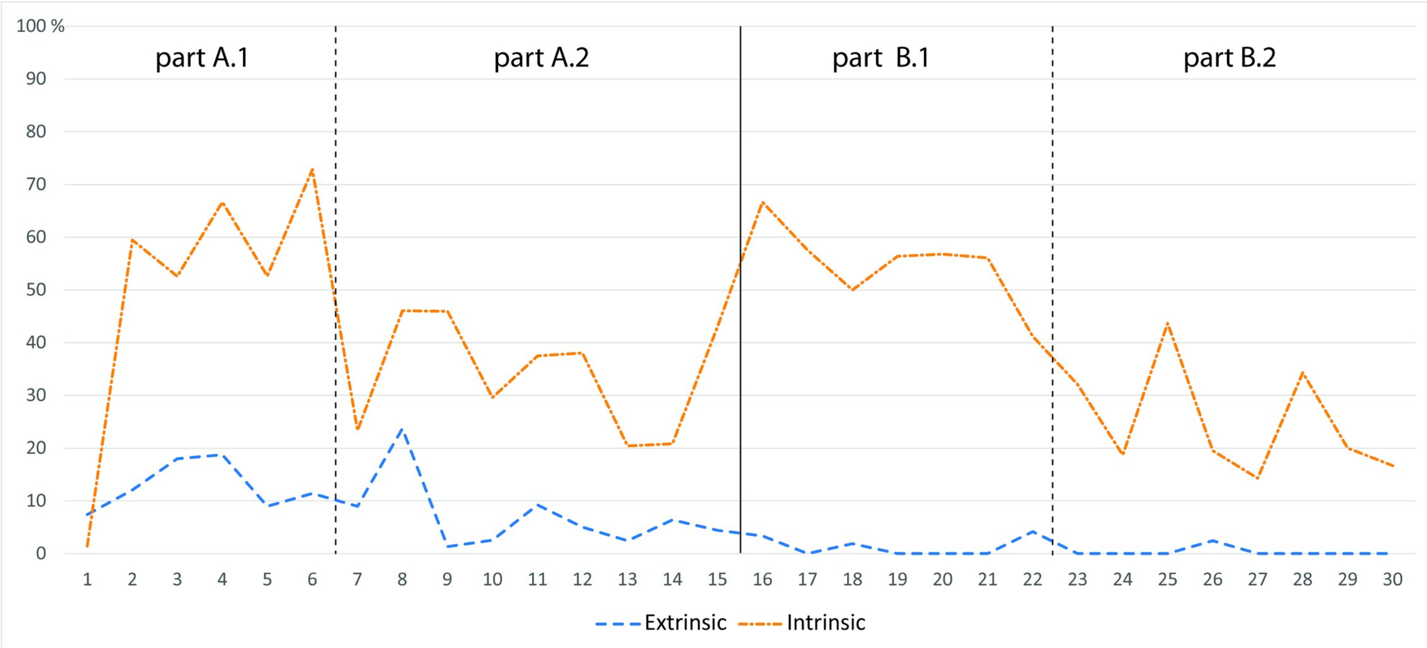

Fig 13. Ratio of the direct map-to-legend/legend-to-map saccades to the total number of direct saccades (%) between the defined AOI (instructions, legend, map, button bar).

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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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2.2 The 3D hype: Evaluating the potential of real 3D visualization in geo-related applications

Juřík, V., Herman, L., Snopková, D., Galang, A. J., Stachoň, Z., Chmelík, J., Kubíček, P. & Šašinka, Č. (2020). The 3D hype: Evaluating the potential of real 3D visualization in geo-related applications. *Plos one*, 15(5), e0233353.

Abstract

The use of 3D visualization technologies has increased rapidly in many applied fields, including geovisualization, and has been researched from many different perspectives. However, the findings for the benefits of 3D visualization, especially in stereoscopic 3D forms, remain inconclusive and disputed. Stereoscopic "real" 3D visualization was proposed as encouraging the visual perception of shapes and volume of displayed content yet criticised as problematic and limited in a number of ways, particularly in visual discomfort and increased response time in tasks. In order to assess the potential of real 3D visualization for geo-applications, 91 participants were engaged in this study to work with digital terrain models in different 3D settings. The researchers examined the effectivity of stereoscopic real 3D visualization compared to monoscopic 3D (or pseudo 3D) visualization under static and interactive conditions and applied three tasks with experimental stimuli representing different geo-related phenomena, i.e. objects in the terrain, flat areas marked in the terrain and terrain elevation profiles. The authors explored the significant effects of real 3D visualization and interactivity factors in terms of response time and correctness. Researchers observed that the option to interact (t = -10.849, $p < 0.001$) with a virtual terrain and its depiction with real 3D visualization (t = 4.64, $p < 0.001$) extended the participants' response times. Counterintuitively, the data demonstrated that the static condition increased response correctness (z = 5.38, $p < 0.001$). Regarding detailed analysis of data, an interactivity factor was proposed as a potential substitute for real 3D visualization in 3D geographical tasks.

PLOS ONE

RESEARCH ARTICLE

The 3D hype: Evaluating the potential of real 3D visualization in geo-related applications

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Introduction

3D visualizations are being increasingly used in a number of applied areas for data visualization. Since these visualizations allow three-dimensional perception of graphical content, they are considered a promising tool for a range of applications in geo-sciences, for example, teaching geography and cartography [1–5], urban planning [6–8], crisis management [9–12], precision agriculture [13], visibility analysis [14], virtual tourism [15], navigation in built-up areas

decision to publish, or preparation of the manuscript.

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[16, 17], indoor navigation [18, 19] and others. Different forms of 3D visualization may encourage different types of human behavioural and cognitive responses, i.e. they can affect human sensorimotor and interaction strategies, cognitive processing, and ultimately, human performance. The aim of this study was to evaluate important factors contributing a role in 3D geovisualizations, specifically 3D factors and interactivity factors in the context of different geo-related tasks. In this study, 3D geovisualization is understood as a three-dimensional visual representation of the real world, its parts, or as a representation of the spatially referenced data [20]. The 3D geovisualization may be of a dynamic nature, so it allows for changes of depiction based on the user-computer interaction. Regarding this, 3D geovisualization allows the user to focus on its specific parts or aspects from various positions, perspectives, and other functionalities (see [21]). In this study, authors explored participants response times and accuracy of answers in different forms of geovisualization, specifically focusing on the level of interactivity and 3D visualization type, as stated in detail below in the research hypotheses.

3D visualization types

The types of 3D visualizations vary in the principles that visualizations are built on and the technologies used to display them. The most typical types of 3D visualizations are pseudo 3D visualizations (also known as weak or 2.5D visualizations) and the less common real (or strong) 3D visualizations [22, 23]. Pseudo 3D visualizations depict a scene which is displayed perspective-monoscopically on flat media, such as computer screens or widescreen projection. These scenes are composed solely with the use of monocular depth cues [23]. Real 3D visualizations engage both monocular and binocular depth cues (especially binocular disparity cues) in order to achieve stereoscopic vision. Stereoscopy is a technique using stereopsis [24] to separate the visual signals individually perceived by each eye and present them through a peripheral device, for example, 3D shutter glasses [25]. The slight differences in perspective in image between the left and the right eye are registered and combined to create a 3D representation of the observed scene. Real 3D vision was developed to enhance perception of spatial attributes in an observed scene, i.e. the distances and relative positions of objects in a visual field [26, 27], and to increase depth perception in a scene [28]. Real 3D technology provides a different number of visual cues than pseudo 3D, and therefore, it is expected that the displayed content is processed differently with respect to the visualization type. Hence, real 3D technology has also been proposed as a more effective tool for virtual geovisualization since it provides additional spatial information [1, 29, 30], even though no clear standards for the production and use of real 3D visualizations in geo-sciences are available [22, 23, 31]. Despite the added visual cues in real 3D visualization, the effectiveness and efficiency [32, 33] of stereoscopic 3D visualization in applied issues remains disputed, especially regarding increased response time to solve tasks in a real 3D environment, increased cognitive load and user distraction, neglect of important objects in the scene, or significant visual discomfort while wearing peripheral devices, such as 3D glasses or helmets [23, 28, 34–36]. Several empirical studies support the effectiveness of real 3D visualization [37–40], although their practical use, especially in geo-related issues, remains controversial [30, 41].

Interactivity factor

The shift from static maps to interactive versions is a natural step, as technological progress permits and drives it. Interactivity in current geospatial data visualizations is starting to become available for users to navigate or otherwise work with data to obtain required information and acquire optimal situation awareness [42, 43]. In the present paper, the researchers

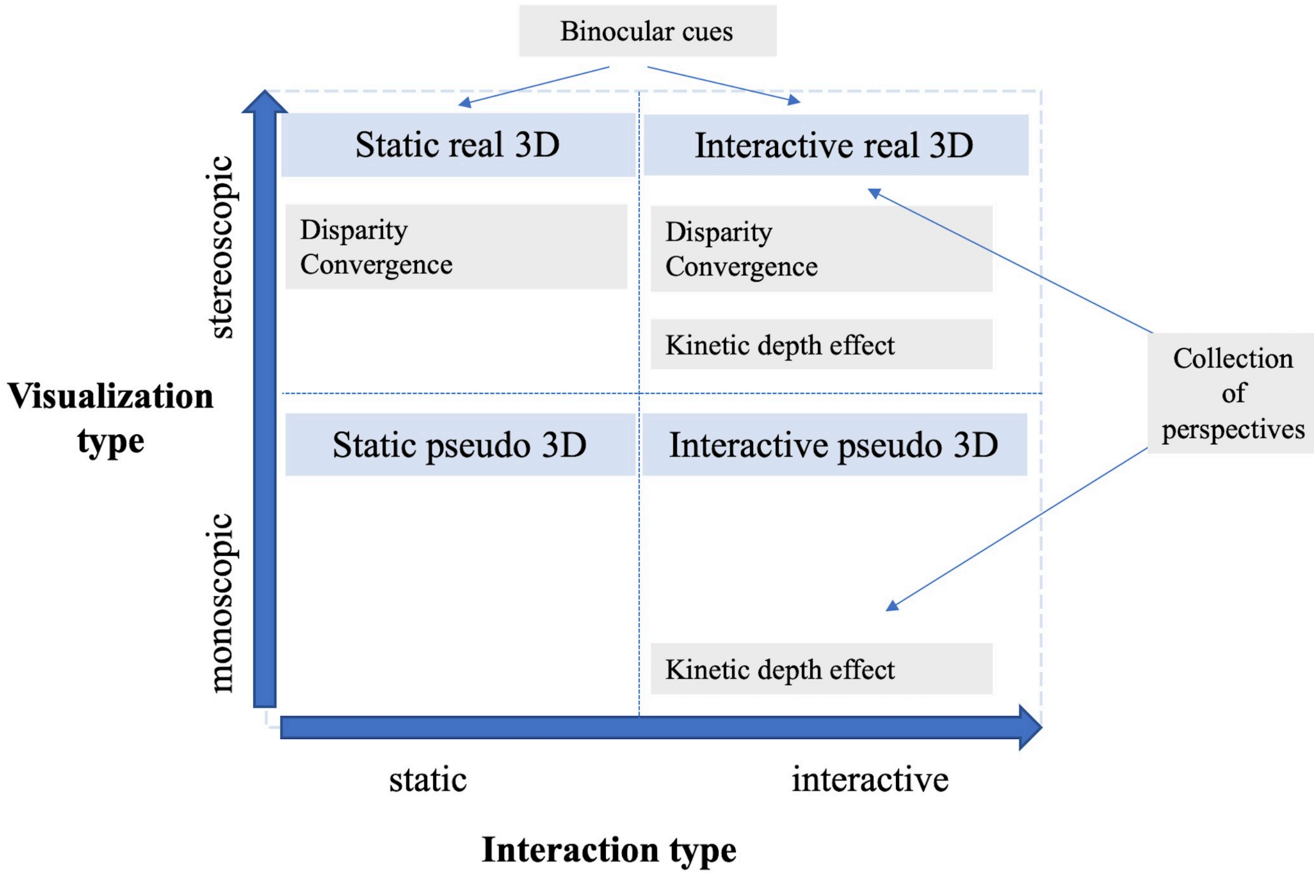

Fig 1. Scheme of the additional depth cues present in various settings.

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focused on navigational (or viewpoint) interactivity, which was discussed in previous studies [43–46], and which forms the core functionality of applications such as Google Earth and other virtual globes. Navigational interactivity in 3D space usually includes functions such as rotation, panning and zooming for spatial information acquisition further promoting e.g. spatial orientation [46]. Previous studies [19, 45, 47–49] suggested a difference between static and interactive scenes in perception and cognitive processes, and respectively emphasized the importance of the specific task type [45]. Interaction with a geovisualization helps complete the spatial information about the scene as the scene is moved and presented from various points of view. Interaction provides a collection of perspectives, and hence the mental model of the scene can be more rapidly processed by the observer, as previously discussed by [36, 50, 51]. Other authors have suggested that interaction only improves task solving in a limited manner since users need not be able to use it properly [52]. Regarding this, the present study questions the role of 3D geovisualizations in the context of interactive and static tasks and suggests that real 3D visualization can be possibly substituted with the option to control visualized content. The summary of the available depth cues present in various settings is shown in Fig 1.

Geographical task factor

A number of studies explored simple 3D geovisualizations [36, 45, 53, 54]. Other studies explored complex stimuli similar to real-world settings [4, 19, 55]. Previous findings suggested that the role of 3D technology in geovisualizations is questionable, especially regarding the specific features of the user interface (interactivity factor, type of task, etc.). Research in geo-applications emphasizes the role of the specific task since there is very limited option to control the equivalence of stimuli—a real map is a unique combination of spatial aspects in which it is difficult to find equivalent stimuli. For this reason, the authors developed an experiment that uses three types of tasks as experimental stimuli (i.e. point, surface and elevation profile structures in the virtual terrain), which represent different geo-related phenomena, such as buildings, water bodies and roads. Participants were asked to determine the elevation of objects (cubes), water bodies and the presented terrain profiles in the virtual terrain. These three task types possessed different spatial complexity and represented different spatial structures. As spatially simple and complex stimuli, the cubes and terrain profiles, respectively, had already been tested in previous studies [36, 49] and were complemented in the present study with semi-complex "surface" stimuli, i.e. water bodies.

Research aims

The present study explored the effectivity of real 3D geovisualization in static and interactive tasks. Effective form does not refer to the simplest/easiest form but to one that offers users sufficient information necessary to make a proper choice and prevent mistakes while also facilitating quick response, i.e. it balances effectiveness (score) and efficiency (speed). Quesenbery [56] suggested three general aims that every user interface should follow: (a) effectiveness in achieving determined objectives, usually completing the task (i.e. correctness), (b) efficiency in control or use (i.e. speed and ease), and (c) the operator's satisfaction in working with such a device. Regarding these points, the suitability of a specific user interface setting can be operationalized and tested. The present study examined the first two above-mentioned points, i.e. goal achievement and speed, as these can be operationalized into objective performance scores and response times in the suggested geo-related tasks. As mentioned in more detail above, previous studies have suggested that real 3D visualization is potentially troublesome and may cause visual discomfort, prolong solution time or promote neglect of important objects in a scene. The aim of this study was to assess the effect of 3D visualization on goal achievement and performance speed under different 3D conditions with different tasks. One of the main questions was the role of real 3D technology in the context of interactive geographic tasks, in which navigational interactivity [43] was suggested as being able to potentially compensate for missing binocular cues (as discussed in [36]). Regarding this, the authors of the present study observed user performance in real 3D, and respectively, pseudo 3D visualizations, both in static (i.e. non-interactive) and interactive environments. The present study is specific in several ways. Compared to the previous research of [28, 57], the authors inspected the effect of interactive 3D visualizations in virtual models of real, existing geographical areas. Previous studies also engaged a limited number of participants, generally only up to 20 people [58–60], thereby limiting general conclusions. Furthermore, the present study emphasized the process of interaction with terrains generated by the participants themselves and avoided the use of automated computer-generated movement.

The research hypotheses were:

a. Tasks in a real 3D environment require a longer time to be solved,

b. Tasks in an interactive environment require a longer time to be solved,

c. Tasks in a real 3D environment result in more correct answers,

d. Tasks in an interactive environment result in more correct answers.

Methods

Participants

The previous study [36] suggested that the 3D visualization type had a significant effect in identifying an object's elevation in a static (non-interactive) 3D geovisualization (*Cohen's d* = 1.06). The authors of the present study considered the experiment's design (e.g. computer screens instead 3D wide-screen projection) and other observations concerning similar issues [49]. Only a relatively mild effect was expected. Regarding this, 91 participants were engaged in the experiment. Since the study examined the topic of perception, volunteers, specifically humanities students with no or minimal previous training in geo-visualization from Masaryk University (17 males, 75 females), aged 19 to 53 years (m = 23.46 years; *med* = 23 years; sd = 4.9), were involved. Course-takers of Masaryk University's Experimental Humanities course, which is held annually at the Faculty of Arts, were invited via email. By participating in the experiment, they were rewarded with 16 points towards the above-mentioned course. Before the experiment, all participants were questioned about visual impairments and any other possible medical limitations and informed that they could remove themselves from the experiment at any time. The study was approved by the Masaryk University Ethics committee for the research, identification number of the project: EKV-2016-059. Participants in the study gave their consent by means of a written consent form.

Procedure and materials

The entire experiment was fully computerized. The participants used conventional desktop PCs with 27-inch 3D monitors and wore active shutter 3D glasses (NVIDIA 3D Vision® 2 Wireless Glasses, 60 Hz on each eye). Regular optical mouses were used for UI control. The participants were introduced to the experiment and instructed on the control devices, interface and purpose of the experiment. After the introduction, a questionnaire presented on the PC asked for their demographic data and about any visual impairments. After this, participants were instructed how to proceed through the testing and that they should attempt to be fast as well as accurate since both their speed and correctness would be measured. The testing application was created at the Faculty of Informatics (Masaryk University, Brno) specifically for the purpose of the study. The participants were instructed to follow the information on the screen, for example, when to wear or remove the 3D glasses with respect to the specific test section. After instructions, the participants were pseudo-randomly assigned into the specific experimental groups (based on the task type category). The participants then commenced a training session to learn how to navigate/control the interactive geovisualizations and how to put on/take off the 3D glasses. After the training, the participants completed 24 assigned tasks in the experiment. At the end of the experiment, participants were debriefed and rewarded with sweets.

Research design

The study employed a within-between multi-factorial design. The first factor was *3D visualization type* (two levels: pseudo 3D visualization and real 3D visualization), the second factor was *interactivity type* (two levels: interactive type and static, or non-interactive, type) and the third factor was *task type* (three levels: cubes representing objects, e.g. buildings, surfaces representing water bodies, and terrain profiles representing, e.g. roads). This legend (buildings, water bodies, roads) was described to the participants at the beginning of the experiment to better illustrate the purpose of the experiment and tasks. Taking into account the length of the experiment and potential fatigue in the participants, the research sample was pseudo-randomly

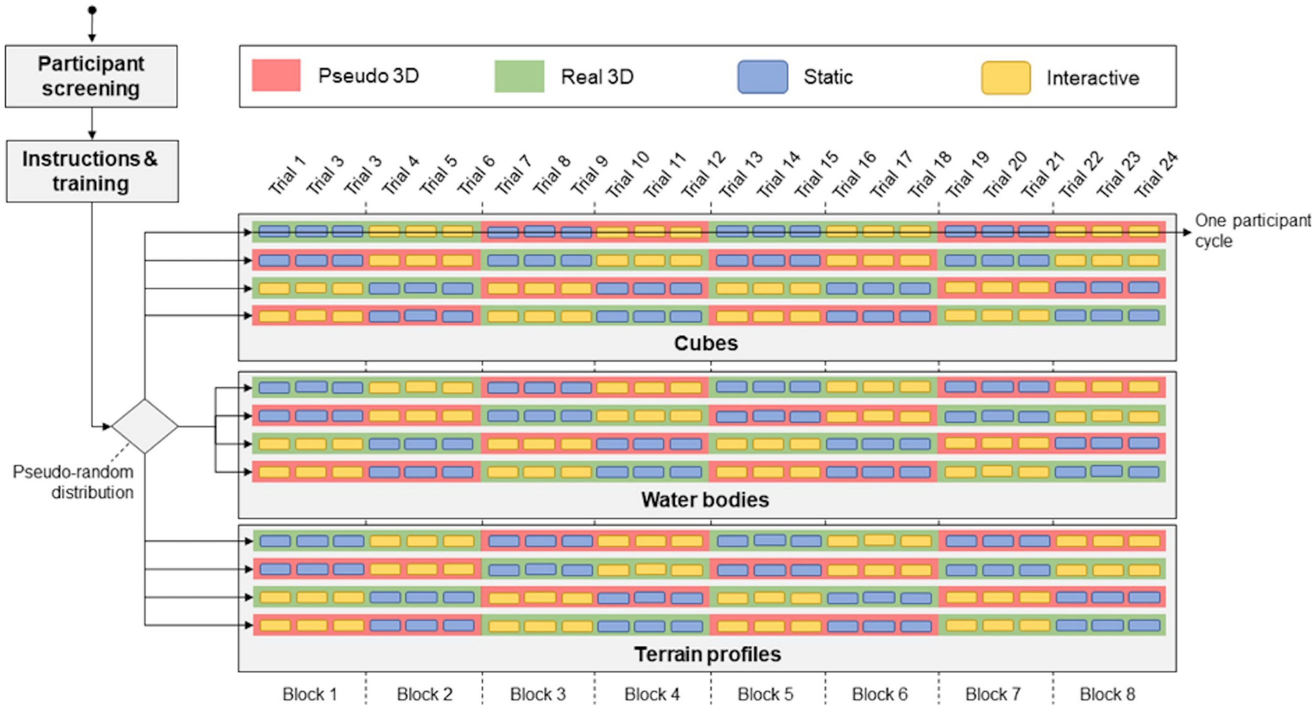

Fig 2. Diagram of the procedure of the experiment.

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divided into three subsamples (regarding the ratio of males and females) with respect to the specific task type (cubes, water bodies, terrain profiles). This meant that each subsample dealt with only one type of task (24 trials). Each task measured (i) response time (in seconds) and (ii) correct elevation estimation (participants were asked to select one of three possible options and scored 1 point for a correct answer and 0 for an incorrect answer). Time, correctness and the number of the mouse clicks participants made was recorded automatically with the software developed for testing.

The research design was balanced, each participant underwent 24 tasks divided into 8 blocks. Each block consisted of 3 trials of the same type (e.g. interactive real 3D). In an effort to reduce the primacy effect, the participants commenced the test's static real 3D, static pseudo 3D, interactive real 3D and interactive pseudo 3D condition alternately (Fig 2).

Description of the tasks

Comparing the positions of cubes in the terrain. Participants were asked to identify a cube placed at the highest elevation in the digital terrain model. Participants were shown a virtual scene with three cubes of the same red colour and asked to identify which one was located at the highest elevation. The cubes represented, for example, buildings. As point-symbols, buildings are considered the simplest spatial structure. Participants could identify the cubes with a mouse click. After clicking, the cube turned yellow, and participants could confirm their answer by clicking the "NEXT" button (Fig 3). Participants could also change their answers by clicking on one of the other cubes before pressing the "NEXT" button.

Comparing the positions of water bodies in the terrain. Participants were asked to identify the water body located at the highest elevation in the digital terrain model. Participants

Fig 3. Example of Task 1 –Cubes in the terrain. Yellow indicates that this object was selected by the participant. Adapted from [61] under a CC BY license, with permission from [ČÚZK], original copyright [2018/2019].

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were shown a scene with three structures, illustrated as water bodies with the same blue colour, and asked to select which was positioned highest. Water bodies have a surface character, and in terms of their complexity, are considered stimuli between point symbols and areal symbols. As in the cube tasks, responses were made with a mouse click, turning the flat area yellow (Fig 4), and the task was finished by confirming the choice with the "NEXT" button.

Identifying terrain profiles. Participants were shown a scene with three structures located in the digital terrain model, each one representing a specific terrain profile between two points. A terrain profile presented as a 2D curve was displayed on the right side of the screen. Participants were asked to identify which of the three terrain profiles conformed to the shape of the curve depicted on the right. Since the elevation curve (complicated 3D structure) was not depicted, i.e. needed to be mentally computed, profile tasks are considered the most difficult. Again, as in the previously described tasks, the choice was made with a mouse click, turning the selected profile yellow (Fig 5), and the final answer was confirmed with the "NEXT" button.

Stimuli

An original testing application based on the Unity® game engine was developed for the experiment. This application renders large 3D terrain models in real-time and automatically collects data for further analysis. The 3D models of terrain were generated from a fourth-generation Digital Terrain Model of the Czech Republic (DTM 4G), which was originally created from airborne laser scanning and processed at a ground resolution of 5 × 5 m. DTM 4G is distributed by the ČÚZK (Czech Office for Surveying, Mapping and Cadastre). The terrains were selected so that the relief zones were similar in all territories. The study proceeded from a geographical regionalization of the Czech Republic [62], and all terrains depicted were highlands

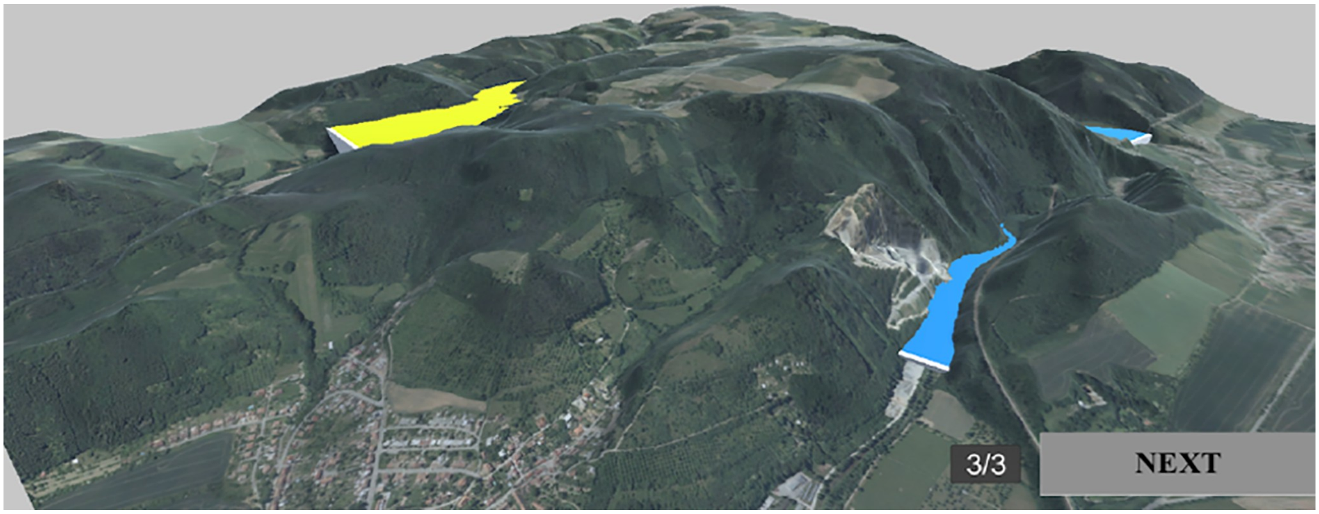

Fig 4. Example of Task 2 –Water bodies in the terrain. Yellow indicates that this object was selected by the participant. Adapted from [61] under a CC BY license, with permission from [ČÚZK], original copyright [2018/2019].

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(relative height variation of 200 to 300 m). Terrains were covered with corresponding orthophotography data [61]. The 3D models were vertically scaled with a fixed factor of 3.0. Non-interactive (static) expositions were designed with respect to the position of the virtual camera from which the scene was viewed—screenshots of the terrains were created from two specific

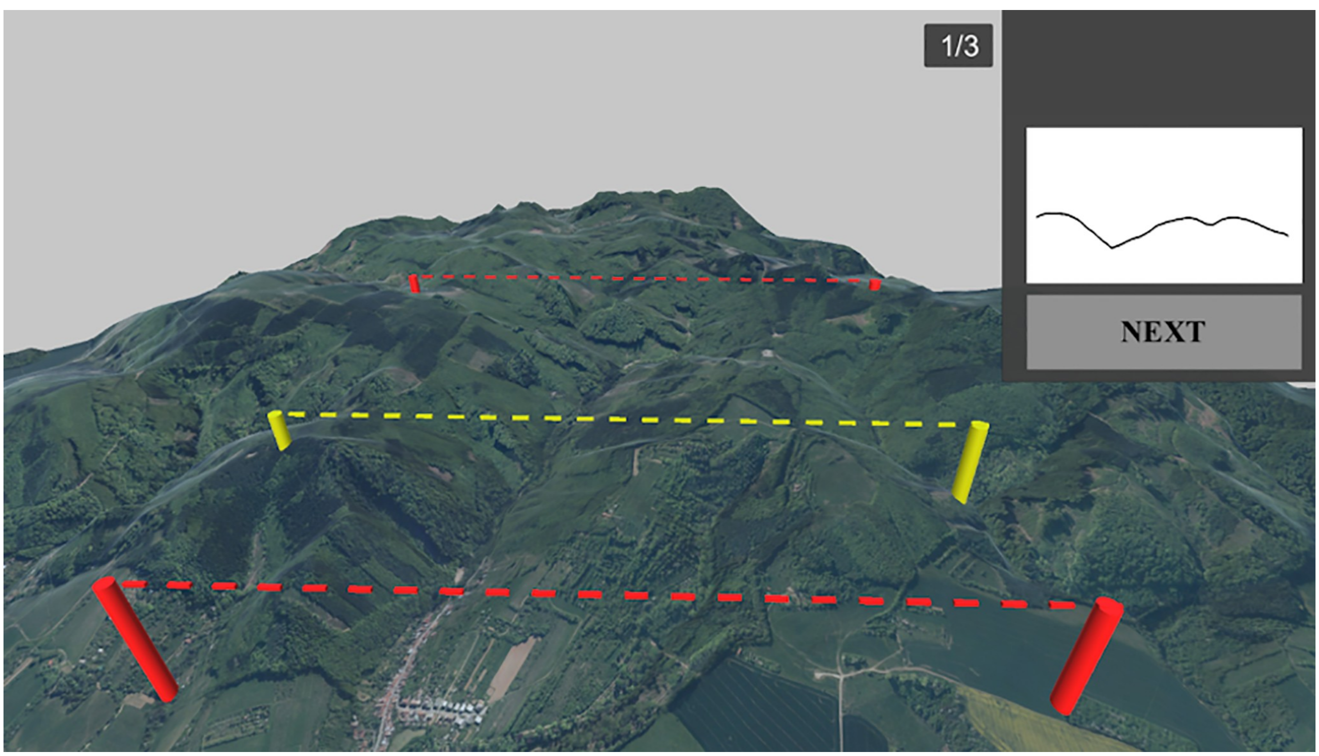

Fig 5. Example of Task 3 –Terrain profiles. Yellow indicates that the profile was selected by the participant. Adapted from [61] under a CC BY license, with permission from [ČÚZK], original copyright [2018/2019].

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angles (45 degrees and 75 degrees), and the virtual camera was maintained at the same height in all static scenes. These static scenes were further used in testing, and the interactive scene was rendered in the real time.

Analysis

As the dependent variables, the researchers analysed response times (RTs), correct elevation estimation (scores) and the number of mouse-clicks (clicks under interactive conditions). Correct answers scored 1, and incorrect answers scored 0. The RTs indicated asymmetric distribution, therefore linear mixed effect (LMER) modelling [63] was applied for analysis (due to the leftward inclination, a box-cox transformation was applied to the response time data). Score data were analysed with the use of generalized linear mixed effect models (GLMER), with logit as a link function and raw correctness as the dependent variable (1 = correct, 0 = incorrect). For the response times and scores, the visualization type (real 3D, pseudo 3D), interactivity type (interactive, static) and task type (cubes, water bodies and terrain profiles) and their interactions were considered fixed factors. The experiment included individual participants (according to their assigned identification numbers) as random intercepts. The models were executed using R software [64], R packages lme4 [65] and lmerTest [66]. The *p*-values for fixed effects were obtained using Satterthwaite approximation for degrees of freedom. All reported confidence intervals were obtained via bootstrapping (100000 iterations for LMER and 1000 iterations for GLMER) [63]. The mouse clicks were checked with the use of Spearman correlations to search for possible correspondence between RT and correctness.

Results

Response time

Overall, the linear mixed effects model for RTs revealed significant main effects of visualization type ($t = 4.64$, $p < 0.001$) and interaction type ($t = -10.849$, $p < 0.001$). Specifically, the real 3D environment increased the response time by 0.23 s ± 0.05 (95% CI [0.13309, 0.32925), and the option to interact prolonged response time by 0.54 s (se = 0.05s), 95% CI [-0.63256, -0.43963]. The main effect of the task type was also significant ($t = 9.56$, $p < 0.001$). Terrain profiles took 0.88 s ± 0.09 longer to solve than cubes (95% CI [0.69630, 1.05498]) and water bodies took 0.31 s ± 0.09 longer to solve than cubes (95% CI [0.13034, 0.48149]). The interaction effect of task and visualization factors was significant ($t = -2.49$, $p = 0.0130$) in water bodies compared to cubes. Real 3D visualization significantly reduced the response time in water bodies by 0.18 s ± 0.07 (95% CI [-0.31702, -0.03610]) and terrain profiles compared to cubes ($t = -2.34$, $p = 0.0195$). The 3D visualization significantly reduced the response time in terrain profiles by -0.17 s ± 0.07 (CI [-0.30700, -0.02639]). The interaction factor prolonged the response time in terrain profiles compared to cubes ($t = 2.50$, $p = 0.0126$) by 0.18 s ± 0.07 ([0.03815, 0.31652]). No other fixed effects were significant regarding response time ($p > 0.5$).

Fig 6 highlights that the response times exactly matched the expected trends of interactivity and real 3D visualization prolonging the task solving process. As the most spatially complex tasks, the terrain profiles took longest to solve, while cubes were solved the quickest. The largest difference in speed was observed between cubes solved in static pseudo 3D conditions and terrain profiles in interactive real 3D conditions.

Correctness

Generalized linear mixed effects modelling (the Hosmer–Lemeshow Test suggested adequate goodness of fit: $\chi^2 = 3.3563$, $df = 8$, $p = 0.91$) on correctness revealed a significant main effect

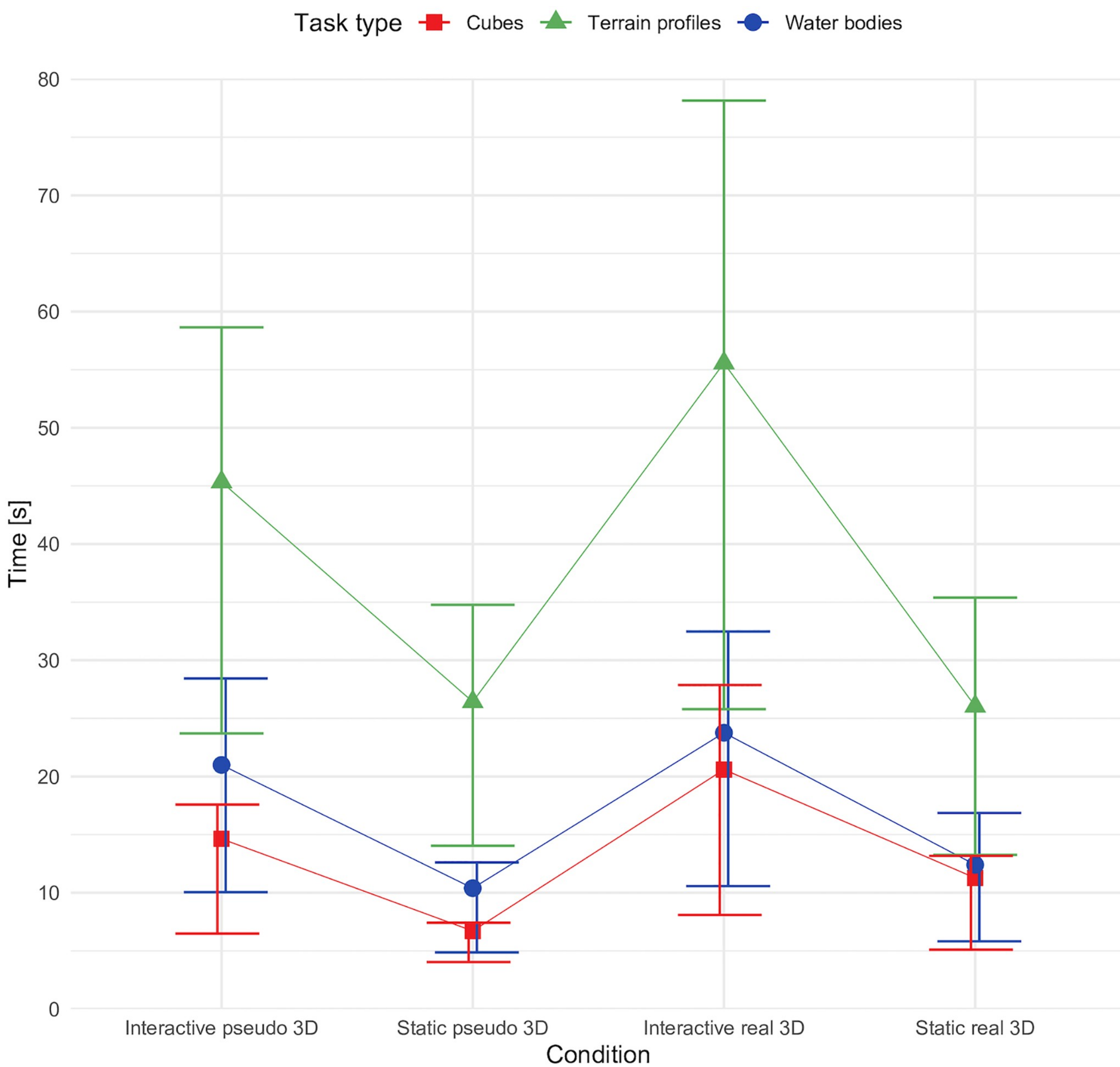

Fig 6. Participants' response times according to conditions.

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for interaction type (β = 1.842, z = 5.38, $p < 0.001$, 95% CI [1.30245, 2.40780]), suggesting that the static tasks were overall solved with greater accuracy. Water bodies were solved with greater accuracy than cubes (β = 0.564, z = 2.23, p = 0.0258, 95% CI [0.08624, 1.05926]). The interaction effects were significant for visualization type and interaction type (β = -2.232, z = -5.30, $p < 0.001$, 95% CI [-2.88130, -1.49627]). Interactive pseudo 3D conditions tended to encourage greater accuracy than static real 3D conditions. The effect of interaction was also observed in interaction type and task type in the case of terrain profiles (β = -1.376, z = -3.16, p = 0.0016). The terrain profiles were solved with less accuracy than cubes (95% CI [-2.09665, -0.65452]), and water bodies were solved with less accuracy than cubes (β = -2.318, z = -5.40,

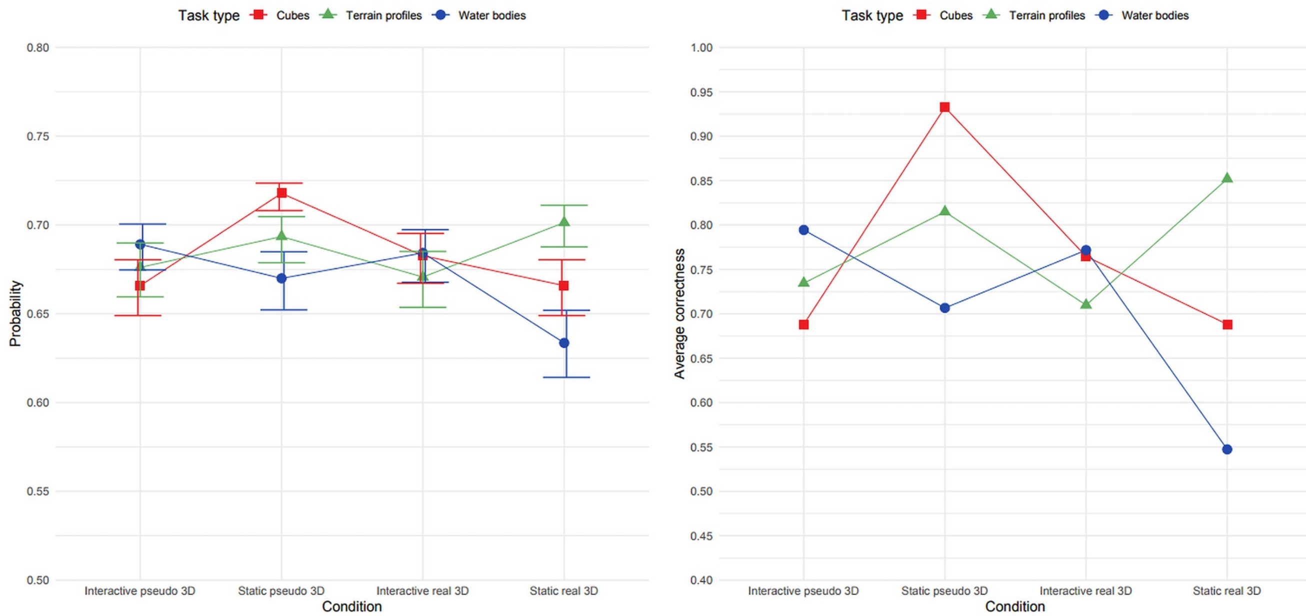

Fig 7. Calculated probabilities of accurate scoring according to conditions (left); participants' average correctness scores (right).

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$p < 0.001$, 95% CI [-3.01544, -1.70323]). A triple interaction effect was observed in terrain profile tasks ($\beta = 2.624$, $z = 4.57$, $p < 0.001$), 95% CI [1.73593, 3.49377]), with a trend demonstrating that the terrain profiles were solved with greater accuracy in static real 3D conditions than cubes. The same trend was observed for water bodies ($\beta = 1.670$, $z = 0.557$, $p < 0.001$), where water bodies were solved with greater accuracy than cubes (95% CI [0.76593, 2.52489]) in the static real 3D condition.

Fig 7 (left) depicts the probabilities of accurate responses in different types of tasks with regards to the specific 3D and interactive condition, suggesting that no specific pattern between performance, tasks and conditions existed for correctness. The correctness scores in Fig 7 (right) illustrate that the study's expectations on participant performance were not met and barely corresponded to the trends indicated by the time responses. The visual trend in both static conditions suggested a greater dispersion between individual types of tasks (cubes, water bodies, terrain profiles). Close values in the interactive conditions demonstrated interactivity as a feature that eliminated extreme values in participant performance.

Mouse clicks

Fig 8 charts the frequency of mouse clicks in the interactive tasks. The graph also contains data from static tasks. The number of mouse clicks participants performed while solving tasks in a specific condition corresponded to the response times, especially with respect to specific task type. A significant close positive correlation between RT and the number of mouse clicks was observed (*Spearman's rho* = 0.827, $p < 0.001$). No correlation or trend was observed between correctness and the number of mouse clicks (*Spearman's rho* = -0.056, $p = 0.079$). Generally, visual inspection suggested that more clicks were done in real 3D tasks, and the number of mouse clicks had an increasing trend in the terrain profiles tasks (Fig 8). The frequency of mouse clicks was lowest in the cube tasks.

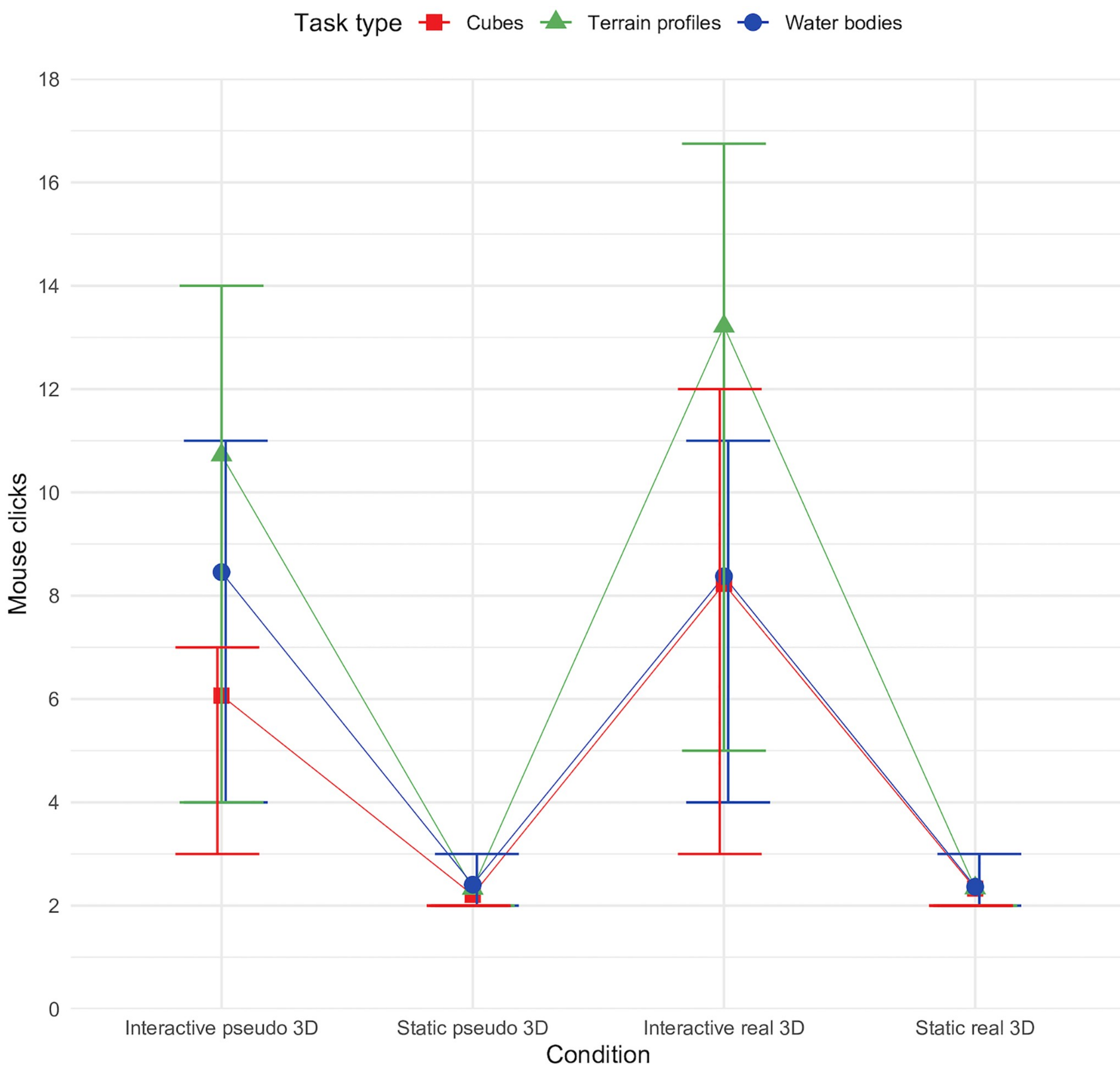

Fig 8. Number of mouse clicks according to the conditions.

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Discussion

The study examined the effectivity of stereoscopic real 3D visualizations and pseudo 3D visualizations under static and interactive conditions. Several effects were observed that contributed to the participants' correctness and response times in solving the tasks. The number of mouse clicks to answer questions was also inspected.

Response time

The response time patterns generally corresponded to the expectations that interactive and real 3D tasks would take longer to solve. This trend was consistent across all tasks. Participants who used the real 3D visualization generally took longer to solve the tasks ($t = 4.63$, $p < 0.001$). This effect was expected based on previous studies [23, 28, 35] and illustrated the possible increase in information load using 3D glasses and reading 3D maps. Similarly, an increase in response time was observed in the case of interactivity, participants spending more time solving interactive tasks ($t = -10.849$, $p < 0.001$). This effect was also expected based on previous studies [36, 49], which suggested interactive tasks were more engaging and time consuming. Both findings met the study's expectations on the effect of 3D visualization in geovisualizations. Regarding the speed of responses, a clear trend was identified with respect to the specific task types. The terrain profile tasks took participants significantly more time than other tasks, indicating that spatially complex tasks, such as assessing elevation relationships in the terrain, require more time to process than spatially simple scenes (e.g. point structures in the terrain). The effect of interaction on task type and visualization type factors was significant (t = -2.49, $p = 0.0130$) in water bodies compared to cubes, where real 3D visualization significantly decreased the response time in water bodies. In the case of terrain profile tasks compared to cubes, the 3D visualization significantly reduced the response time in terrain profiles (t = -2.34, p = 0. 0195). This may indicate that 3D visualizations can potentially increase efficiency in spatially challenging tasks, i.e. when a task is spatially more complex, and that real 3D visualization tools may assist in solving tasks more quickly.

Correctness

The empirical results show that the interactive tasks were generally solved with significantly less accuracy than the static tasks ($\beta = 1.842$, $z = 5.38$, $p < 0.001$), which did not confirm the hypothesis of a generally higher effectivity in an interactive setting (e.g. [49]). Since a positive effect was identified from interactivity in pseudo 3D conditions ($\beta = -2.231$, $z = -5.29$, $p < 0.001$), interactivity seemingly has the potential to promote spatial assessment of virtual terrains in pseudo 3D settings. From this point of view, interactivity can be seen as complementing the missing binocular depth cues in pseudo 3D visualizations. Regarding the interactivity factor, the cubes were solved with greater accuracy in interactive conditions than in terrain profiles ($\beta = -1.376$, $z = -3.15$, p = 0. 0016), and then water bodies ($\beta = -2.318$, $z = -5.40$, $p < 0.001$), which illustrates the increasing effectivity of interactivity in the cube tasks (spatially simple structures). A triple interaction effect was observed in terrain profile tasks ($\beta = 2.624$, $z = 4.57$, $p < 0.001$), with a trend demonstrating that the terrain profiles were solved with greater accuracy in real 3D static condition than cubes. The same trend was observed in the case of water bodies ($\beta = 1.670$, $z = 0.557$, $p < 0.001$). Water bodies were solved with greater accuracy in static real 3D conditions than cubes, illustrating the positive effect of real 3D visualization in tasks based on elevation profiles (i.e. spatially complex structures). In the static conditions, greater differences (dispersion) were observed in the participants' performance in all three types of tasks, however the participants' performance in the interactive conditions was similar, which indicates that interactivity may have the potential to eliminate extreme values and also emphasize the specific factors of task types, i.e. that the concrete settings may encourage specific task solving. This finding corresponds to previous research [45], which concluded that the type of task contributed a more important role in static conditions than interactive settings, also highlighting the need for task-focused research.

Mouse clicks

The frequency of mouse clicks in the interactive tasks, not surprisingly, corresponded to the response times. A significant close positive correlation was observed between the RT and the number of mouse clicks ($p < 0.001$). This finding was not surprising considering that interaction itself takes time and corresponded to previous findings [49]. No significant correlation or trend was observed between correctness and the number of mouse clicks (*Spearman's rho* = -0.056, p = 0.079). Generally, the visual inspection suggested that real 3D conditions promoted mouse-clicking, i.e. the tendency to interact with the scene. The number of mouse clicks demonstrated an increasing trend in the terrain profiles tasks (Fig 8), which can be classified as spatially more complex, demanding greater interaction.

The empirical findings appear counterintuitive in several ways, especially regarding the correctness scores, as no clear pattern indicated the advantage of a specific factor in the participants' correctness performance. Regarding the previous research, it can be suggested that this indicates a lack of participants' attention or the motivation to find easy-looking tasks. To encourage confidence in their responses, participants were not motivated to collect more information about the scene, which might have also led to errors. A similar effect was discussed in [36, 52]. This could be considered a "metacognitive mistake", i.e. anticipating a task as easy may have decreased the participants' mental efforts, thereby reducing their full use of the potentially available information. No clear pattern indicated the dependence between response time and correctness. The general trend in the correctness scores did not correspond to the solving speed. This speed-accuracy trade-off may have reframed what participants thought was the purpose of the tasks and encouraged them to guess the answers. The participants may have focused more on speed than accuracy and responded with the first available option. The pattern of response time scores may simply have emulated the primary expectations for interface properties in geovisualizations, i.e. that interaction takes more time and real 3D is visually more difficult, therefore the RT performance corresponded to the ease of use.

Conclusion

In the present study, real 3D visualization was compared to pseudo 3D visualization in a digital terrain model experiment. The efficiency and effectiveness of stereoscopic real 3D visualization was examined in both static and interactive conditions, using three types of task as experimental stimuli representing different geo-related phenomena. The results suggested that real 3D visualization (t = 4.64, $p < 0.001$) and the interactivity option (t = -10.849, $p < 0.001$) increased response time. Counterintuitively, our data demonstrated that the static condition increased response correctness (β = 1.842, z = 5.38, $p < 0.001$). With respect to the more detailed analyses of factor interactions in the presented models, it can be summarized that interactivity has the potential to increase performance when a pseudo 3D visualization is applied (potentially complementing real 3D binocular depth cues) and that real 3D visualization may increase performance in tasks dealing with more complex terrain shapes, i.e. structures such as terrain profiles, which require deeper mental computation. Generally, it can be concluded that 3D visualizations using geospatial data is a broad issue and influenced by various factors, the most important factors being the type of visualization, interactivity, specific applications, task type, and also the user group aspects. As concluded in previous studies [30, 36, 41, 49], the benefits and limitations of stereoscopic 3D visualizations are still not completely clear in the various applications of geo-sciences, especially regarding the interactivity factor. Future research should explore interactive and advanced geospatial tasks in terms of the discussed theory as well as the present study's findings that the option to interact and the specific nature of the task may strongly affect the cognitive processing of the presented stimuli.

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Writing – original draft: Vojtěch Juřík.

Writing – review & editing: Lukáš Herman, Adrianne John Galang, Zdeněk Stachoň, Petr Kubíček, Čeněk Šašinka.

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3 Relationship between individual dispositions and the way visualizations are processed

Identical phenomena can be visualized and communicated using different visualization methods. The primary question on whether alternative visualizations differ in terms of effectiveness in communicating a message and whether different cognitive processes are involved is accompanied by developing questions. Do individual distinctions influence preference for any alternative visualization? Do individual differences manifest themselves in the effectiveness of the cognitive processing of visualizations? Individual differences necessarily arise from the differing levels of abilities and skills of individuals. These are both cognitive characteristics, such as intelligence or spatial aptitude, and acquired skills. The latter include, for example, visual literacy or domain knowledge. Other individual variations arise from different ways of organizing cognitive processes and are referred to as cognitive style. This concept is used to refer to the way individuals think, perceive, and orient themselves in the environment. The cognitive style describes how cognitive processes are organized, not the level of cognitive processing. Kozhevnikov (2007) considers cognitive style to be heuristic and he argues that cognitive style of a person is present in his or her perception at all levels, from the highly automated elementary levels to more complex and conscious levels. The first study examines, among other things, the influence of the cognitive style, the other two focus on the effect of the medium, also from the perspective of the individual's spatial abilities.

One of the first papers which explored the effect of cognitive style on the work with maps was Šašinka et al. (2018), The Impact of Global/Local Bias on Task-Solving in Map-Related Tasks Employing Extrinsic and Intrinsic Visualization of Risk Uncertainty Maps. The paper presents and summarizes the results of three studies investigating the cognitive processes involved in processing two alternative visualization methods. The first two studies sought a link between performance on alternative visualizations and analytical or holistic processes as measured by the Compound Figure Test (Navon, 1977). The third follow-up study uses an eye-tracking method that provides deeper insight into the method of visualizations processing. The paper also presents for the first time the author's methodological approach of "extensive-intensive research design", which combines confirmatory and exploratory methods of data analysis (See 2.1). The primary aim of the paper was to find out whether different strategies of visual information processing are used in response to different types of visualization. In a population of participants with higher levels of map literacy, a correlation was found between performance on extrinsic visualization and the global letter subtest of the Compound Figures Test (CFT), which captures a holistic mode of processing. And conversely, a correlation was found between intrinsic visualization and the local letter subtest of CFT, which is saturated with analytical cognitive processes. A second follow-up study involving participants with a basic level of map literacy did not confirm the trend. A third exploratory study using eye-tracking, identified differences in the processing of the task. The intrinsic method showed greater variability in the behavior depending on the type of task, as well as relatively more time overall spent on decoding the legend compared to the time spent on visually searching for information in the map. Based on the findings, a further study was carried out comparing both visualization methods in greater detail (See 2.1).

The study, "Cartographic Design and Usability of Visual Variables for Linear Features", investigated the effect of alternative visualizations with respect to linear features. The study used a similar experimental design as the previous one and, again took into account individual differences. The results indicate that for some types of tasks, color hue and size can convey the information more effectively than shape and color. In addition, it was demonstrated that another aspect influencing the task performance may be individual facets of cognitive style, it depends, however, on the type of visualization used. A correlation to achievements by using the visualization A (color hue and size), was found, in particular, in the local letters subtest (CFT) and the Object-Spatial Imagery and Verbal Questionnaire (Blazhenkova & Kozhevnikov, 2009). On the other hand, the visualization B (shape and color value) and both subtests of the CFT, also showed correlations.

In the study "Identification of altitude profiles in 3D geovisualizations: the role of interaction and spatial abilities", the effect of the medium (pseudo vs. real 3D) on the ability to interpret 3D spatial phenomena was investigated. The hypothesis that participants using real 3D would be more effective, was not confirmed. Similarly, no relation was found for any task type between an individual's level of spatial abilities and their performance in completing geovisualization tasks. The only – yet unambiguous – effect was that of interaction. The possibility to actively interact with the visualization significantly reduced the error rate (albeit at the cost of longer solution times).

The conclusion that (passive) real 3D visualization alone does not provide a significant advantage over the technically simpler medium of pseudo 3D (see Chapter 2) supported the previous premise. Perception must always be understood as an integral part of sensorimotor activities. In the follow-up research topics, emphasis was already placed not only on active interaction with the environment (visualization), but also on the social context, namely collaboration. Only a limited part of activities happens completely outside the social context. The process of communicating meaning through visualizations in group activities, in particular, is then largely influenced by personal characteristics. The qualitative study, "Collaborative Immersive Virtual Environments for Education in Geography", investigates the experience of participants while working with contour lines in immersive virtual reality. One of the main advantages mentioned by participants was the possibility to actively interact with the environment, which among other things allowed them to change the visualization from 2D to 3D views and vice versa. Observations and interviews with participants showed, in turn, a substantial variability in the individuals' behaviors and needs. Differences were evident, among others, in the degree of the need to communicate and check whether the procedure is correct while solving the task, or in the concentration on the task itself. Similar conclusions were also made in a follow-up study (Jochecová et al., 2022, Geography Education in a Collaborative Virtual Environment: A Qualitative Study on Geography Teachers) in which participants reflected, among other things, on the anonymity of collaboration in virtual reality in terms of students' personal dispositions. They consider anonymity as a certain advantage for more timid students.

3.1 Cartographic Design and Usability of Visual Variables for Linear Features

Kubíček, P., Šašinka, Č., Stachoň, Z., Štěrba, Z., Apeltauer, J., & Urbánek, T. (2017). Cartographic design and usability of visual variables for linear features. *The Cartographic Journal*, 54(1), 91-102.

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.

The text of the article is not included in the thesis for licensing reasons.

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

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.

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.

The text of the article is not included in the thesis for licensing reasons.

3.3 Collaborative Immersive Virtual Environments for Education in Geography

Šašinka, Č., Stachoň, Z., Sedlák, M., Chmelík, J., Herman, L., Kubíček, P., Strnadová, A, Doležal, M., Tejkl, H., Urbánek, T., Svatoňová, H., Ugwitz, P., & Juřík, V. (2018). Collaborative immersive virtual environments for education in geography. *ISPRS International Journal of Geo-Information*, 8(1), 3.

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.

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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].

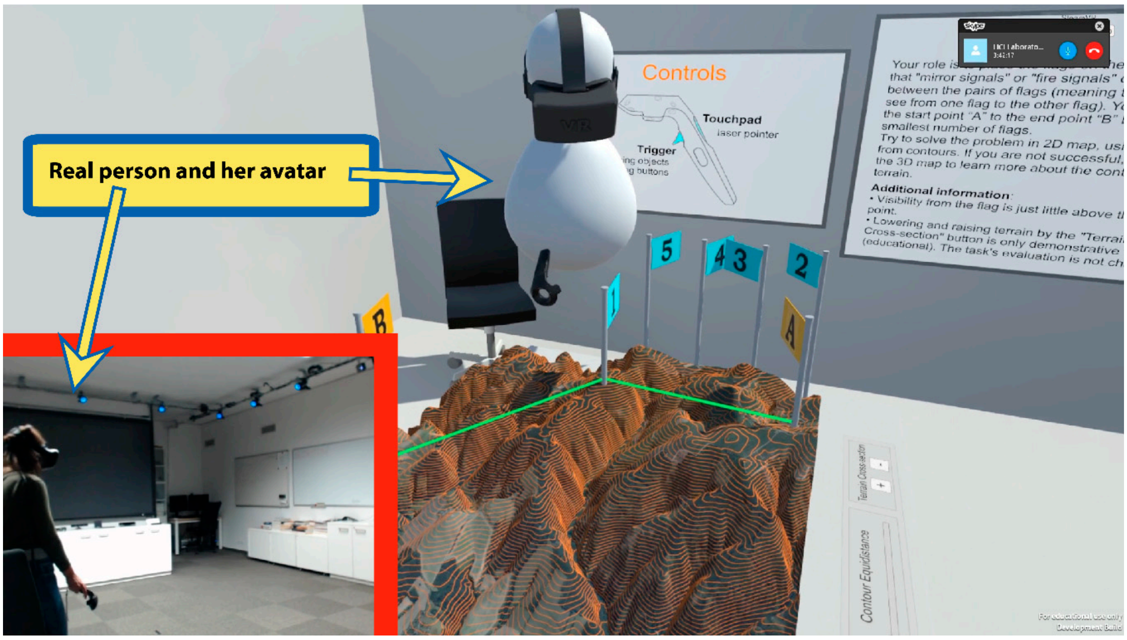

Figure 1. Objective reality (left corner) and virtual room.

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.

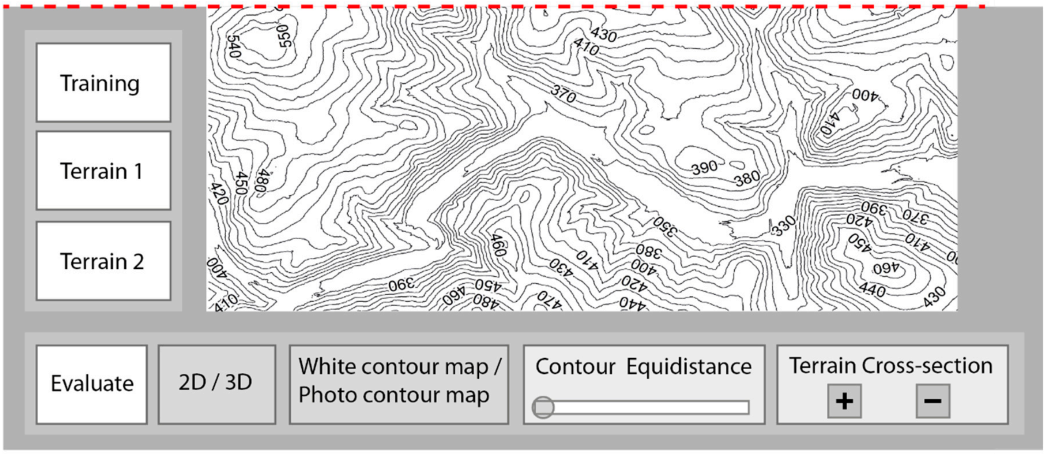

Figure 2. Virtual control panel for model manipulation.

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.

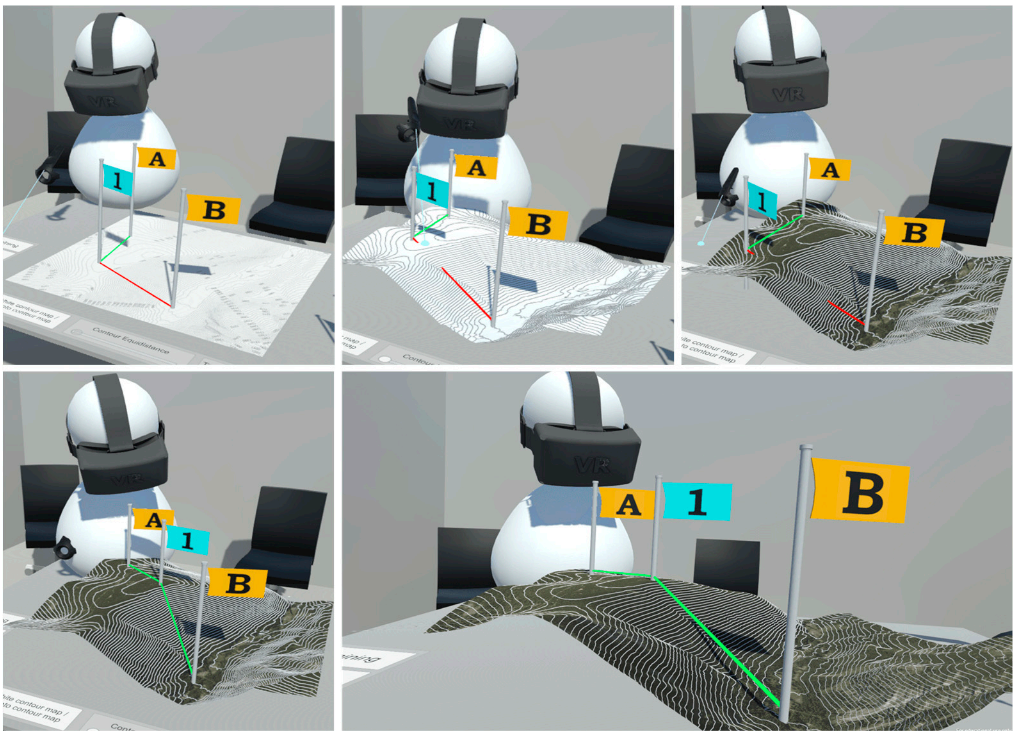

Figure 3. Incorrect (**upper**) and correct (**lower**) answers for the mirror signals task in the collaborative immersive virtual environment (CIVE).

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.

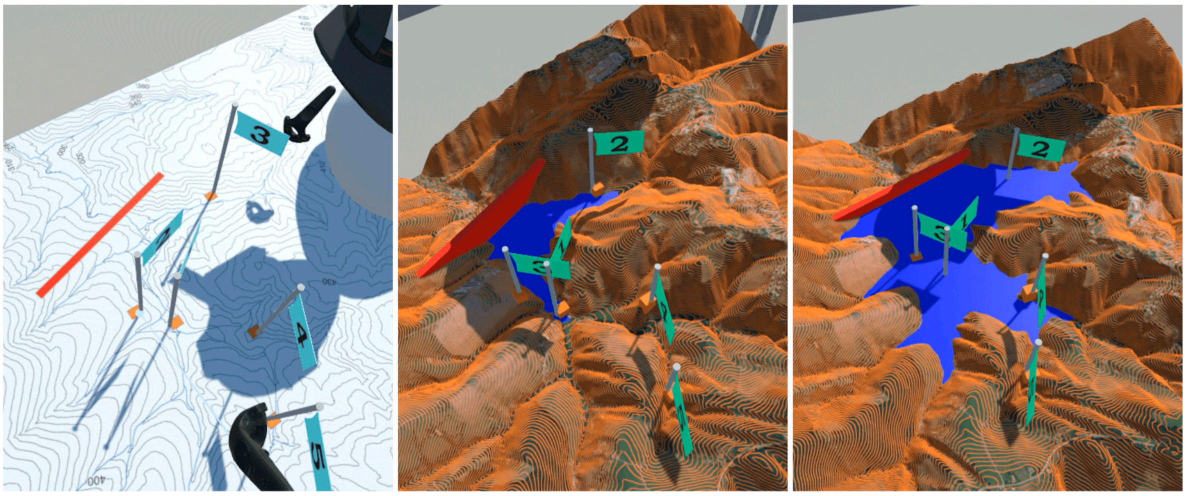

Figure 4. Flooded valley educational task in the CIVE. **Left**—flags with numbers are placed onto the 2D contour line map; **middle**—water level starts rising in the 3D visualization; and **right**—3D visualized dam is completely flooded.

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.

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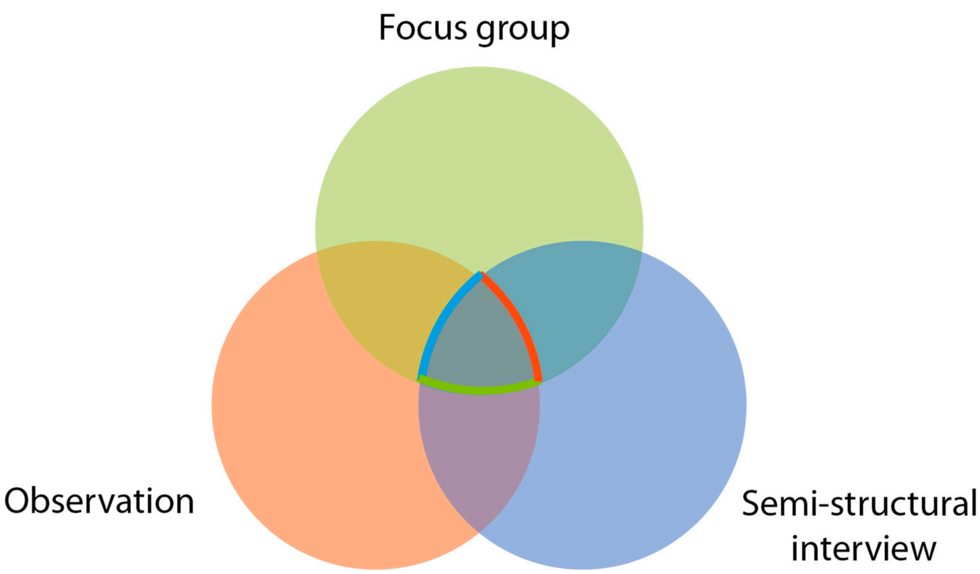

Figure 5. Triangulation of research techniques for data collection.

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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.

2.5. Participants

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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.

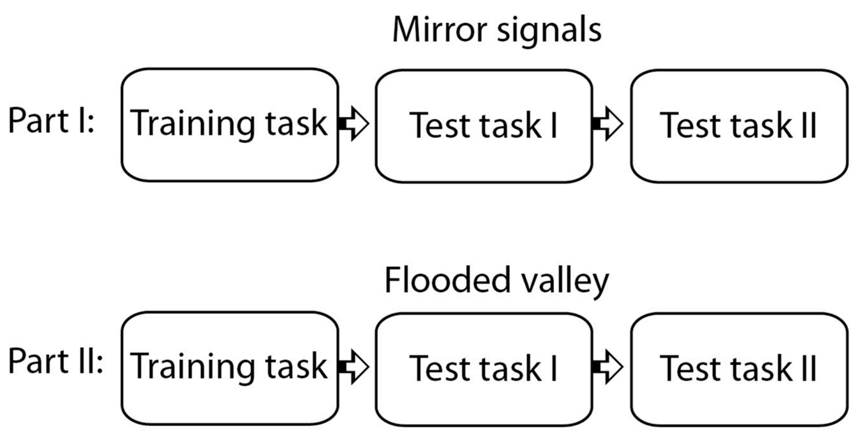

Figure 6. Step 4: collaboration in the CIVE—research tasks administration in detail.

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.

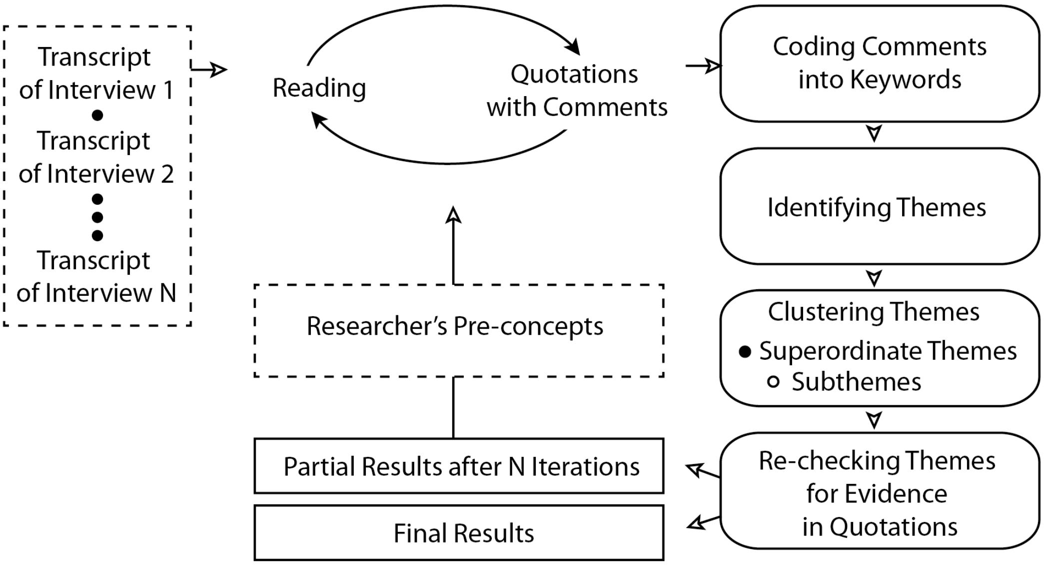

Figure 7. Scheme of the interpretative phenomenological analysis.

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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4 Differences in perception as an influence of cultural–historical experience

From individual differences, the focus was shifted towards cross-cultural differences. The performed studies draw mainly on the holistic-analytic theory (Nisbett et al., 2001, Nisbett and Miyamoto, 2005). The centerpiece of the theory is the emphasis on cross-cultural variations in cognitive processes, which are significantly determined by socio-cultural aspects including different philosophical systems. According to the authors, the cultural context – the environment into which individuals are born and in which they grow up – has a major influence on the organization of cognitive processes. This starts from the elementary – visual perceptive – level to complex levels, such as categorization at the semantic level. The authors draw on the East-West dichotomy, in which Eastern countries (e.g., Japan) represent holistic countries and Western countries (e.g., the U.S.A.) represent analytically embedded cultures. The studies in this chapter focus on different levels and aspects of cognitive processing of visual information.

The first study, "Cultural variations in global and local attention and eye-movement patterns during the perception of complex visual scenes: Comparison of Czech and Taiwanese university students", presents an experiment that investigates cultural variations using focal objects and backgrounds (Masuda and Nisbett, 2001, Duan et al., 2016). The topic is based on the cross-cultural research line of Jiří Čeněk (Čeněk and Šašinka, 2015, Čeněk, 2017). In the context of this thesis, it represents one of the basic experimental design types on which the cross-cultural analytical-holistic theory was built and which serves as a starting point for research on visualizations in a cross-cultural perspective. In accordance with the hypothesis, Czech participants, in contrast to Taiwanese participants, showed a more analytical approach and paid more attention to the focal objects compared to the background.

In the cross-cultural study "Effect of Size, Shape and Map Background in Cartographic Visualization: Experimental Study on Czech and Chinese Populations", utilizing the visual search paradigm, the influence of culture and the complexity of map background were investigated. The assumption that the presence of map background in the case of a more holistic and thus field-dependent Chinese culture relatively increases the search time, was not confirmed. The Chinese script was considered as another cultural phenomenon that would potentially positively affect the search speed, for example with small and harder to distinguish shapes. However, no cross-cultural effect was detected here either. Nevertheless, Czech participants solved all task types considerably faster. This finding led to the need to amend the test batteries for cross-cultural research with psychological tests (See 5.3), which would capture the potential bias caused by, e.g., culturally conditioned psychomotor pace.

The follow-up study of "Cross-cultural differences in figure-ground perception of cartographic stimuli", already worked with a complex cartographic symbol set, or rather two alternative types of legends – iconic and more schematized. The participants were asked to search for point symbols in the first subtest, and to search for background segments in the second subtest. Contrary to expectation (Varnun et al., 2010), Chinese participants were significantly slower at locating the background. As expected, Czechs were also faster in searching for point symbols (i.e., focal objects). Over all, the obtained results of the map tasks do not correspond with the underlying theory. At the same time, even the complementary framed-line test of differences (Kityama et al., 2003), which was used by the authors specifically to demonstrate cultural variations, identified Chinese participants as relatively more analytical.

The last of the cross-cultural research was focused on higher cognitive processes. The design of the study called "Cross-Cultural Differences in Cognitive Style, Individualism/Collectivism and Map Reading between Central European and East Asian University Students", was inspired by the experiment of Norenzayan et al. (2002), which examined the tendency to categorize based on a one-dimensional rule (analytically), or a rule of overall similarity (holistically). Participants were asked to identify and label a continuous map area covering at least four territorial units that they considered to belong together. The visualizations were designed in a way so that either the one-dimensional or the holistic-similarity rule applied. The results imply that Czech participants exhibited significantly lower levels of collectivism than Chinese/Taiwanese participants, and similar levels of individualism. In accordance with the hypothesis, the results of the map task show that Czech participants categorized more analytically, while Chinese/Taiwanese categorized more holistically. However, the effect of this significant difference was relatively small.

The aforementioned studies examined cross-cultural differences in cognition across different types of tasks and using different types of well-established psychological methods. Some of the results support the cross-cultural theory which is based on the West-East dichotomy and analytic-holistic thinking. At the same time, however, a substantial part of partial results is in direct contradiction with the assumptions, and the results cannot be considered as overall conclusive in the perspective of the considered theory. I believe that the theory in question is limited by the nature of the populations under study, which often cannot be considered homogenous as assumed. At the same time, the universality of the analytic and holistic styles can also be questioned, as they would necessarily manifest themselves to the same extent at different levels of cognitive processes and in different types of tasks. Kozhevnikov et al. (2014) emphasizes the ecological perspective and argues that the cognitive style is adapted to particular facets of the environment and thus is also relatively flexible and task specific.

4.1 Cultural variations in global and local attention and eye-movement patterns during the perception of complex visual scenes: Comparison of Czech and Taiwanese university students

Čeněk, J., Tsai, J. L., & Šašinka, Č. (2020). Cultural variations in global and local attention and eye-movement patterns during the perception of complex visual scenes: Comparison of Czech and Taiwanese university students. *Plos one*, 15(11), e0242501.

ABSTRACT

Previous research on cross-cultural differences in visual attention has been inconclusive. Some studies have suggested the existence of systematic differences in global and local attention and context sensitivity, while others have produced negative or mixed results. The objective in this study was to examine the similarities and differences in holistic and analytic cognitive styles in a sample of Czech and Taiwanese university students. Two cognitive tasks were conducted: a Compound Figures Test and a free-viewing scene perception task which manipulated several focal objects and measured eye-movement patterns. An analysis of the reaction times in the Compound Figures Test showed no clear differences between either sample. An analysis of eye-movement metrics showed certain differences between the samples. While Czechs tended to focus relatively more on the focal objects measured by the number of fixations, the Taiwanese subjects spent more time fixating on the background. The results were consistent for scenes with one or two focal objects. The results of a correlation analysis of both tasks showed that they were unrelated. These results showed certain differences between the samples in visual perception but were not as systematic as the theory of holistic and analytic cognitive styles would suggest. An alternative model of cross-cultural differences in cognition and perception is discussed.

PLOS ONE

RESEARCH ARTICLE

Cultural variations in global and local attention and eye-movement patterns during the perception of complex visual scenes: Comparison of Czech and Taiwanese university students

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Abstract

Previous research on cross-cultural differences in visual attention has been inconclusive. Some studies have suggested the existence of systematic differences in global and local attention and context sensitivity, while others have produced negative or mixed results. The objective in this study was to examine the similarities and differences in holistic and analytic cognitive styles in a sample of Czech and Taiwanese university students. Two cognitive tasks were conducted: a Compound Figures Test and a free-viewing scene perception task which manipulated several focal objects and measured eye-movement patterns. An analysis of the reaction times in the Compound Figures Test showed no clear differences between either sample. An analysis of eye-movement metrics showed certain differences between the samples. While Czechs tended to focus relatively more on the focal objects measured by the number of fixations, the Taiwanese subjects spent more time fixating on the background. The results were consistent for scenes with one or two focal objects. The results of a correlation analysis of both tasks showed that they were unrelated. These results showed certain differences between the samples in visual perception but were not as systematic as the theory of holistic and analytic cognitive styles would suggest. An alternative model of cross-cultural differences in cognition and perception is discussed.

Introduction

Multiple research findings (for review see [1, 2]) suggest the existence of systematic cross-cultural differences in cognitive processing around the world. Much of the research investigates the cultural differences between "the East" (i.e. China, Japan, South Korea) and "the West" (i.e. Canada, USA, Western Europe) and anticipates the existence of systematic and relatively stable differences in cognition or cognitive styles.

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It is uncertain which factors cause variations in cognitive processes. It is reasonable to assume that they are based on the interplay of multiple factors that include sociocultural, environmental and biological influences, such as philosophical tradition [1], parent-child interaction [3, 4], socioeconomic status and personal wealth [5], literacy [6], the complexity of the physical environment [7], differences in the anatomical and functional aspects of the central nervous system [8, 9], or means of subsistence [10, 11]. Probably the most used explanatory factors for the existence of cultural differences in cognition are the cultural syndromes of individualism and collectivism (independent and interdependent self, respectively) [12, 13]. The theory of individualism/collectivism (and independence/interdependence, respectively) suggests fundamental differences in how individuals relate to society, how this relationship is constructed, and whether individuals or groups are the basic units of analysis. Collectivistic cultures are characteristic for emphasizing interdependence and orientation in social groups (e.g. extended families, communities). In individualistic cultures, emphasis is placed on individual independence and autonomy [12, 14].

Despite the growing body of literature on the topic, research in this area is far from complete. Besides the uncertain causal relationships between cognitive and cultural and environmental variables, at least two other "weak spots" or points of interest can be found in the existing body of research on holistic and analytic cognitive styles. First, despite several exceptions [5, 15–21], the research almost exclusively focuses on a simplified and reductionist comparison of "Western" (North America and Western Europe) and "Eastern" (East and Southeast Asia) populations, thereby ignoring all other cultural regions and the possible variations in cognitive processes in these regions. Furthermore, some evidence exists of the presence of differences in perceptual and cognitive processes, not only between people from different countries but also different regions within these countries [10, 19, 22]. Second, several recent studies have shown contradictory or mixed results, or minor effect sizes [21, 23–27], and call the theory of cognitive styles into question. Some advocate the prevalence of universal, bottom-up processes, while others acknowledge the need for replication in research on cognitive styles.

At least two models have attempted to explain the differences in cognitive style. Nisbett [1, 2] formulated a model (in the present paper, referred to as the "general holistic–analytic model") of cognitive styles that is based on a vast amount of empirical evidence and that postulates systematic differences exist in cognitive processes between Easterners (holistic cognitive style) and Westerners (analytic cognitive style). More specifically, it describes differences in: (a) object categorization [28, 29], (b) reasoning about contradictions [30], (c) field dependence and object-background differentiation [31], (d) context sensitivity and selective attention on objects and relationships, (e) processing of global and local attributes of objects [32], (f) change detection [33, 34] and (g) memory [35]. If we accept the axioms of the general holistic–analytic model, holistic individuals (compared to their analytic counterparts) should: (a) use more intuitive and less rule-based strategies in object categorization, (b) use dialectical thinking instead of rules of formal logic, (c) have more problems with separating objects from the background, (d) focus more on the background and relationships between objects and less on the salient (or focal) objects and their attributes [15, 36], (e) focus more on the global and less on the local features of objects, (f) be more sensitive to the contextual and less to the focal object changes, and (g) recall objects in complex scenes less successfully. An important attribute of this model is that these differences should be coherent. This means that if a holistic individual focuses relatively more on the global features, he or she should also focus relatively more on the background. In other words, the scores obtained by multiple methods should be (cor) related.

Kozhevnikov et al. [37] proposed an alternative model (in the present paper, referred to as the "hierarchical–ecological model") of cognition by emphasizing the ecological nature of cognitive style, viewing cognitive styles as patterns of adaptation to the environment. According to this view, cognitive style is environmentally dependent, flexible and task specific. This model is based on Nosal's [38] earlier model; she proposed a hierarchical model of cognitive styles: a cognitive–style matrix that organizes cognitive styles along two axes or levels consisting of information processing (perception, concept formation, higher-order processing, metacognitive processing) and cognitive style families (context dependence and independence, rule-based and intuitive processing, internal and external locus, integration and compartmentalization). The most used cognitive styles are positioned along these axes. According to Kozhevnikov's model, the different cognitive styles would not necessarily have to (cor)relate since an environment might, for example, support both the development of global processing (holistic characteristic) and focus on salient objects (analytic characteristic).

In this research, the possible cross-cultural variations in two cognitive processes, (a) global and local attention and (b) context sensitivity, were examined in samples of Czech and Taiwanese university students. According to the research conducted by Hofstede [39], the Czech Republic is relatively high in individualism (individualism score = 58), while Taiwan is a typically collectivistic country (individualism score = 17). The selected samples therefore reflect the above-mentioned need to investigate samples beyond the traditional "USA vs. China/Japan" borders, which is also logical from a theoretical point of view. Even though both countries have experienced unique and sometimes turbulent periods in recent history (wars, waves of migration, communist dictatorship, etc.) and are not seen as typical representatives of individualistic or collectivistic cultures, we might still assume the presence of differences in cognitive style. The psychology of people in the Czech Republic has been shaped by typically European influences, such as Christianity and Greek philosophy [1]. The country has a relatively less complex physical environment [7] and is a typical wheat culture [11]. Taiwan, however, is still part of the Asian cultural space, with Buddhism and Taoism as the main religions, a tradition of Chinese philosophy, a relatively more complex environment, and rice as a main means of subsistence. As such, we might expect Czechs (individualistic country) to perceive more analytically, while the Taiwanese (collectivistic country) to perceive more holistically.

To investigate global and local attention, a hierarchical Navon figures test was used. In the present study, we refer to our version of the PC-administered Navon figures test as the Compound Figures Test (CFT; see details in Materials and Methods section). This test presents figures at two hierarchical levels: global and local [32, 43]. The global level is generally represented by a letter (e.g. "H"), number (e.g. "3"), or shape (e.g. square). The global-level feature of the figure comprises multiple local-level features of the same type (e.g. local letters which form a global letter, or local numbers which form a global number).

Tests using hierarchical figures have been previously used in multiple cross-cultural examinations focused on processing the global and local features of objects [32, 40, 41]. With some exceptions [24], they report a relative advantage in the processing speed of global characteristics of stimuli (global advantage/precedence/preference) in Asian subjects compared to Westerners. The cross-cultural differences in context sensitivity (attention to an object vs. attention to the background) were examined using natural scenes (free-viewing paradigm) combined with eye-movement recording in a design similar to previous research conducted by other authors [15, 23, 36]. Some of the research found distinct differences in the eye-movement patterns between Chinese and Americans [36] and Chinese and Africans [15], while other enquiries supported a contradictory hypothesis on the lack of any systematic cultural differences in scene viewing [23].

The formulation of hypotheses in the present paper is based upon the general holistic–analytic model [2]. We formulate the hypotheses according to this model and not the competing model by Kozhevnikov [37] because most cross-cultural studies on the topic are also based on this model and it offers a strong empirical basis for the formulation of such studies. As mentioned above, we applied two methods to assess the cognitive style of respondents and expected that performance in these methods would be modulated by cultural group. The hypotheses were formulated with respect to the metrics (scores) obtained by these methods. To examine the global vs local attention, we applied a CFT that has two main metrics to work with: a global precedence score (calculated as a difference in global and local reaction times; see the Stimuli section for details) and an error rate. In the second method, we investigated context sensitivity (attention to an object vs. attention to the background) in free-viewing task with a set of complex natural scenes (composed of one or two objects and a background; see the Stimuli section for details) combined with eye-movement measurement. The measurements included several common eye-tracking metrics, namely the number of first fixations, number of fixations, fixation time and transitions between parts of the scenes.

Global vs local attention (CFT)–a) The Taiwanese respondents should demonstrate a stronger global preference than Czech participants in CFT processing speed [32]. CFT–b) No significant differences in the error rate of responses between the two groups were expected [32]. Context sensitivity (scene perception)–The Taiwanese respondents should: a) make fewer first fixations on a focal object (percentage of first fixations on a focal object), b) make fewer focal object fixations (average number of focal object fixations), c) fixate focal objects for a shorter time (average focal object fixation time), d) make more background fixations (average number of background fixations), e) fixate backgrounds for a longer time (average background fixation time), and f) make more focal object to background transitions. In the case of stimuli with two focal objects, the Taiwanese were expected to h) make more direct transitions between both focal objects. In addition, because a cognitive style is defined according to the general holistic–analytic model as a complex set of behaviours, g) a correlation was expected between the eye-movement measurements in the perception of scenes and the global preference score of the CFT.

Scene perception related hypotheses a–e) were formulated according to the research by Chua et al. [36] and Duan et al. [15]. Hypotheses f–h) were based on the general holistic-analytic model, but were not, to our best knowledge, previously tested [1, 2, 42]. They reflect the assumption that holistic cultures "*tend to engage in context-dependent and holistic perceptual processes by attending to the relationship between the object and the context in which the object is located*" [42, p.1]. Furthermore, if the holistic and analytic cognitive style, as defined by the general holistic–analytic model [1], represents the quality of cognitive processes, where holistic perceivers compared to their analytic counterparts should, for example, perceive the global characteristics of stimuli relatively more quickly and also focus more on the relationships between objects in a scene, then the scores obtained by the methods measuring these qualities should also correlate with each other (hypothesis g)). If this is not the case, the hierarchical–ecological model [37] of cross-cultural differences in cognition might be more plausible.

Our research contributes by improving the understanding of cultural similarities and differences in visual attention and perception in at least three ways: (i) it is one of relatively few studies that explores multiple facets of cognitive style [24], (ii) it is, to our best knowledge, the first study to compare Asians and Central Europeans by measuring eye-movement patterns in viewing a scene, (iii) it is the first cross-cultural eye-tracking research that controls the number of focal objects in a scene (1 or 2).

Materials and methods

The Research Ethics Committee of Masaryk University has reviewed the application to conduct the research project and has approved this project (Proposal No.: 0257/2018) to be conducted on 13 March 2019. Informed consent was obtained in writing from all participants.

Stimuli

Besides the two experimental tasks described in this section, a personal questionnaire was administered and asked respondents to state their gender, age, experience in living in a foreign country (more than one year, yes or no), the size of their household before entering university and the current size of their household. All tasks were administered in either Czech or traditional Chinese according to the cultural background of the participant.

Compound Figures Test. To assess global and local distribution of attention, we applied a Compound Figures Test: a numerical PC version of the original Navon test [43]. CFT has been applied in previous studies [44–47]. The test was administered using the Hypothesis software [48, 49].

In each task, the participant was presented with a large (global) number (Fig 1A) comprising multiple smaller (local) numbers. In the CFT, only four numbers were used as global and local numbers: 2, 4, 5 and 8. The participant was instructed to identify either the global (global task) or local level of the stimulus (local task) and select from four possible responses (one correct answer and three distractors) the correct answer as quickly as possible with a mouse-click. Before the test, the participant was given three practice trials and received feedback whether their response was correct. The participant did not proceed unless he or she selected the correct answer in each practice trial. The entire test comprised six practice tasks (three local and three global) and 32 test trials (16 for local and 16 for global processing). The local task preceded the global task in all cases. A fixation cross was displayed for 0.5 seconds before each trial (Fig 1B).

The reaction times and error rate of the responses were measured in each test. The mean speed and error rate of the local and global tasks were calculated separately. Four average values were therefore recorded for each participant: global reaction time (RT), local reaction time, global error rate, and local error rate. The main score, or the global preference score, was calculated in the CFT [24, 32] as local RT-global RT and served as a major indicator of local and global attention. Let us remind that we assumed the Taiwanese respondents would demonstrate a stronger global preference than Czech participants in CFT processing speed. The error rate of responses was a control variable, i.e. a high number of mistakes indicated the

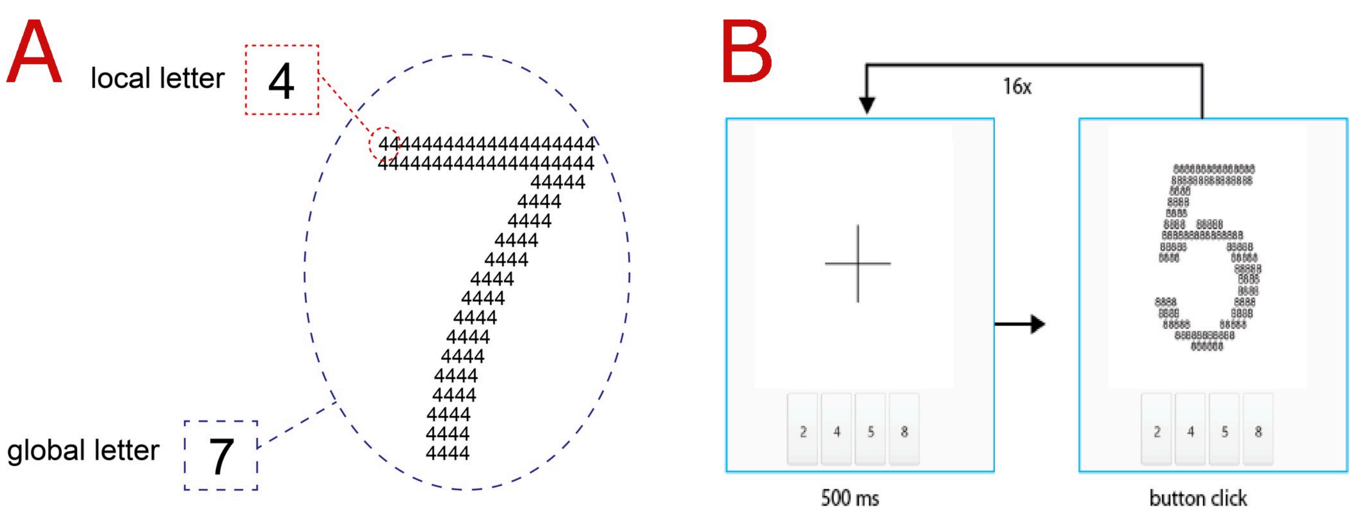

Fig 1. CFT stimulus example and procedure. (A) CFT stimulus. (B) CFT procedure. A fixation cross is displayed for 500 ms before each stimulus. After the fixation cross is displayed, a compound letter is presented. Depending on the task (local vs. global), the participant identifies the local or global feature of the stimulus and responds by pressing the corresponding number.

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decreased validity of the test results due to, for example, less motivation or misinterpretation of the test. No significant differences in the error rate of responses between the two groups were therefore expected.

Complex scenes. To investigate the possible cultural differences in context sensitivity of the two samples, 60 images of real-world scenes were used. The pictures were downloaded from free online image depositories (wallpaperflare.com, pxhere.com). Half of the scenes were similar to those used in other research [15, 23, 36], consisting of one focal object (animals or inanimate objects such as vehicles, buildings, doors and windows on a facade) against backgrounds of different complexity (Fig 2A and 2B) from relatively uniform to moderately complex. The other half of the stimuli were similar but contained two focal objects (Fig 2C and 2D) of the same category. In the scenes containing one focal object, the object was positioned either centrally (10 images), at the left (9 images), or at the right (11 images). In the scenes with two focal objects, the positions of the objects were not controlled. The scenes for both groups were the same size (1024 x 688 px) and the scenes were placed on the black background.

The participants were instructed to view a series of pictures and evaluate how much they liked each picture on a scale of 1 to 5 (1 –very good, 5 –very poor). These data were not analysed. Two practice runs preceded the testing. A fixation cross was displayed before each test until the moment the participant fixated on it. After the participant successfully fixated on the cross, it disappeared, and an image was displayed for four seconds.

This timing was selected according to previous research on perceiving scenes using different durations to display stimuli. For example, Chua et al. [36] and Evans et al. [23] displayed the stimuli for three seconds, and Duan et al. [15] displayed stimuli for five seconds. Chua et al. [36] showed that the proportion of object fixations varied throughout the course of testing. After a stimulus was displayed, participants mostly fixated on focal objects (bottom-up process driven by salience) for around 300–400 ms. The proportion then varied throughout the testing, and any potential differences in fixation count and duration may have disappeared after a long enough (e.g. 10 s) exposure to the scene [26].

Fig 2. Examples of real-world scenes. (A), (B) Samples of one focal object scenes. (C), (D) Samples of two focal object scenes. Copyright statement: All images used in this figure are free for commercial and personal use.

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The testing was presented in two separate batches: pictures with one focal object and pictures with two focal objects. A one-minute break was given between the batches. The sequence of batches was balanced: half of the participants first viewed the batch with one focal object and the other half viewed the batch with two focal objects. The sequence of pictures in each batch was pseudo-random. The eye-movement data were recorded for each test.

Apparatus

The CFT data were collected using Hypothesis software (see above) and the Google Chrome web browser. The participants viewed the stimuli without a chinrest. In Taiwan, a 19″ (EIZO FlexScan S1901) LCD monitor with a resolution of 1280 x 1024 was used. The viewing distance was approximately 65 cm. In the Czech Republic, a 22″ (AOC I2267FW) monitor with a resolution of 1680 x 1050 was used. The viewing distance was approximately 70 cm. The size of the instructions with illustrative examples and size of the stimuli (the compound hierarchical letters) were the same for both groups (900 x 675 px and 440 x 500, respectively).

In Taiwan, eye-movements were tracked with an EyeLink 1000 desktop type eye-tracker. The stimuli were presented on a 19″ (ViewSonic P95f+) CRT monitor with a resolution of 1024 x 768. In the Czech Republic, eye-movements were tracked using an SMI Red eye-tracking system with an integrated 22″ monitor (Dell P2213) with resolution of 1680 x 1050 px. The size of stimuli was same in both countries (1024 x 688 px). A chin rest positioned approximately 70 cm away from the monitor was used to minimize any disruptions caused by head movements. The visual angle of stimuli in Czech Republic was approximately 31.5˚ horizontally and 21.5˚ vertically. The visual angle of stimuli in Taiwan was approximately 30.1˚ horizontally and 21.8˚ vertically. In both countries, the sampling rate was set to 500 Hz, with 9 points of calibration. The minimum accuracy of calibration was set to 1˚ of visual angle. The same threshold was used for all participants.

Participants and procedure

The test battery was translated using the parallel translation method, which is commonly used to reduce method bias in cross-cultural test adaptations [50, 51]. Two bilinguals translated the test materials (test instructions). Both versions were then assessed for any potential differences. If the translations differed, the differences were discussed by the research team until a consensus on optimal translation was reached.

The research participants in both countries were recruited through university groups on social networks. Participation was limited to people of Czech or Taiwanese nationality possessing no eye-diseases or colour blindness and normal or fully corrected vision. A formal administration procedure was created, and the process of administration in both countries, including the instructions given to participants and the task sequence, remained the same. The test battery was administered in both countries by a local administrator (Czech and Taiwanese, respectively) to prevent a potential method bias [52]. Administrators of the test battery at both sites were also trained to administer the battery in the same manner. The test battery was administered in the following sequence: after entering the laboratory, participants a) read and signed an informed consent form, b) filled in a sociodemographic questionnaire, c) completed the CFT, and d) completed the complex scenes task.

The minimum required sample size was estimated before the experiment commenced using G*Power 3.1 [53] for ANOVA, fixed effects with effect size = 0.25, $\alpha = 0.05$, Power = 0.8, and 4 groups (2 [area: object vs. background] × 2 [nationality]). The required total sample size was 128 respondents. In total, we gathered data from 129 participants (60 Taiwanese, 69 Czechs). The detailed procedure of data cleaning and number of participants in each of the

Table 1. Research sample characteristics summary.

Variable	Taiwanese (N = 60)	Czech (N = 69)
% of women	71.6	71.0
Age–Mean (SD)	21.1 (2.07)	21.5 (2.65)
% of participants living abroad for longer than a year	8.3	14.5
Household size–Mean (SD)	4.1 (1.16)	4.0 (1.16)

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statistical analyses are described in the respective sections of the Results. See Table 1 for a summary of the sample's characteristics.

In the present paper, we used the following statistical programmes: G*Power 3.1 [53] for power analysis; R 3.5.2 [54] for eye-tracking data pre-processing and statistical analysis; Ogama 5.0.1 [55] for eye-tracking data cleaning, ROI (Regions of Interest) definition and fixation calculation. Stimuli, data files, R scripts and procedural descriptions are publicly available in the OSF repository (https://osf.io/eubwn/; DOI 10.17605/OSF.IO/EUBWN).

We applied the following analyses. The cultural differences in the CFT were tested with independent samples and paired sample t-tests. Cultural differences in the scene perception task were tested using mixed ANOVAs with one between-subject factor (cultural group) and one within-subject factor (ROI), post-hoc tests, and independent sample t-tests. In all analyses, partial eta squared (ηp^2; ANOVA) and Hedges' g (g; post hoc tests, t-tests) effect sizes were calculated. Finally, for an exploratory analysis of relationships between the main eye-tracking metrics and other variables, we used linear regression.

Results

Analysis 1: Compound Figures Test

In the first stage, the average error rate and average reaction time (speed) scores were computed for the local and global tasks (16 trials for each subtest). The error rate score was taken as an indication that the participant understood the task correctly. If the error rate of a certain participant was high, the participant was excluded from further analysis. Before the data were cleaned, the overall average error rate was 0.9% for the local task and 3.0% for the global task. The Taiwanese participants had a slightly higher average error rate in both local (1.0%) and global (4.9%) tasks compared to the Czech participants (0.8% for local and 2.2% for global). The maximum number of errors in the local task was one (corresponding to an error rate of 6.25%–out of 16 trials in total). Several participants (6 Taiwanese, 2 Czechs) had higher error rates in the global task. The number of errors in a task greater than four (corresponding to a 31.3% error rate–out of 16 trials in total–or higher) cannot be attributed to a temporary lapse in attention or "mouse misclick", but rather suggest a misunderstanding in the nature of the task. When we removed these eight participants from the data set, the overall average error rate in the global task dropped to 3.4%. The average error rate of Taiwanese (1.2% for local and 1.5% for global) and Czech (0.8% for local and 1.3% for global) participants was almost identical, and the differences were not significant, with negligible effect sizes (global task: $t(101.59) = 0.26$, $p = 0.795$, $g = 0.048$; local task: $t(99.11) = 0.69$, $p = 0.487$, $g = 0.130$). In the next stage of CFT data cleaning, we examined the average processing speed of global and local tasks. One Taiwanese participant was excluded from further analysis as an extreme outlier (reaction time for a local task more than 11 standard deviations from the group mean).

After data cleaning, the data from 120 respondents (53 Taiwanese, 67 Czechs) were analysed according to reaction time. The data for reaction times are summarized in Table 2. The data shows that both the reaction times and variability were generally higher in the Taiwanese

Table 2. Summary of statistics for reaction times and global preference by nation (in seconds).

Measurement		Taiwanese (N = 53)	Czech (N = 67)
Local RT (sec)	Mean	2.06	1.02
	SD	0.255	0.132
	Median	2.04	0.97
	IQR	0.242	0.143
Global RT (sec)	Mean	1.89	0.89
	SD	0.229	0.139
	Median	1.86	0.87
	IQR	0.324	0.210
Global preference	Mean	0.17	0.13
(Local RT–Global RT)	SD	0.180	0.116
	Median	0.16	0.13
	IQR	0.252	0.143

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sample. The mean reaction times were also higher in the local task. To test the differences in global vs. local RTs in each group, we performed two paired t-tests separately for both nationalities. The differences were significant for global vs local RTs in both the Czech sample (t(66) = 8.98, p = 4.692e-13),13 with a large effect size (g = 0.936), and for the Taiwanese sample (t (52) = 6.89, p = 7.413e-9),9 with a medium effect size (g = 0.699).

For reaction times, we subsequently calculated the global preference score using the *local RT-global RT* equation, a procedure used in multiple studies with Navon-type hierarchical stimuli [24, 32, 56, 57]. We applied an independent t-test to determine the differences in global processing between both groups. No significant differences were found between the Taiwanese (M = 0.17, SD = 0.180) and Czech (M = 0.13, SD = 0.116) participants, t(84.646) = 1.51, p = 0.136. The effect size was small (g = 0.289).

Analysis 2: Complex scenes

Eye-movement data pre-processing. The differences in data format created by using two different eye-tracking systems forced us to pre-process the eye-movement data before calculating the eye-metrics in Ogama. For this purpose, R 3.5.2 [54] was used. The cleaned data was subsequently imported into Ogama [55]. In Ogama, the following steps were performed: a) data loss analysis, b) definition of ROIs, c) calculation of fixations, d) fixation detection verification. Data loss in the entire sample was relatively low. In the case of Czech participants, data loss varied between 0.13 and 13.77% (mean = 2.89), and in the Taiwanese participants, between 0.02 and 6.99% (mean = 2.91). Two (stimuli with one focal object) or three (two focal objects) ROIs were defined. The ROIs for focal objects were defined around their contours, and the background ROI covered the entire image except for the focal objects and black borders (Fig 3).

Fixations were calculated next. Ogama uses a dispersion-type algorithm [58] to detect fixations. We used the settings suggested by Popelka [59]: maximum distance of 15 pixels, minimum number of 40 samples, size of 31 pixels for the fixation detection ring, automated elimination of first fixation and no merging of consecutive fixations. The number of fixations was checked for each participant and stimulus to identify participants with potential problems in fixation detection (extremely low or high numbers of fixations). Nine participants (8 Czech, 1 Taiwanese) were discarded from further analysis.

As mentioned above, the data for this task were cleaned using a two-step procedure. We first conducted a data loss analysis and then calculated fixations, verifying whether they were

Fig 3. ROIs. (A) Sample one focal object image with ROI. (B) Sample two focal objects image with ROI. Copyright statement: All images used in this figure are free for commercial and personal use.

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correct. From this, we eliminated 13 participants because of the quality of their eye-tracking data. The most common reason for excluding participants was problematic detection of fixations: 8 participants indicated an extremely low number of fixations per trial (e.g. 0 or 1), while the common numbers of fixations per trial were much higher (entire sample median = 12). We excluded participants with median fixations per trial of less than 9. One respondent demonstrated the opposite behaviour: an extremely high number of fixations per trial (median = 22). Both effects were clear indications of a problem in detecting fixations (caused, for example, by shimmering glasses). We also lost the data of three participants due to system error during recording. One participant was discarded for high data loss (13.8% of lost data). After the participants with faulty and missing eye-tracking data were removed, the final analysed sample comprised 116 participants (58 in both groups).

Eye-movement data analysis. We expected that Taiwanese and Czechs would show different eye-movement patterns, suggesting differences in visual attention between both groups. More specifically, we analysed the percentage of first fixations on focal objects, the numbers of fixations on focal objects and backgrounds, the focal object and background fixation time, and the transitions between the ROIs. Because two different types of stimuli based on number of focal objects were used, stimuli with one or two focal objects were analysed separately. The parameters for all eye-tracking metrics and for both types of stimuli are summarized in Table 3.

One focal object. We first calculated the proportions of first fixations from all first fixations on the focal object. The data shows that in most cases, both Czech (M = 91.0, SD = 8.2) and Taiwanese (M = 92.6, SD = 7.2) participants first fixated on the focal objects. The

Table 3. Summary statistics of eye-tracking metrics for all stimuli according to nationality (fixation time in milliseconds).

Stimulus type		**One focal object Mean (SD)**		**Two focal objects Mean (SD)**	
Nationality		**Czech**	**Taiwanese**	**Czech**	**Taiwanese**
Fixations	% of first fixations on FO	91.0 (8.2)	92.6 (7.2)	98.7 (3.9)	98.3 (2.9)
	Number of FO fixations	8.2 (1.3)	6.8 (1.1)	8.7 (1.7)	7.5 (1.1)
	Number of BG fixations	4.6 (1.2)	4.6 (1.3)	4.0 (1.1)	4.5 (1.1)
	FO fixation time	1949 (383)	2023 (353)	1982 (436)	2035 (299)
	BG fixation time	966 (264)	1218 (290)	838 (235)	1138 (231)
Saccades	Number of within FO saccades	6.3 (1.3)	4.5 (1.0)	4.4 (1.1)	3.2 (0.8)
	Number of within BG saccades	2.8 (1.0)	2.6 (1.2)	2.2 (0.9)	2.3 (0.9)
	Number of FO–BG transitions	3.7 (0.7)	3.6 (0.7)	3.7 (0.8)	3.9 (0.7)
	Number of FO–FO transitions	NA	NA	2.4 (0.8)	2.0 (0.6)

https://doi.org/10.1371/journal.pone.0242501.t003

differences were not significant: t(114) = 1.163, p = 0.247, with a small effect size (g = 0.214). The focal object in most cases was first fixated on by both cultural groups.

Both groups showed significantly more fixation counts on focal objects than the backgrounds in the mean number of fixations: F(1, 228) = 308.78, p = 2e-1616, $\eta p^2 = 0.58$. The main effect of culture was significant: F(1, 228) = 17.92, p = 3.34e-0505, $\eta p^2 = 0.07$, as was the interaction between culture and ROI: F(1, 228) = 19.07, p = 1.91e-0505, $\eta p^2 = 0.08$. Fig 4 indicates that the Czech participants (M = 8.2, SD = 1.3) made significantly more focal object fixations than the Taiwanese (M = 6.8, SD = 1.1), t(114) = -6.229, p = 8.079e-0909, with a large effect size g = 1.15. No significant differences were found between the Czech (M = 4.6, SD = 1.2) and Taiwanese (M = 4.6, SD = 1.3) participants in the number of background fixations, t(114) = -0.093, p = 0.93, g = 0.02.

In fixation time, both groups spent more time observing the focal object than the background: F(1, 228) = 436.05, p = 2e-1616, $\eta p^2 = 0.66$. The main effect of culture was significant: F(1, 228) = 14.51, p = 0.00020002, $\eta p^2 = 0.06$., as was the interaction between culture and ROI type: F(1, 228) = 436.05, p = 0.038038, $\eta p^2 = 0.02$. No significant differences were found between the Czech (M = 1949, SD = 383) and Taiwanese (M = 2023, SD = 353) participants in focal object fixation time, t(114) = -1.080, p = 0.283, g = 0.20. The Taiwanese (M = 1218; SD = 290) fixated longer on the background than Czechs (M = 966, SD = 264) in background

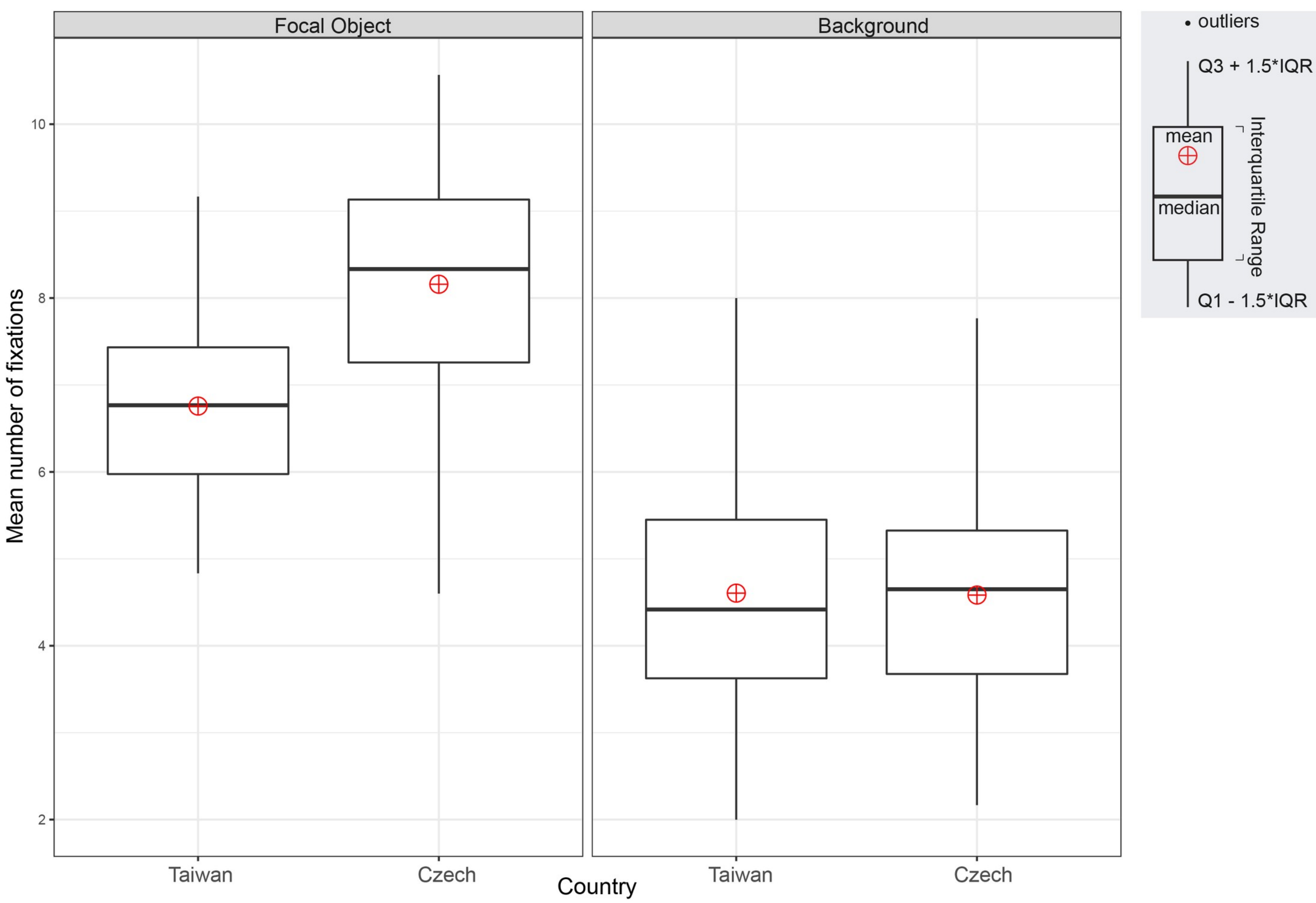

Fig 4. Mean number of fixations: One focal object stimuli.

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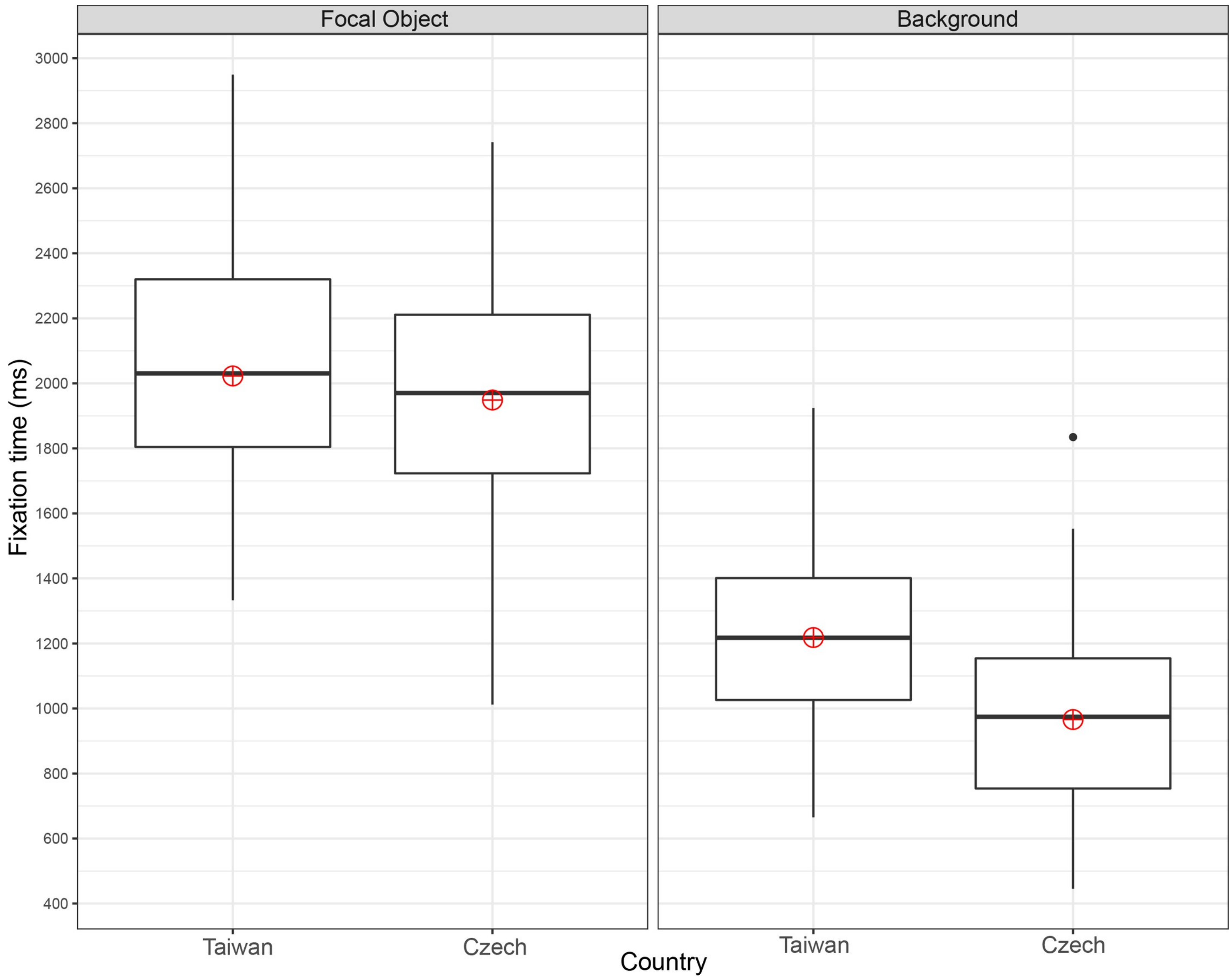

Fig 5. Mean fixation time: One focal object stimuli.

https://doi.org/10.1371/journal.pone.0242501.g005

fixation time, t(114) = 4.903, p = 3.161e-0606, with a large effect size g = 0.90 (Fig 5). We also tested for focal object to background transitions. No differences in the number of transitions were found between the Czech (M = 3.7, SD = 0.7) and Taiwanese (M = 3.6, SD = 0.7) participants, t(114) = 0.494, p = 0.623, g = 0.09.

Two focal objects. The same analyses were performed for stimuli with two focal objects. The proportion of first fixations was not significantly different in the Taiwanese (M = 98.3, SD = 2.9) and Czech (M = 98.7, SD = 3.9) groups, t(114) = -0.628, p = 0.531, with negligible effect size g = -0.116. One focal object was significantly first fixated on by both cultural groups.

In terms of the number of fixations, both groups fixated more on focal objects than backgrounds F(1, 228) = 532.04, p = 2e-1616, $\eta p^2 = 0.70$. The main effect of culture was significant: F(1, 228) = 4.65, p = 0.032, $\eta p^2 = 0.02$, as was the interaction between culture and ROI: F(1, 228) = 26.15, p = 6.7e-0707, $\eta p^2 = 0.10$. Fig 6 indicates that the Czechs (M = 8.7, SD = 1.7) made significantly more fixations on focal objects than the Taiwanese (M = 7.5, SD = 1.1), t

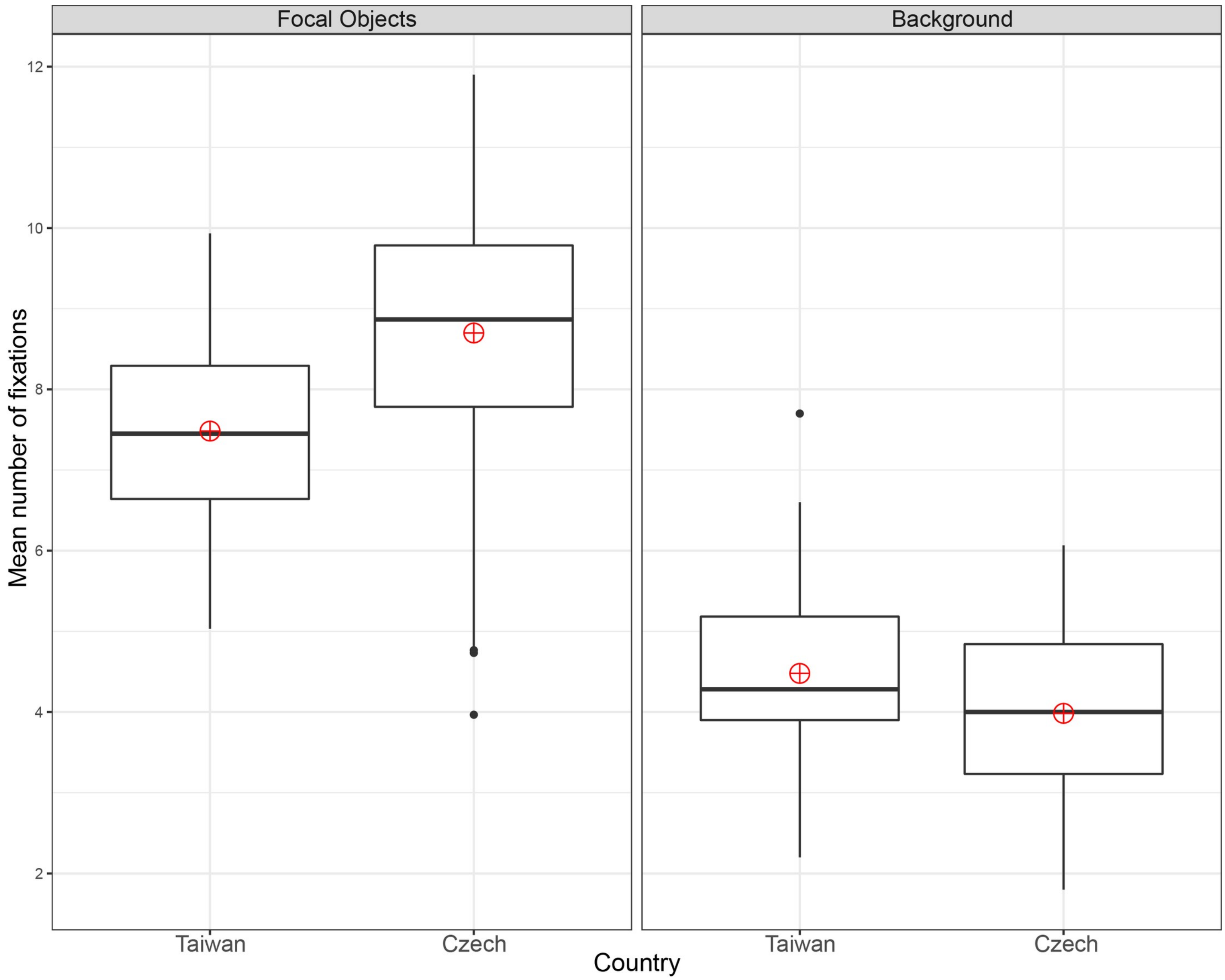

Fig 6. Mean number of fixations: Two focal objects stimuli.

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(114) = 4.595, p = 1.123e-0505, g = 0.85. By contrast, the Taiwanese (M = 4.5, SD = 1.1) participants fixated on the background significantly more than their Czech counterparts (M = 4.0, SD = 1.1), t(114) = 2.417, p = 0.017, with small effect size g = 0.45.

In terms of fixation time (Fig 7), both groups observed the focal objects longer than the background: F(1, 228) = 622.67, p = 2e-1616, $\eta p^2 = 0.73$. The main effect of culture was significant: F(1, 228) = 18.70, p = 2.29e-0505, $\eta p^2 = 0.08$., as was the interaction between culture and ROI type: F(1, 228) = 18.70, p = 0.002, $\eta p^2 = 0.04$. No significant differences were found between the Czech (M = 1982, SD = 436) and Taiwanese (M = 2035, SD = 299) participants in focal object fixation time, t(114) = -0.765, p = 0.446, g = 0.14. The Taiwanese participants (M = 1138; SD = 231) also fixated on backgrounds significantly longer than the Czechs (M = 838, SD = 235), t(114) = 6.953, p = 2.379e-1010, with large effect size g = 1.28.

Finally, the number of transitions in both groups was compared. In this case, both transitions between focal objects and background and transitions between focal objects were

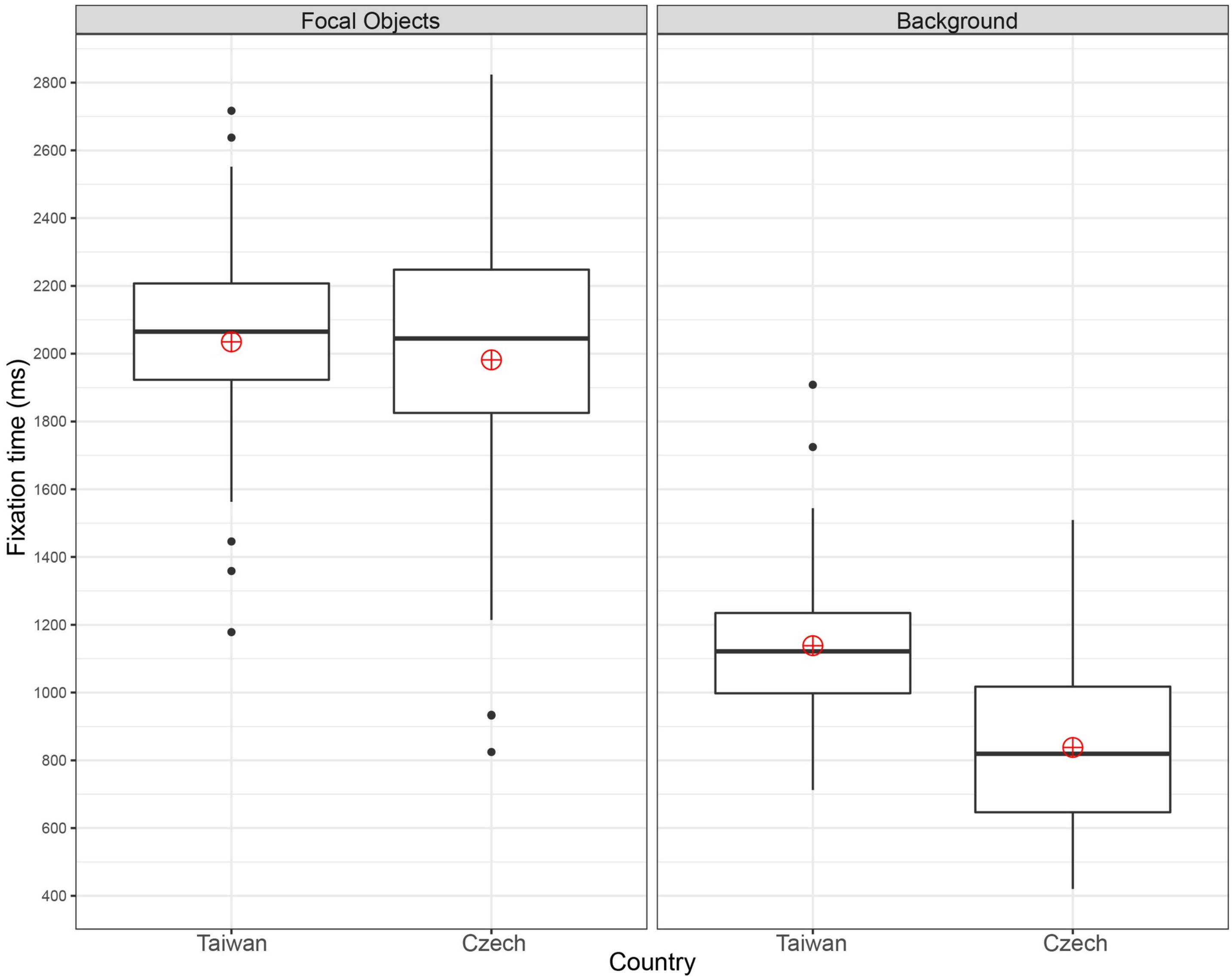

Fig 7. Mean fixation time: Two focal objects stimuli.

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analysed. While no significant differences were consistently found in one focal object stimuli between the Czech (M = 3.7, SD = 0.8) and Taiwanese (M = 3.9, SD = 0.7) participants in the focal object to background transitions, $t(114) = -1.322$, $p = 0.189$, $g = 0.24$, the Czech participants (M = 2.4, SD = 0.8) transitioned significantly more between the two focal objects than the Taiwanese (M = 2.0, SD = 0.6), $t(114) = 2.939$, $p = 0.004$, $g = 0.54$.

Analysis 3: Relationship between eye-movement metrics, CFT and other variables

Only data from respondents not excluded from one of the two previous analyses (CFT, complex scenes) were part of this analysis. We calculated 108 cases (56 Czech, 52 Taiwanese). To determine whether the eye-tracking metrics had any relationship with other collected variables, we calculated a relative focal object/background number of fixations, fixation times and number of saccades by dividing the focal object metrics of each participant with their background metrics. A series of three multiple linear regressions was subsequently performed on CFT global preference scores, sex, age, household size, experience with living abroad and nationality as independent variables, and relative number of fixations, relative fixation times and relative number of saccades (each in a separate model) as dependent variables. We expected a significant positive relationship between CFT global preference and the relative eye-tracking variables, meaning that the more global the attention patterns, the more the focal objects were focused on. We did not hypothesize any relationships between eye-tracking metrics and other variables included in the models for exploratory purposes.

Nationality was a significant predictor of the relative number of fixations: $F(6, 101) = 2.82$, $Pr(>|t|) = 0.00239$, with an adjusted R2 of 0.092, relative fixation time: $F(6, 101) = 2.65$, $Pr(>|t|) = 0.00273$, with an adjusted R2 of 0.085, and relative number of saccades: $F(6, 101) = 2.25$, $Pr(>|t|) = 0.011$, with an adjusted R2 of 0.065. No significant regression equation was found for any other variable in these three tested models. When nationality was excluded from the models, the adjusted R2 of the models had a maximum value of less than 0.006. That means the focal object to background eye-tracking patterns appeared to be independent of the global preference scores and sociodemographic variables mentioned above, except for the participants' nationalities.

Discussion

The present study introduces several new findings into the ongoing debate on cross-cultural similarities and differences in visual perception and cognition according to the theory of holistic and analytic cognitive styles [2, 29]. The study examined two dimensions of cognitive style: global vs. local attention (measured by CFT) and context sensitivity (measured by eye-tracking metrics as complex scenes were perceived). In summary, both Czech and Taiwanese showed a strong global preference effect in the CFT: global processing speed was significantly quicker compared to local feature processing. No significant differences were found between the groups in the global preference scores. No cultural differences were noted as affecting the proportion of first fixations on focal objects in the eye-tracking metrics calculated in the scene perception task. Both groups fixated more frequently on and spent more time observing the focal objects than the background. Czech participants fixated more frequently on focal objects than the Taiwanese, while the Taiwanese spent more time observing the background. The results were consistent across one and two focal object scenarios. No differences were found between the groups in the number of focal object/background transitions. The Czech participants made more direct transitions between focal objects in the dual focal object scenario. No significant relationships were found in the relative (focal object vs background) eye-tracking metrics, such as number of fixations, fixation time, number of saccades, CFT, global preference score, sex, age, household size or experience living abroad.

Compound Figures Test

As mentioned above, global vs. local attention was investigated using a CFT [43]. The tasks consisted of two sub-tasks that would indicate a person's tendency for global (attention to global characteristics) vs. local (attention to local characteristics) processing. From these two scores, a global preference score was calculated, which served as an indicator of global vs. local attention: the higher the score, the more globally oriented a person was. The results suggested that the Taiwanese in our sample perceived slightly more globally than the Czechs. The results, however, were not significant with small effect size, and therefore did not provide any strong evidence of cross-cultural differences such as those reported by McKone et al. [32]. The results were more in favour of the findings of a preregistered study conducted by Hakim et al. [24], which did not detect any cultural differences in global processing between American, international Asian and Chinese samples, or the study by von Mühlenen et al. [60], which did not detect any differences between samples from the UK and India.

It is important to note that the differences in results may have been caused by the methods of administration and precise nature of the task. Hakim et al. [24] instructed the participants to identify target letters (E or H) in compound letters while stimuli were presented centrally. The respondents only responded whether the target letters were present on the global or local levels, without reporting the specific target, and stimuli were displayed until a response was given. Von Mühlenen et al. [60] asked the participants to identify a specific target (H or T) by pressing the respective key. The Navon task was assigned in combination with emotionally charged (happy, neutral, sad) images to affect the emotional state of the participant. Stimuli were presented until a response was given or for a maximum of 5 seconds. McKone et al. [32] presented the stimuli laterally to test hemispherical differences in global/local processing. We therefore declare that it would be premature to draw final conclusions on the issue of cross-cultural differences in global vs. local attention.

An interesting effect observed in the global and local reaction times should be noted. Although both groups were slightly quicker in responding to global tasks than local tasks, the reaction times of the Taiwanese group were, in both cases, approximately twice as long. This finding replicated the results of the CFT reported by Lacko [45] in samples of Czech and continental Chinese participants. Chinese participants were also significantly slower. Since the test instructions in both Czech and traditional Chinese included the instruction to solve the task "as quickly as possible", such a large difference in reaction times should not be an indicator of method bias [50, 61] but more probably of the differences in response styles between both samples. These differences in speed of response might also be explained by the avoidance of risk-taking behaviour inherent to Confucian ethics [62], or the notion of "losing face" typical for some Asian cultures [63]. These assumptions should be tested in future research, for example, by manipulating individual/group administration of the task, or with the administrator persona (e.g. Would the perceived social status of the administrator influence the tendency of the participants not to make mistakes?).

Complex scenes

The second dimension in differences of perception, i.e. context sensitivity, was investigated by measuring eye-tracking patterns while complex real-world scenes were observed. Two types of real-world scenes were shown in which the number (one or two) of focal (perceptually salient) objects was changed. According to previous research [15, 36], we expected Czech participants to focus relatively more on focal objects (first fixations, number of fixations, fixation time) than the Taiwanese, and also, because of the expected holistic nature of eye-movement patterns of the Taiwanese, we assumed that they would make more transitions between various parts of the stimuli. Stimuli with one and two focal objects were analysed separately.

No significant cross-cultural differences were found in the percentage of first fixations on focal object(s). The results were consistent across both stimulus types. Both groups mostly first fixated on the focal object, which is consistent with previous findings [15, 23, 36] and suggests the prevalence of bottom-up perceptual processes soon after the stimulus is displayed. The early visual attention was mainly driven by the perceptual properties of the stimulus, and the subjects primarily fixated on highly salient objects [64].

In both the one and two focal object conditions, the Czech participants made significantly more fixations on the focal objects and spent less time fixating on the background than the

Taiwanese. In the case of stimuli with two focal objects, the Taiwanese made significantly more background fixations. These results agree with the assumption that analytic perceivers focus more on the focal object and its properties and that holistic perceivers focus relatively more on the background [1]. The Czechs also transitioned significantly more between both focal objects, which might again be an indicator of relatively higher focus on objects [1]. However, contrary to our expectations, no cross-cultural differences in focal object to background transitions were detected in either the one or two focal object conditions. As holistic perceivers, if the Taiwanese observed the image as a "whole", we would expect them to make more transitions.

The results showed that the Czechs made more transitions between focal objects. The main eye-tracking metrics (number of fixations, fixation time) in this study replicated the results of studies conducted by Chua et al. [36] and Duan et al. [15] and demonstrated the expected higher focus of Czechs on focal objects (number of fixations) and of Taiwanese on backgrounds (fixation time). As mentioned by Rayner et al. [26], it is questionable whether the number of the points of interest in the scene affected the scanning patterns across cultures. Our results showed that the cross-cultural differences in scanning patterns were consistent for both stimuli with one and two focal objects.

Theoretical implications

The present study is one of few that have attempted to compare multiple components of cognitive styles within the framework of the general holistic–analytic model [1, 2]. It defines cognitive style as a bipolar dimension in which analytic perception is defined as rule-based, formally logical, field independent, with selective attention focused on salient objects and locally oriented, while the holistic pole is rather intuitive, dialectical, field dependent, sensitive to context, with attention focused on the "whole" and globally oriented. Two tasks were used to analyse cognitive style: hierarchical figures (global and local processing) and complex natural scenes (attention to object and background). Using linear regression, no significant relationships were found between the tasks, which is in line with other studies [8, 24] that used more methods to validate the analytic–holistic cognitive styles theory and found them unrelated.

The results raise questions of a) the validity of the concept of cognitive styles and b) its dichotomous nature. In terms of a), Cuneo et al. [65] tested the discriminant validity of methods for analytic–holistic style diagnostics and found that questionnaire methods overlapped with personality and that maximum performance methods (Group Embedded Figures Test) overlapped with intelligence. Further research should test the construct, concurrent and discriminant validity of cognitive styles, especially in relation to personality and intelligence. Some methods not based on maximum performance attempt to overcome this problem by using two independent tests: one for each of the opposing poles of cognitive styles. In terms of b), if the concept of cognitive styles is valid and non-overlapping with other constructs, its nature might be different from the possibly reductionist dichotomic analytic–holistic (or "East–West") definition of the general holistic–analytic model. Kozhevnikov et al. [37] proposed an alternative hierarchical–ecological model of cognitive styles (see Introduction) that has the form of a hierarchical matrix in which cognitive style families are organized along levels of informational processing. According to this model, the different cognitive styles would not necessarily have to (cor)relate, because an environment might, for example, support the development of global processing (holistic characteristic) and focus on salient objects (analytic characteristic). This model might explain the lack of correlation between different methods of cognitive style analysis observed in this and some other studies [8, 24, 45]. Future research should therefore attempt to verify the hierarchical–ecological model [37] of cognitive styles and specify the number of cognitive style families. Conducting research on the stability/flexibility of cognitive styles and investigating the developmental aspects (e.g. children of different ages) of cognitive style and its adaptive nature (e.g. research on expatriates during the process of cultural adaptation) is also suggested.

Limitations

This study carries some limitations. Most importantly, only student samples were used for this research. The potential differences in results obtained from student samples and the results from Czech and Taiwanese general population subgroups would be based on the adopted theoretical perspective. If we adopt the dichotomous approach of the general holistic–analytic model [1], which states that East is holistic and West is analytic, we would expect to find similar patterns in the similarities and differences between other Czech and Taiwanese subpopulations. We might also expect larger effect sizes if more diverse subpopulations (e.g. uneducated individuals, children, seniors) are compared. However, if we adopt the approach of the hierarchical–ecological model [37], we could expect substantially different patterns of global attention or context sensitivity in different subgroups, because these subgroups might mature and live in fundamentally different social and physical environments that require distinct ways of cognitive adaptation. Furthermore, a study by Waxman et al. [66] showed evidence of cross-culturally divergent developmental changes in attentional patterns. Our results, therefore, are not generally applicable to all citizens of the Czech Republic or Taiwan.

Potential differences in eye-tracking systems in the Czech Republic and Taiwan need to be mentioned among the limitations of our study. However, we gave special attention to this issue throughout all stages of the research to eliminate any possible confounding effects and assure full equivalence in measurement. Both eye-tracking systems were set to the same sampling frequency. Both eye-tracking systems also had similar spatial accuracy and precision [67]. The spatial accuracy threshold was the same for both measurements (max. 1˚ of visual angle), and the calibration error was the same in both samples (0.56˚ of visual angle). Fixation calculations were also conducted simultaneously for both datasets in Ogama software, and the ROIs were the same for both cultural groups. Only robust eye-tracking metrics (number of fixations, fixation time, transitions in ROIs) were calculated [49], and the ROI specification of the scenes was binary in character (figure vs. background). Therefore, the size of the stimuli (figures) used in this experiment was two levels higher (approx. 10˚ of visual angle) than the variability in accuracy of eye-tracking in the participants (approx. 0.1˚ of visual angle). Therefore, the interference in data caused by using two eye-tracking systems can be considered negligible in our research design.

Another point to consider is the nature of the task, as it might be a method factor that affects eye-movement patterns and potential cross-cultural differences in these patterns. As previously mentioned, the eye-movement task was an implicit, free-viewing task for evaluating the "aesthetic preferences" of each image. It should be noted that the eye-movement patterns might differ depending on the nature of the task, as demonstrated by Yarbus [68] in his seminal monograph. In his qualitative study, instructions were manipulated and the differences in eye-movement patterns were subsequently observed. Castelhano et al. [69] found differences in aggregate eye-movement metrics depending on whether the observers searched for a target or memorized the stimuli. The need to consider the nature of the task while evaluating cross-cultural differences is also emphasized by Alotaibi et al. [16]. Greene et al. [70], however, demonstrated quantitatively with pattern classifiers that the task-related effects on scene viewing might be overrated, at least in the case of brief presentations of stimuli, when an observer's gaze seems to be mostly driven by the saliency of various parts of the scene. Nevertheless, the observed similarities and differences between both groups in eye-movements should not be generalized to other possible scene perception designs (e.g. passive viewing, visual search or recognition).

While some studies reported differences between Americans and Chinese [36] and Chinese and Africans in a free-viewing task [15], studies conducted by Rayner et al. [25] combined with a memory task showed negative results. Similarly, no cross-cultural differences were found in a change-blindness experiment performed by Masuda et al. [34]. Future eye-tracking research exploring the perception of complex scenes should attempt to combine several tasks (e.g. free-viewing, visual searches, flicker-tasks).

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4.2 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.

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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

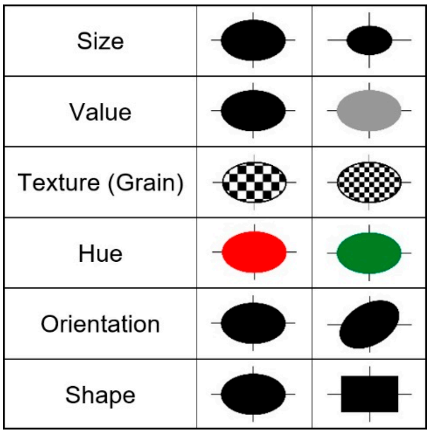

Figure 1. Bertin's six basic variables ([3]; depiction adapted from [20]).

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 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

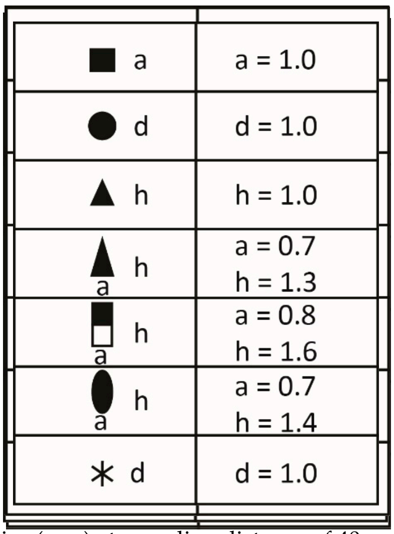

Figure 2. Minimum size (mm) at a reading distance of 40 cm (adapted from [34]).

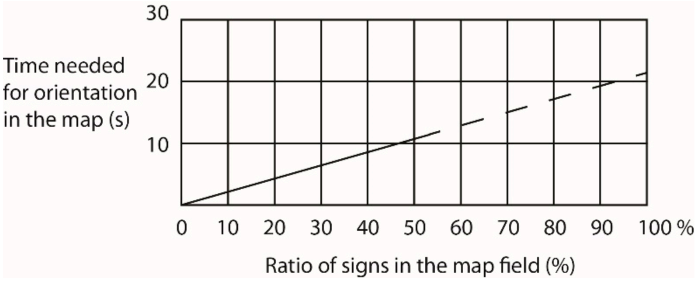

Figure 3. Map reading speed (adapted from [34]).

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.

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).

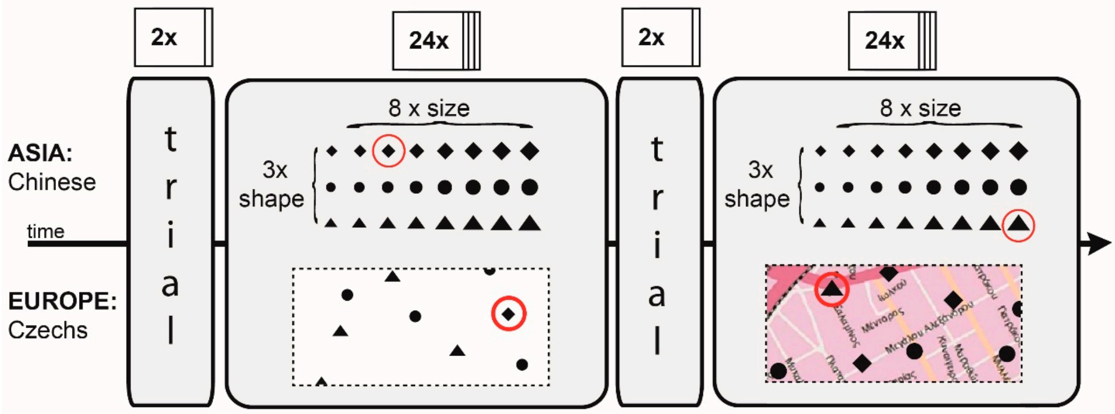

Figure 5. Schema of the procedure used for testing.

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.

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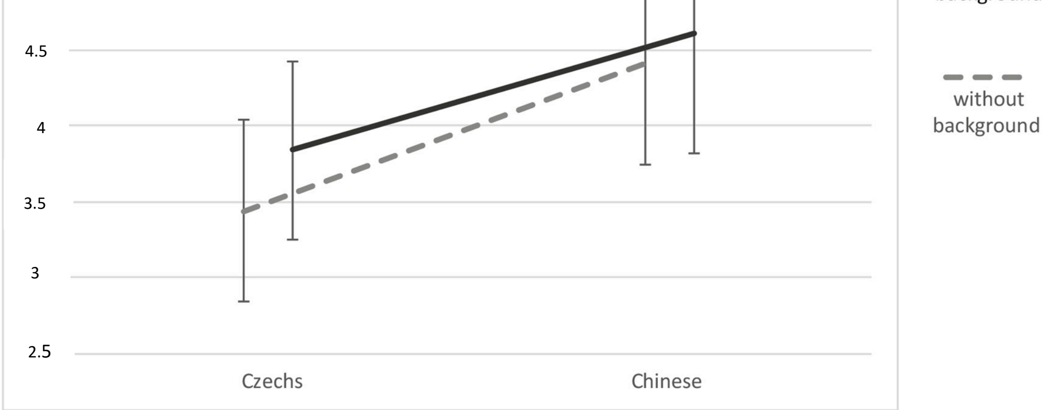

Figure 6. Comparison of mean detection times with background and without background (in seconds, N = 69).

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)

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

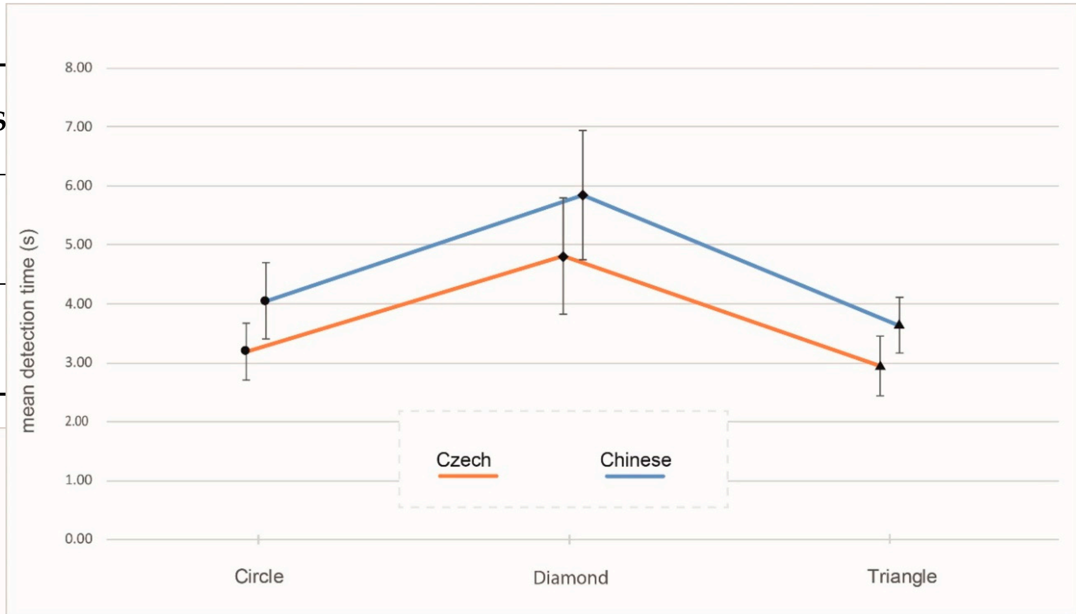

Figure 7. Mean detection times regarding point symbol shape (in seconds, N = 69).

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)

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

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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4.3 Cross-cultural differences in figure–ground perception of cartographic stimuli

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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.

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Cross-cultural differences in figure–ground perception of cartographic stimuli

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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.

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Cultural differences; map reading; visualization; visual perception; user testing

Introduction

Psychologists' interest in the relationship between culture and cognition dates back to the beginning of the twentieth century. Pioneering single-culture studies conducted by Rivers (1905) inspired further research in the field. Early research focused mostly on the role of the environment and past experience on perception. Segall (Segall, Dasen, Berry, & Poortinga, 1990) formulated hypotheses about the relationship between the physical characteristics of perception and the environment. Blakemore and Cooper (1970) demonstrated the influence of individual experience on the development of perceptual abilities. Hudson (1960) and Deregowski (1972) conducted experimental studies on the interpretation of depth cues in African cultures. Other experiments used visual illusions to explore cross-cultural differences in the perception of symmetry, spatial orientation, perceptual constancies, or object recognition (see Deregowski, 1980). The formulation of Gestalt principles of perceptual grouping and figure–ground organization (Wagemans et al., 2012) inspired an entire line of cross-cultural research based on the Navon hierarchical stimuli method (Navon, 1977).

The focus of more recent studies enriched the investigation of the role of experience and environmental factors in perception and cognition by the incorporation of socio-cultural, economic, and political factors (Berry, Poortinga, Breugelmans, Chasiotis, & Sam, 2012) into the model of relationships between culture and cognition. The theory of holistic and analytic perception was formulated on the basis of the earlier theories of cognitive styles that are defined as relatively stable modes of informational processing (Kozhevnikov, 2007; Tiedemann, 1989), primarily on Witkin's theory of field dependence (Witkin & Goodenough, 1977). The research projects conducted within the boundaries of the theory were so far mainly focused on the comparison of two economically developed cultural regions: The West (USA, Western Europe) and East Asia (China, Japan, South Korea).

The theory postulates that there are two distinct cognitive styles: holistic and analytic. Whereas the analytic style is typical for Westerners, who rather attend to focal (i.e. perceptually salient and semantically relevant) objects and their characteristics than to background or context information in a visual scene, the holistic style is typical for East Asians, who mostly attend to the relationships between objects in a visual scene and to context information (Nisbett & Miyamoto, 2005). Different sociocultural factors can produce the development of distinct cognitive styles, such as the differences in philosophical systems, the complexity of social relations, self-construals, social practices, and child-rearing practices (Nisbett & Masuda, 2003). The abovementioned differences between the two distinguished cognitive styles are further pronounced by the use of different writing systems, which require a different set of skills to master (Huang & Hanley, 1995).

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There are several methods commonly used to measure holistic and analytic cognitive style and its manifestations, which vary in their overall visual complexity from relatively simple tasks to more elaborate and complex tasks. The simplest of these methods is the Framed-line test (FLT; Kitayama, Duffy, Kawamura, & Larsen, 2003), currently considered the benchmark of holistic and analytic cognitive style diagnostics. The test is designed as a succession of geometrical figures that are comprised of a square frame and a vertical line. First, a frame with the vertical line is presented to a participant. Subsequently, a second frame is showed to the participants and the size of the second frame can be either the same as the original, or it can be increased/decreased. Participants are supposed to outline a line that is identical to the observed line in either the absolute length (in the absolute task) or in the ratio to the size of the surrounding frame (in the relative task). The difference in the length of the original and drawn lines is measured. "The absolute task is facilitated by the ability to decontextualize (i.e., analytic perception), whereas the relative task is facilitated by a contextualized mode of visual processing (i.e., holistic perception) (Kitayama & Cohen, 2010, p. 579)." The Western participants should perform better in the absolute task, whereas most of the people from East Asia should perform better in the relative task. These differences in the development of cultural strategies of attention become apparent at 5–7 years of age (Duffy, Toriyama, Itakura, & Kitayama, 2009).

Other studies used relatively more complex visual stimuli in order to identify the differences in visual perception and cognition among cultures. Several studies used change-blindness tasks for this purpose; in some cases, they were combined with priming manipulation. The studies compared members of various cultural groups and subgroups, such as American and Japanese (Masuda & Nisbett, 2006; Miyamoto, Nisbett, & Masuda, 2006), American and East Asian exchange students (Masuda & Nisbett, 2006), or Caucasian, African, Asian, Latino, and Multiracial American (Choi, Connor, Wason, & Kahan, 2015). The common feature of these studies is that they used real-world scenes as stimuli, and that participants were supposed to detect changes in objects and in the context (background). In all of the abovementioned research, participants with Western/Caucasian background had more difficulties (longer reaction times, lower success rates) with contextual information processing. Additionally, participants, who were primed with independence, which is considered to be a self-construal and value system typical for Westerners, showed patterns similar to those of Western participants (Choi et al., 2015).

Several other studies used complex visual stimuli in order to determine the manifestations of cognitive style across cultures. Kuwabara and Smith (2012) used cluttered cartoon scenes in a visual search task. American children showed more object-centered attention compared to their Japanese counterparts. Masuda and Nisbett (2001) used both static and animated scenes with animals in visual recognition tasks. In the first phase, the respondents were viewing the scenes, which contained animals on various backgrounds. In the second phase, they were supposed to recognize the animals presented in the first phase. The authors manipulated the background during the recognition phase. The Americans showed a better performance compared to the Japanese when recognizing animals on the background that differed from the original background presented in the scene viewing phase, which suggests a better ability of Westerners to decontextualize an object from its background.

Several eye-tracking studies support the existence of cultural differences in visual cognition. Zhang and Seo (2015) created a set of stimuli containing food items representing focal objects. The food items were placed on backgrounds that differed in the level of their visual saliency. They administered the method on a sample of Americans and Chinese, measuring first fixations on the food and overall food fixation time. They found that Americans fixated on the objects earlier and spent more time looking at the food. With the rising level of background saliency, both groups looked at the food later and spent less time looking at it. Similar results were obtained by Chua, Boland, and Nisbett (2005), who used pictures that contained living and nonliving objects with realistic backgrounds. They found that Americans looked at the objects sooner, had longer fixations on objects, and made fewer overall fixations.

As mentioned before, the elements of a visual scene can be characterized by perceptual salience (bottom-up process) and semantic relevance (top-down process) (Spotorno & Faure, 2011), which both determine the probability of a given object to be included in the mental representation of the stimulus. The salience of the element is determined by low-level visual characteristics of the element such as size, color, texture, spatial position of the element, overall complexity of the scene (Ma, Xu, Wong, Jiang, & Hu, 2013), and the relationships among the objects and between the object and the entire image (Spotorno & Faure, 2011). The semantic relevance is influenced, for example, by the task goals and instructions, and it is controlled by a top-down cognitive processes. Furthermore, the semantic relevance of the elements of a stimulus seems to be co-determined by cultural influences (Lee, Shin, Weldon, & Sohn, 2016). From this point of view, the attention allocation strategies among cultures differ due to the differences in adaptive benefits associated with each strategy.

Cartographers by themselves or in cooperation with psychologists began to systematically investigate group differences in empirical map studies 60 years ago (Montello, 2002). The general approach has changed overtime, but most of the studies typically use gender, age, cognitive abilities, and the style or expertise of users as explanatory variables (e.g. Brodersen, Andersen, & Weber, 2002; Fabrikant, Rebich-Hespañha, Andrienko, Andrienko, & Montello, 2008; Li, Çöltekin, & Kraak, 2010; Ooms et al., 2015; Kubíček et al., 2017; others). Far less attention has been brought to cultural differences in map perception, map reading, or analysis, with some exceptions. For example, Chang and Antes (1987) focused on gender and cultural differences between college students from the United States and Taiwan, where males performed significantly better than females in topographic map reading and Taiwanese students performed better than those students from the United States. Stea, Blaut, and Stephens (1996) asserted that mapping (as a way of communicating the nature of large environments) is a component of all contemporary cultures; thus, it constitutes cultural universality. Blades et al. (1998) focused on the cultural differences in mapping abilities of young children from England, South Africa, Iran, Mexico, and the United States. They stressed the fact that mapping abilities are well developed in all cultures, in the case of young children. Montello (1995) stressed the existence of cultural universals and differences in spatial cognition, but claims the importance of universality of cognitive structures and processes and also claims that cultural differences are often exaggerated. Davies and Pederson (2001) and Stachoň and Šašinka (2012) bring examples of differences in spatial processing and representation between people living in different environments. From other fields connected to cartography and geography, the work of Louis (2006) suggests that there are cultural differences in spatial planning strategies that are not only based on indigenous values of a landscape but also on differences in the cartographic techniques employed to represent indigenous spatial perceptions.

Contemporary critical cartography research incorporates cultural diversity approaches in mapping (e.g. Krygier & Wood, 2005) and turns our focus to the study of the cross-cultural differences in the cognitive processing of maps. The mentioned examples bring us to the different roles of spatial representations in the minds of people from various cultures and also to the issue of whether or not the cartographer should pay attention to the cross-cultural differences.

The aim of this article was to investigate the potential differences in the cognitive processing of maps. The rationale of the research is based on the theory of holistic and analytic cognitive style that provides a framework for the comparison of perceptual and cognitive processes across cultures. The abovementioned cross-cultural research in psychology inspired us to try to look at a map as a complex visual stimulus composed of multiple elements with various levels of visual salience and semantic relevance, and to explore possible cultural differences in the visual perception of maps. Figure 1 describes the expected relationships among key variables, and their operationalization. Nisbett and Masuda (2003) argue that specific sociocultural factors (e.g. individualism/collectivism, self-construal, language) influence the development of holistic or analytic cognitive style. Cognitive style as a psychological construct (Rayner & Riding, 1997) and latent trait (Allen & Yen, 2002) can be detected and measured with psychological tests (e.g. FLT) and manifests itself in daily life, e.g. during map work. Based on the theory, we expected that East Asians are generally more holistic and this would be manifested in the FLT by their ability to perform relatively better in the relative task. At the same time, users with holistic cognitive style would be relatively more effective in the exploration of map background in comparison to analytics who primarily pay attention to focal objects. We administered two performance methods to a sample of Czech and Chinese university students in order to measure cognitive style (FLT) and its manifestations in map reading (visual search task).

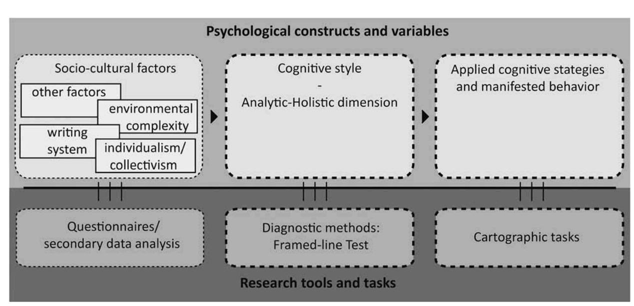

Figure 1. Model of cultural influence on perception and cognition.

Methods

The abovementioned interdisciplinary research in psychology, geography, and cartography suggests the existence of cross-cultural differences in mental representation of space and its understanding. Inspired by prior cross-cultural perception research, we wanted to investigate whether there might be differences in map-reading behaviors between Europeans and Asians. We thus included a version of the FLT to help explain potential map-reading differences across studied ethnic groups. Based on previous studies (e.g. Kitayama et al., 2003; Nisbett & Miyamoto, 2005), we hypothesized that:

(1) Both Europeans and Asians identify thematic figural symbols overlaid on a reference map more rapidly than background segments of this reference map.
(2) Europeans identify thematic figural symbols more rapidly than Asians, and Asians identify background segments of the map more rapidly than Europeans.
(3) An increased figure/ground contrast increases symbol localization speed for Europeans but not for Asians.
(4) In FLT, Asians perform better in the relative task and Europeans perform better in the absolute task.

Participants

We invited a total of 133 students from various undergraduate and postgraduate programs at Mendel University in Brno, Masaryk University in Brno, the University of Economics in Prague, and from Wuhan University in China to participate in our study. Of those participants, 64 participants were Czech (age: Mean = 22.0, SD = 2.96), and 69 were Chinese (age: Mean = 21.0, SD = 2.19), and all had normal or corrected-to-normal vision. We aimed for a balanced gender ratio in both ethnic groups (approx. 30% males in the Czech and 38% in the Chinese sample). Study participation was voluntary. Participants were invited to orally give their informed consent for participation in the study prior to taking part in the experiment.

Procedure and materials

The test was run on 21.5″ monitors (at 1600 × 900 pixel resolution). The distance between the computer screen and participants' eyes varied between 40 and 50 cm, and the size of the displayed map stimuli was 770 × 695 pixels. The test procedure was kept constant across the Czech and Chinese versions of the experiment, as shown in Figure 2. Participants solved the identical experiment, but in their native language (i.e. in Czech or in Standard Chinese). A maximum of five participants were tested in the same session. At the beginning of the test session, participants were informed that the experiment would consist of two test portions related to map reading and visual perception. The entire experiment took about 25 min on average.

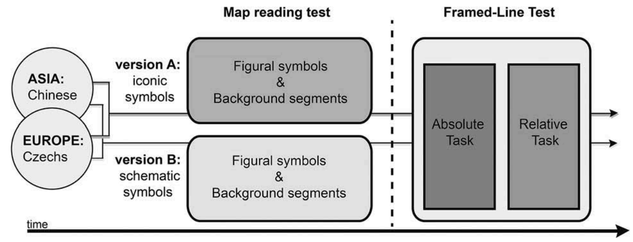

Figure 2. Schema of the testing procedure; both cultural groups passed through both versions of the test (A and B version).

The experiment was administered with the Hypothesis software, an online testing environment that runs in a web browser and captures participant responses in a digital database. For more details about Hypothesis, see Šašinka, Morong, and Stachoň (2017), Popelka, Stachoň, Šašinka, and Doležalová (2016), or Svatoňová and Kolejka (2017). Initially, participants were asked to complete the map portion of the experiment, and were randomly assigned to either stimuli version A or B. Map trials were randomized. Subsequently, all participants were asked to complete absolute and relative tasks of FLT.

Map stimuli

We designed a factorial experiment with informationally equivalent map stimuli to solve two typical map-reading tasks, including 1) localization of a given figural symbol in a reference map (21 trials), and 2) the localization of a given geometric configuration (background segment) from the map (20 trials). Both types of tasks were explained at the beginning of the test.

We prepared two test versions (A and B) with an identical background map showing a Greek city (including Greek map labels) that we selected from the OpenStreetMap database. We specifically chose Greek to avoid potential familiarity with a particular writing system for the chosen Czech and Chinese participant groups.

Test versions only differed in the visual contrast of the figural symbols to the background map. In test version B, figural symbols of different shapes and colors also include identical black outlines, to increase the visual saliency of the figural symbols from the background map (see Figure 3). In this version, the symbols thus appear more uniform in shape and size.

Figural symbols in both map versions are distributed equally across the background map. As previously mentioned, the background map is identical in both versions of map stimuli. Test version and culture are independent variables, whereas speed of localization of the figural symbols and the background map configurations are dependent variables.

The respondents were instructed to locate and select (by mouse click) the given figural symbol (see Figures 4 and 6) or given configuration (segment) selected from the background (see Figures 5 and 6). We measured participants' response time in milliseconds.

This was followed by an adaptation of the FLT which was identical for both groups (see further).

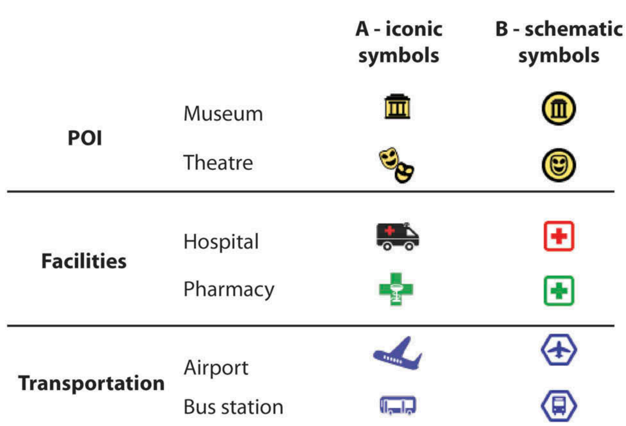

Figure 3. Examples of three groups of objects used for A and B versions of map stimuli.

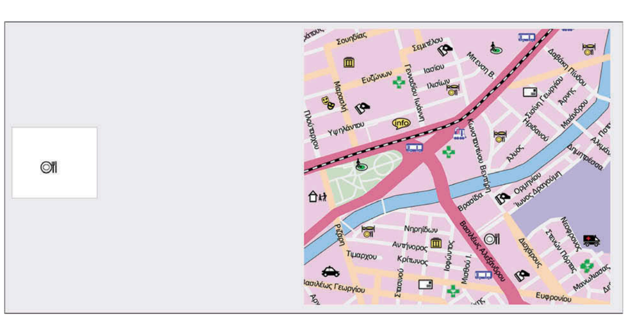

Figure 4. Example of the test stimulus used in map-reading test version A "Locate the symbol shown on the left." © OpenStreetMap Contributors.

FLT stimuli

The second portion of the experiment consisted of a modified version of the original FLT proposed by Kitayama et al. (2003). Our version is composed of a total of 16 stimuli, 8 stimuli each for both the absolute and relative tasks. The line-drawing practice task was put at the beginning of the test, followed by instructions for the absolute task. The absolute task preceded the relative task. Each stimulus started with a presentation of a square or circle frame with a line extended downward from the center of the upper edge (original stimulus; see left part of the Figure 7). The original figure was presented for 5 s. Immediately after the original figure, a blind screen was presented for 100 ms. After the blind screen, an empty frame with a dashed line was presented (test stimulus; central part of Figure 7).

A reference stimulus was shown first with either a square or a circle of a standardized edge/diameter length of 160 pixels. The geometric shape also contained a vertical line of a given length in the middle of the shape, as shown in Figure 8. The reference stimuli were all positioned in the center of an empty, white display. Participants were then shown a second stimulus, again containing a square/circle, but of a different size than the reference stimulus. They were then asked to draw a vertical line using the mouse, starting with a mouse click at the top edge of the rectangle/circle and by dragging the mouse downward. A second mouse click ended the line drawing. For the absolute task trials, participants were asked to draw a line of the same absolute length as presented in the preceding reference stimulus in the empty rectangle/circle shown second. For the relative task trials, participants were instructed to draw a line of the same length proportions in an empty rectangle/circle of a different size that corresponded to the same length proportion shown in the preceding reference stimulus (right part of Figure 7). Each task differed in the length of the given vertical line in the reference stimulus. Positions on the display and the sizes of the geometric shapes into which participants had to draw were randomized. We recorded the length of the drawn line (i.e. number of pixels) for each trial.

Results

Map-reading test

Below, we report on the quantitative results of the map-reading portion of the test. Of the 133 participants, we removed 6 participants because they did not

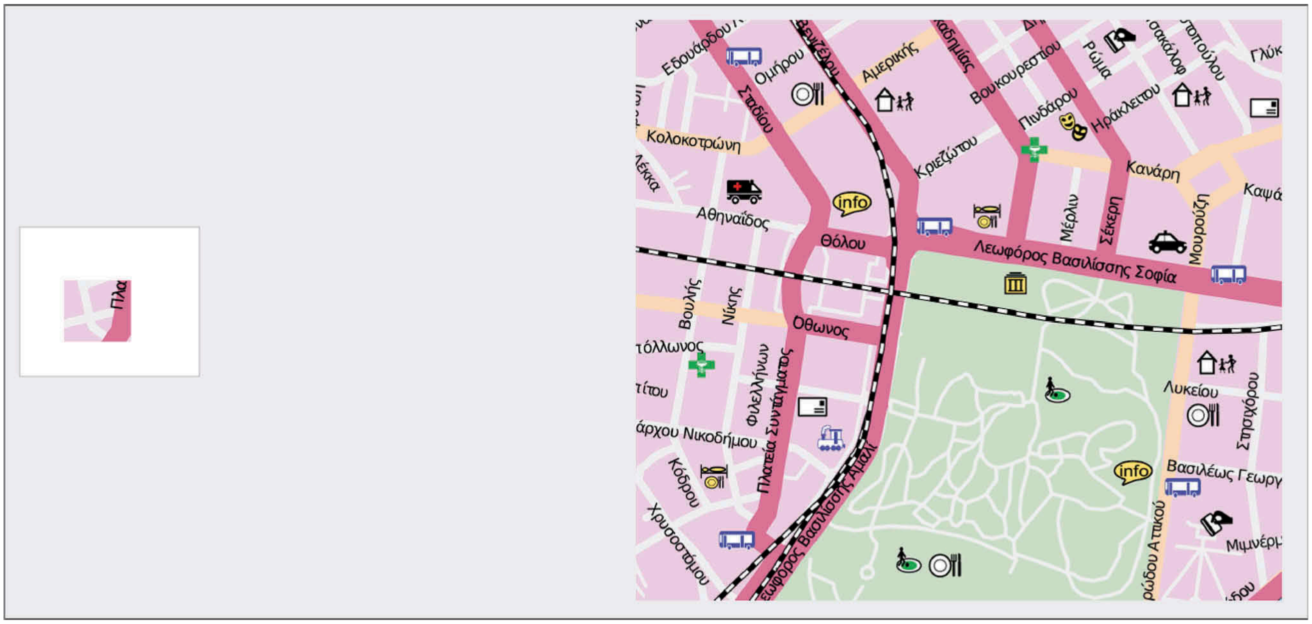

Figure 5. Example of the test stimulus used in map-reading test version B “Locate the background segment shown on the left.” © OpenStreetMap contributors.

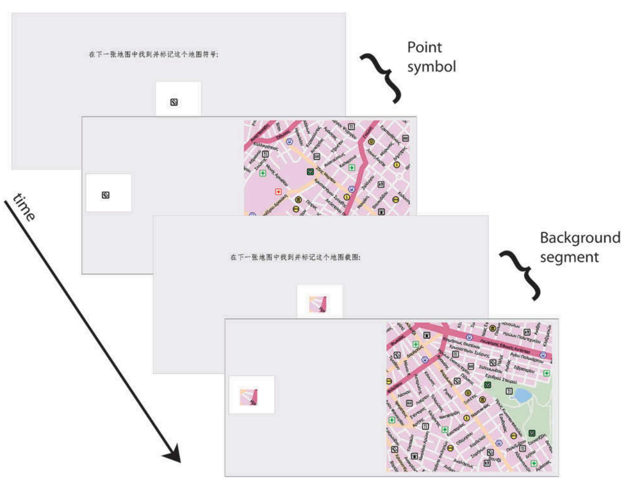

Figure 6. Map stimuli and presentation sequence for the map test version B, with increased figure/ground contrast (Chinese version of the test). © openstreetmap contributors.

finish the entire portion of the experiment due to technical problems with the Hypothesis application. This only happened with Chinese participants, because the required Internet connection at test locations in China was generally unstable. As a result of data pre-processing, we retained response data for 64 Czech and 63 Chinese participants.

Performances were assessed using two mixed, repeated measures ANOVAs, with the cultural background as a between-subject factor, and the figure-background search task as a within-subject factor. Because of the between-subject design of this portion of the experiment, we performed the analysis separately for versions A and B of the map-reading test. The cross-cultural differences were primarily measured by the relative performance in both types of tests. Additionally, we used a 2 × 2 ANOVA to discover potential interactions between culture and the level of visual contrast (symbol versions A vs. B). In all cases, we reported on participants’ efficiency represented by their response times (in seconds).

As expected, both Czech and Chinese participants were faster in localizing figural symbols compared to the localization of the background segments from the maps (see Figure 9). A repeated measures ANOVA analysis of the map-reading test shows significant differences between both groups regarding the figural symbols and background segment tasks ($F(1, 67) = 224.63$, $p < .001$, $\omega_p^2 = .76$ in case of version A and $F(1,54) = 149.58$, $p < .001$, $\omega_p^2 = .73$ in case of version B).

Post hoc tests indicated that Czech respondents working with version A ($M = 3.11$, $SD = 1.81$) were significantly faster when searching for figural symbols than Chinese respondents ($M = 4.23$, $SD = 1.74$), $t(59.61) = -4.75$, $p < .001$, $d = .63$. Also Czech respondents working with version A ($M = 6.59$, $SD = 5.2$) were significantly faster when searching for background segments than Chinese respondents ($M = 9.91$, $SD = 4.98$), $t(70) = -4.79$, $p < .001$, $d = .65$. There were no significant differences in detection speed between the Czechs ($M = 3.86$, $SD = 1.65$) and Chinese ($M = 4.13$, $SD = 1.84$) when having to identify figural symbols in version B, while Czech respondents were

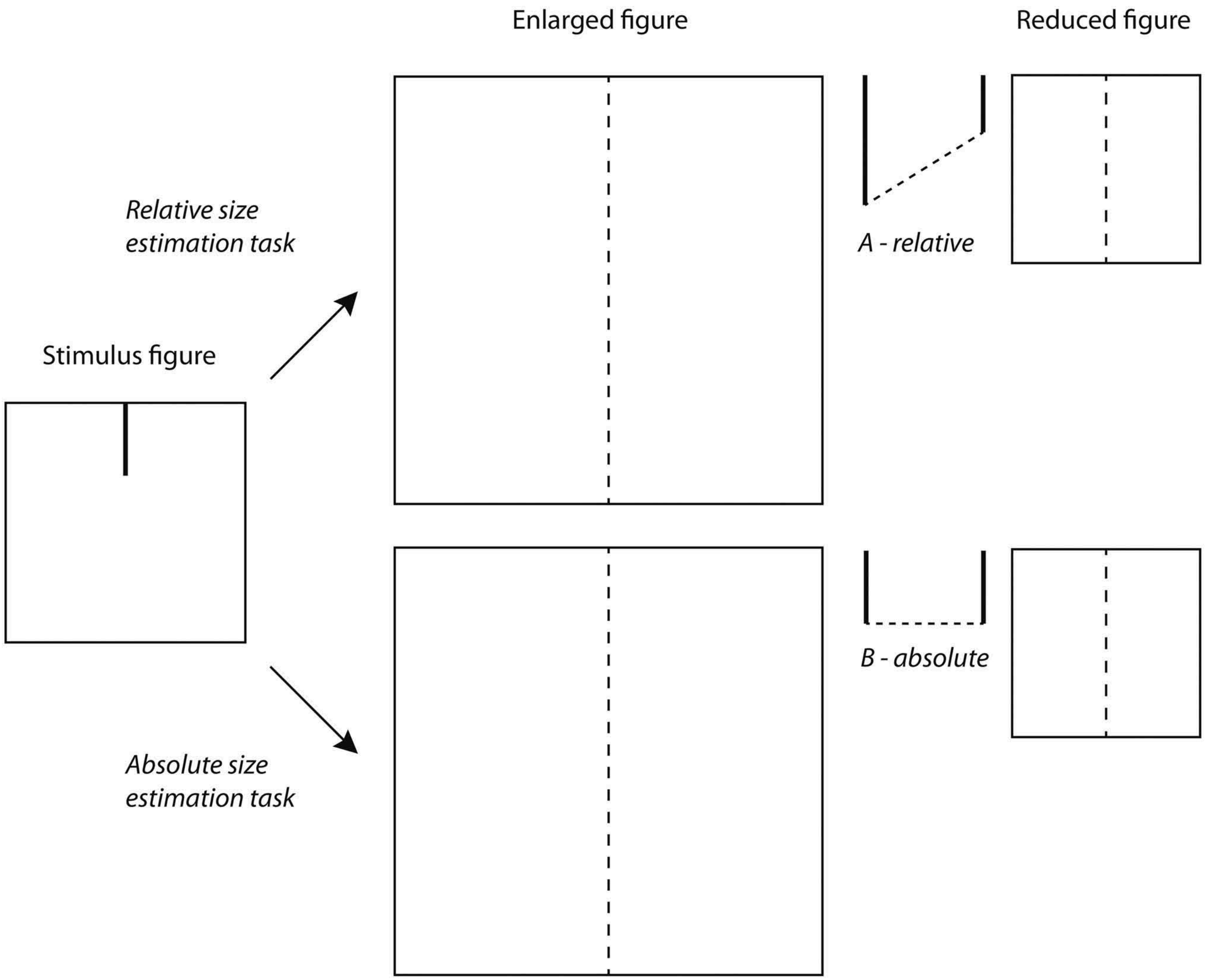

Figure 7. Principle of framed-line test.

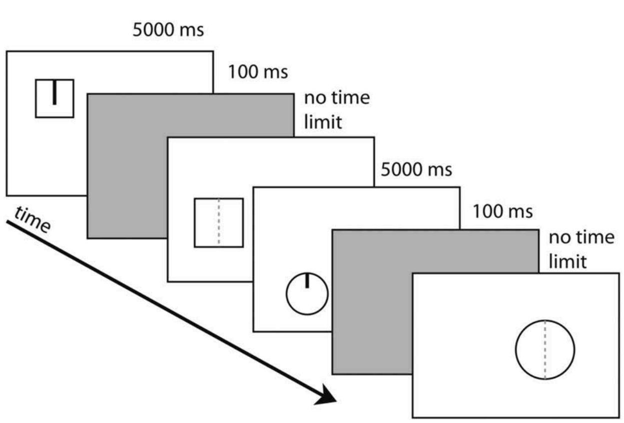

Figure 8. Stimuli and presentation sequence of the framed-line test.

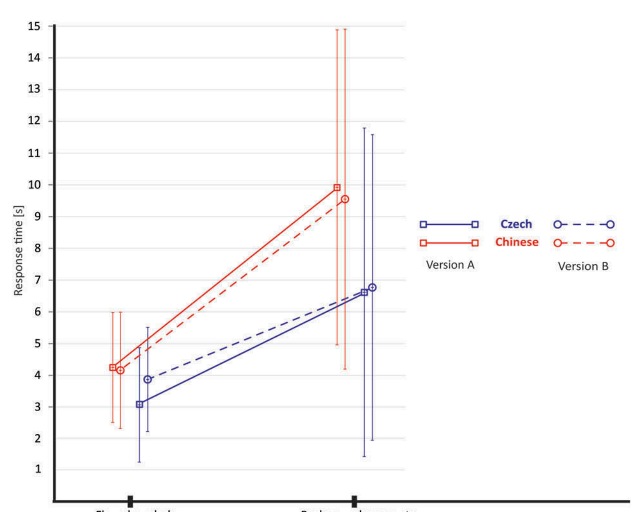

Figure 9. Mean response times with standard deviations (s) for the two cultural groups (Czechs and Chinese), two versions of map-reading test A and B and figural symbols (left) and background segments search (right).

significantly faster identifying background segments (M = 6.72, SD = 4.83) than the Chinese respondents (M = 9.56, SD = 5.38), t(41.37) = −3.88, $p < .001$, d = .56.

To test for potential interaction effects across participants' cultural backgrounds and the level of visual contrast (symbol versions A vs. B), the means were submitted to a 2 □ 2 ANOVA with two between-subject variables (culture of participant: Czech vs. Chinese; version of symbol: A vs. B). We found an interaction effect between culture and version of figural symbol set, F(1, 126) = 6.06, $p < .05$, $\omega_p^2 = .04$. *Post hoc* tests indicate that Czech participants perform significantly faster in localization of the figure in version A (M = 3.11, SD = 1.81) compared to version B (M = 3.86, SD = 1.65), F(1, 63) = 1.66, $p < .01$, d = .43. There were no significant differences in the speed of localization of figures between either version of the figural symbol sets in the case of the Chinese respondents.

Now we turn our attention to the results of the FLT to further investigate potential effects of cultural background on holistic and analytic cognitive style differences.

FLT

We analyzed the length of the response lines drawn by participants in comparison to the correct line lengths. Prior work suggests overall high accuracy rates for the FLT (Kitayama et al., 2003). We counted all responses that diverted horizontally from the dashed line as incorrect responses. We counted the number of incorrect responses of each participant and excluded participants with more than 20% of incorrect responses (i.e. 3 of 16 responses), suggesting that these participants either did not understand or did not follow the given test instructions, or there were other reasons for high error rates, unrelated to the actual tested concept. We also performed an outlier analysis (Hoaglin & Iglewitz, 1987; Hoaglin, Iglewitz, & Tukey, 1986), as a further adjustment of Tukey's (1977) outlier labeling method. The outlier analysis was conducted using the average absolute deviations of lines drawn by the participants from the correct lengths of lines (same absolute length in the absolute task/same proportion to the frame in the relative task). After these two data preprocessing procedures, 10 respondents were eliminated from further analysis and the overall response error rate dropped to approx. 4.5% on average.

This left us with response data from 106 respondents (i.e. 52 Czech and 54 Chinese) in total. We subjected these data to a mixed repeated measures ANOVA with one between-subjects factor (cultural background: Czech and Chinese), and one within-subjects factor (task: absolute vs. relative length judgements).

Figure 10 shows the response mean absolute line length errors of the FLT. As predicted, we can immediately see differences in response accuracy across cultural background. Surprisingly, however, the pattern of differences does not seem to be the same as prior work suggested (Duffy et al., 2009; Kitayama et al., 2003). In aforementioned studies, Asian participants performed consistently and more accurately in judging the line length in the relative task condition. Contrary to these studies and to our expectations, Asians in our study judged line lengths more accurately in the absolute task condition compared to the relative task condition. Czech participants show no clear advantage in the performance, in either the absolute or the relative task condition.

As predicted, the interaction between cultural background of the participants and the perceptual line drawing task is significant, F(1, 104) = 14.65, $p < .0001$, $\omega_p^2 =$ 0,11. However, the effect size is small. *Post hoc* tests reveal that Chinese participants are significantly more accurate in judging absolute length than Czech participants (Chinese: M = 11.88, SD = 4.49; Czech: M = 15.46, SD = 6.71, t(88.61) = 3.21, $p < .01$, d = .63). Conversely, Czech participants seem to be more accurate in the relative task trials (Czech: M = 15.71, SD = 4.33; Chinese: M = 17.15, SD = 3.64). However, these differences are not significant (t(104) = −1.86, $p = .066$).

Moreover, contrary to the results of previous research, the Chinese are also significantly (t(53) = – 7.90, $p < .001$, d = 1.29) more accurate with their absolute length task (M = 11.88, SD = 4.49) compared to their relative task (M = 17.15, SD = 3.64). Accuracy does not significantly differ (t(51) = – .22, $p = .83$) for the Czech participants, for any of their tasks (Absolute task: M = 15.46, SD = 6.71; Relative task: M = 15.71, SD = 4.33).

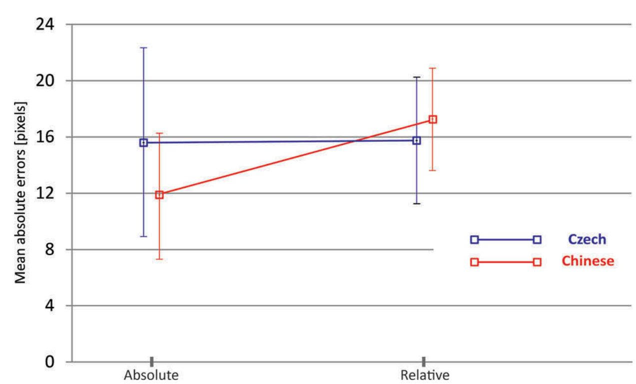

Figure 10. Mean error scores with standard deviations (in pixels) in the absolute and relative task of framed-line test.

Discussion

The goal of this study was to investigate whether holistic and analytic perception described by Nisbett and Masuda (2003) or Kitayama and Cohen (2010) would be relevant to the context of map reading. We set out to reveal possible cross-cultural differences in the map-reading processes of Czech and Chinese map users, explained by a cognitive style assessment using the FLT. In the first part of the article, we introduced the relevant psychological research on cross-cultural differences in visual perception and cognition. In the second part, we discussed the role of culture in the visual search of figural symbols and background segments of the map. In the third part, we discussed the results of the FLT, and we related these to participants' performance in the map-reading portion of the experiment.

First, we found that both Czech and Chinese participants are able to locate figural symbols faster in a reference map, than geometric configurations (background segments) on the same reference map. Overall, this is a gratifying result, meaning that thematically relevant information can be rendered as perceptually salient (Fabrikant, Rebich-Hespaña, & Hegarty, 2010; Garlandini & Fabrikant, 2009; Hegarty, Canham, & Fabrikant, 2010), and this information can be detected rapidly across various cultural backgrounds. The results are also in consonance with the Gestalt principles of perceptual organization (for a comprehensive review, see Wagemans et al., 2012).

As hypothesized, we were also able to detect cross-cultural differences in our map-reading study. Surprisingly, however, our findings are opposite to what prior research outside of cartography had suggested. The theory of holistic and analytic perception proposed by Varnum, Grossman, Kitayama, and Nisbett (2010) claims that Western cultures perceive visuo-spatial information more analytically, and less holistically, than Eastern cultures. Hence, we would have predicted that Czech participants would be able to locate figural symbols more rapidly than the Chinese, and that Chinese participants would be able to locate the background segments relatively faster. Contrary to our expectations, Czechs are significantly faster compared to Chinese participants in the localization of background segments, irrespective of figural symbol design. Furthermore, there are significant differences between the groups in localization of the figural symbols in version A of our map test. No significant differences were found between the groups in the speed of localization of the figural symbols in version B.

Perhaps, some of our contradictory results in the map-reading portion of the experiment can simply be explained by the equally unexpected results we obtained in the FLT. Our FLT results contradict the suggested theoretical model as well (Varnum et al., 2010). Our Chinese participants defied our expectations and the model predictions by being more accurate with the absolute task compared to the Czechs. Conversely, the Czechs were more accurate in the relative task compared to the Chinese. This in essence means that Czech participants show a more holistic cognitive style than our Chinese participants, whereas our tested Chinese participants display a more analytic cognitive style than Czechs. Moreover, a more predictable pattern emerges when systematically comparing FLT and map-reading results. Chinese participants, who show relatively stronger tendencies to analytical visual processing (higher precision in absolute than in relative task in FLT), also show relatively higher differences in the speed of figural symbols localization compared to the speed of background segments' localization and vice versa.

These surprising results could be explained in several ways. Changes of socio-cultural factors can influence the formation of a cognitive style which, in turn, can result in the change of a cognitive style and its manifestations (Matsumoto, Kudoh, & Takeuchi, 1996). Our Chinese participant sample (i.e. young university students) might already show recent cultural factor changes in China. This might be facilitated by increasing access to information disseminated through the various Western digital media channels (i.e. Web, social media, etc.), and increased exposure to hardware, software, learning materials, and digital methods produced by Western tech companies, fostering particular cognitive styles.

Results of several priming studies show that a cognitive style is sensitive to priming manipulations (Ishii, 2013; Nisbett & Miyamoto, 2005; Oyserman & Lee, 2008). We aimed to eliminate possible priming effects using a tight control of the experimental conditions. More research with other control factors related to the participant sample, for example, different age and socioeconomic groups of respondents or longitudinal studies, is needed to systematically identify possible shifts in cognitive style. Furthermore, the theory of "cognitive flexibility" (e.g. Shin & Kim, 2015; Yeatts & Strag, 2014) says that different people differ in the ability to adaptively change their cognitive strategies. This concept stresses the flexibility and adjustability of cognitive processes by human, and thus supports the assumption that changing sociocultural factors may relatively fast modified cognitive style of whole groups.

Perhaps, this result is due to the relatively low overall diversity of tested participants. Irrespective of nationality differences, all tested (Czech and Chinese) participants were in their twenties, living in large urban areas, and studying at a university. We tried to use samples as similar in the key background characteristics as possible in order to avoid sample bias, as described by van de Vijver (van de Vijver & Poortinga, 2005). The field of study was one difference between samples that might have caused the observed differences between the groups. Czech participants were students in various fields without a geographic background. Chinese participants, however, were mainly students with a background in GIS, and also from related fields including Land Resource Management or Urban–Rural Planning. It could be expected that the experience of Chinese students with GIS and maps should have resulted in a slightly superior performance in both cartographic tasks. However, the results did not reflect this tendency at all.

The secondary goal of our study was to identify which type of figural symbol set might lead to greater efficiency in visual search tasks for participants with different cultural background. Symbol sets were designed in order to specifically provide a performance advantage based on the preferred (holistic or analytic) cognitive style. That is, figural symbol set A was designed with relatively more variation in shape and color across individual symbols, while figural symbol set B was designed as more uniform in shape and color, using identical symbol outlines, and with greater visual contrast to the reference map in the background. Consequently, figural symbol set B as a whole would more easily act as a (Gestalt) figure, and hypothetically provide a cognitive advantage for European participants. Contrary to our expectations, Czech participants performed better with figural symbol set A. This might be explained by the relatively more complex set of internal parts of chosen symbols for figural symbol set B. These are crucial for the differentiation between symbols (aside from the shape of the symbol outlines). Although the entire structure of symbols in symbol set B is more distinctive from the background due to the added symbol outlines, and thus its apprehension should be easier (see Stachoň et al., 2013), difficulties with discriminability slowed Czech participants down when working with figural symbol set B. Another explanation offers Lloyd (1997) who found that targets with unique features pop out of the map and search efficiency is independent of number of distractors. In a follow-up study, one could redesign symbol set B to be more distinct from symbol set A by further abstracting the interior shapes of the symbols. One could also further increase figure–ground contrast with the background by reducing the color range of symbol set B.

On the other hand, Chinese participants show relatively better results in the case of figural symbol set B, but the differences were not significant. Perhaps, this could be explained by the different writing systems of Europeans and Asians. Europeans use the Latin alphabet where a particular sign carries no meaning, even though shape differences can be detected. Chinese characters, in contrast, are logograms with mostly visually complex structure, where a single character can have various meanings. Therefore, Chinese participants are perhaps more familiar with studying visual details and parts of a particular figural symbol. This could influence the detection speed in figural symbol set B, where the internal symbol structure is more similar to the structure of Chinese characters.

Conclusions and outlook

The aim of our study was to investigate whether holistic and analytic cognitive styles would be relevant in the context of map reading, and whether map users of different cultural backgrounds (i.e. Westerners and Asians) might differ in their map-reading style. The results of our experiment offer strong evidence that cultural background can indeed influence the map-reading style of map users, which can take shape in figure–ground searching efficiency. However, our findings are in contrast to what the theory of holistic and analytic cognition (Nisbett & Masuda, 2003) would suggest, which describes Westerners as more analytical and East Asians as more holistic. Furthermore, we discovered that the cartographic design of figural symbol sets influences visual search efficiency on reference maps, and this again could be mediated by the varying cultural background of the map users. Our results show that figural symbols with relatively bigger variance in shape are significantly more suitable for the Czech participants compared to the relatively more uniform symbols (symbols with outlines). Conversely, Chinese participants are relatively faster when performing visual search tasks with more uniform figural symbols (i.e. having the same black outline).

Our results underline the importance of varying the cartographic design solutions for map readers with different cultural background. Differences may appear not only in the shape and color of figural symbols but also in the size of the symbol, their anchor point, etc.

Future research should not only be extended geographically (using respondents from other countries) but also thematically, for example, by comparing respondents living in settlements of various densities and sizes (see Stachoň et al., 2013), respondents of various socioeconomic status (see Grossmann & Varnum, 2011), or respondents from different age groups (see Duffy et al., 2009; Waxman et al., 2016).

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

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), 23-43.

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.

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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-

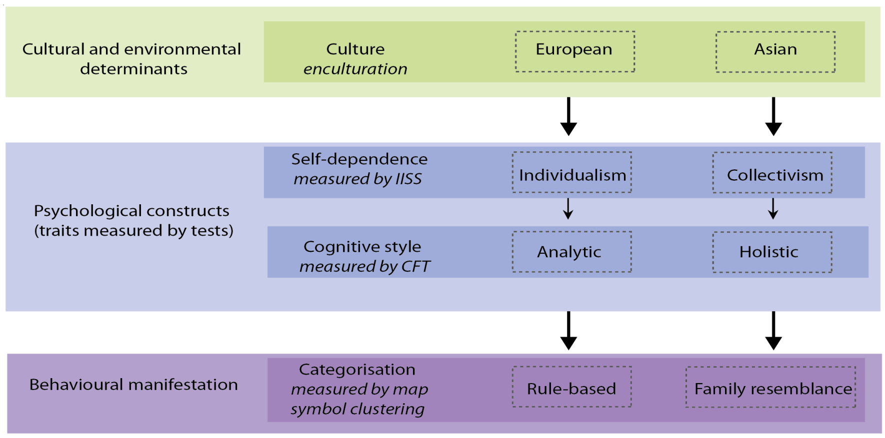

Figure 1 Research model

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).

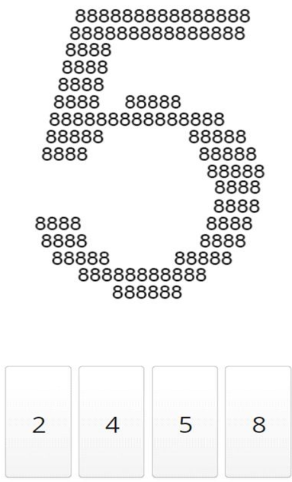

Figure 2 Example of the Navon figure used in the CFT

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.

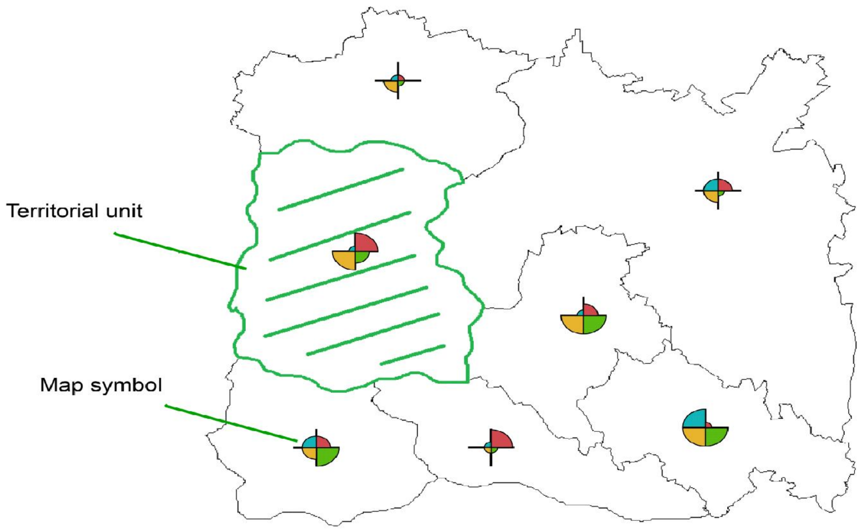

Figure 3 Territorial unit and map symbol in CMMS

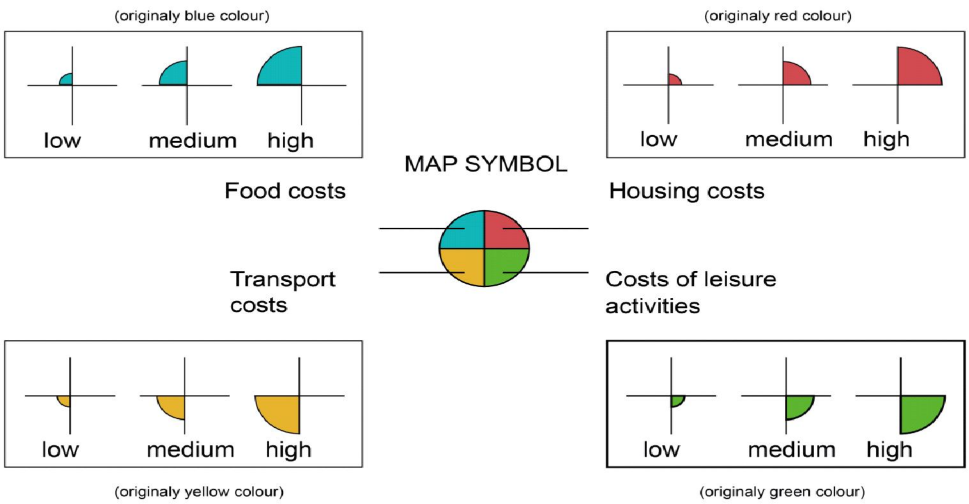

Figure 4 Multivariate map symbol (descriptions were in Czech and traditional/simplified Chinese languages)

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

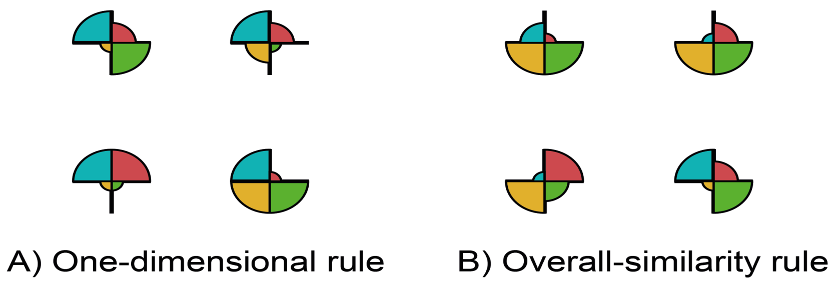

Figure 5 Example of the used analytic A) – left, and holistic B) – right, categorization rules

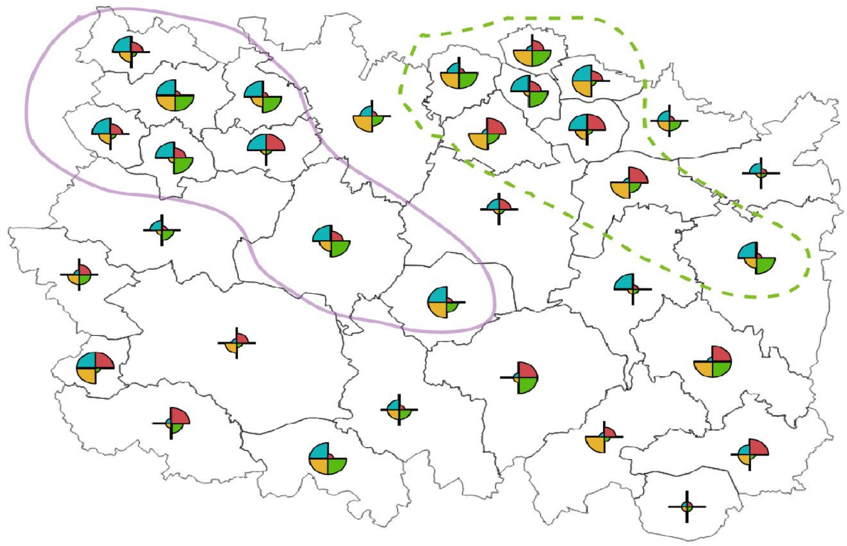

Figure 6 Example of constructed analytic (left solid line) and holistic (right dashed line) map regions

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

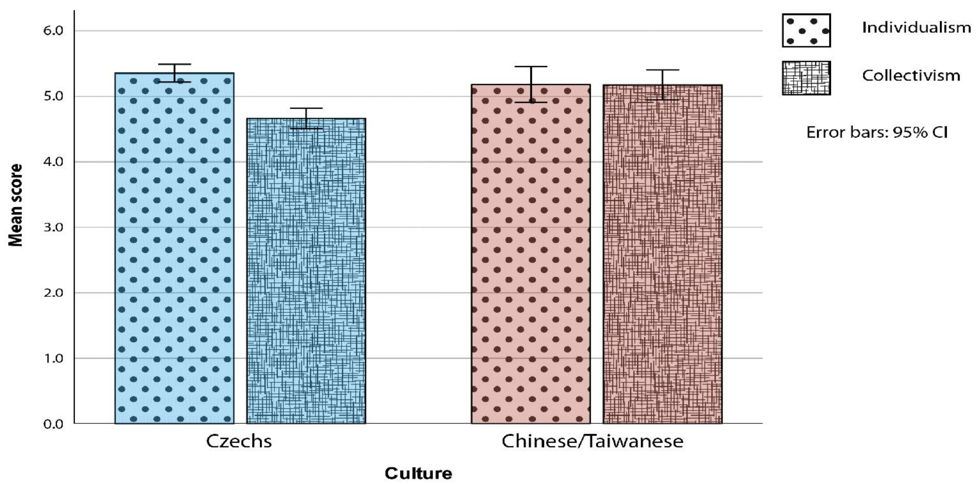

Figure 7 IISS – mean scores

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, η^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,

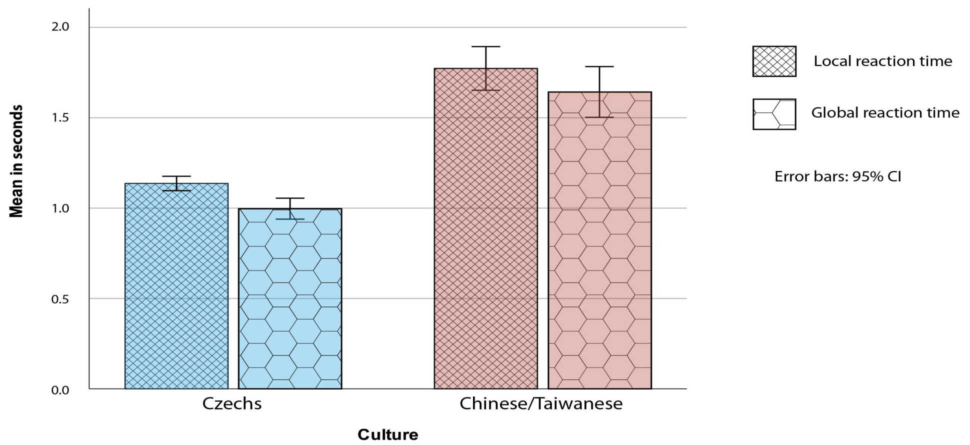

Figure 8 CFT – mean reaction times

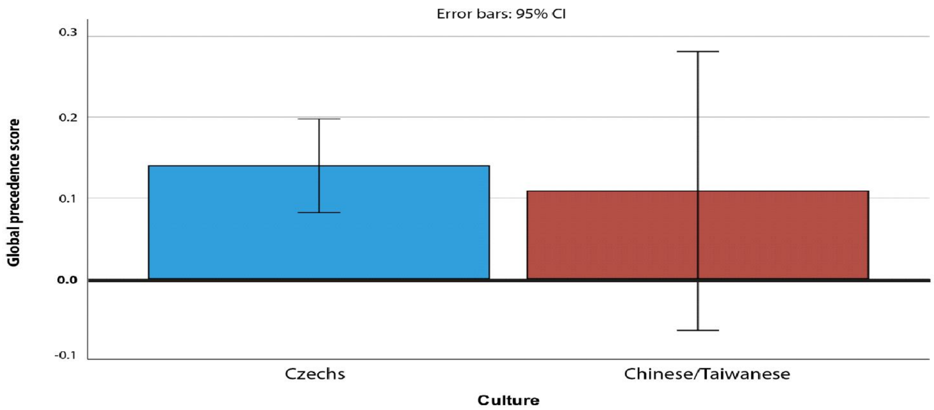

Figure 9 CFT – Mean global precedence scores (higher values mean higher global precedence)

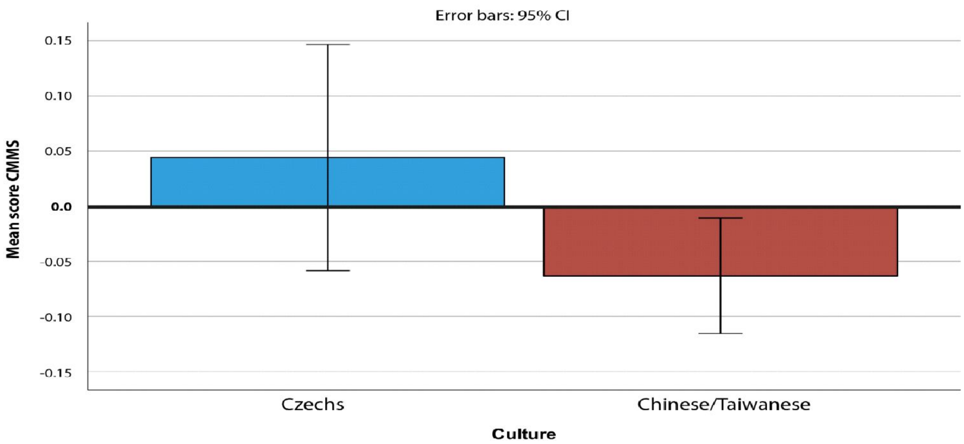

Figure 10 CMMS – Cross-cultural differences in map categorization (High value = analytic, low value = holistic).

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

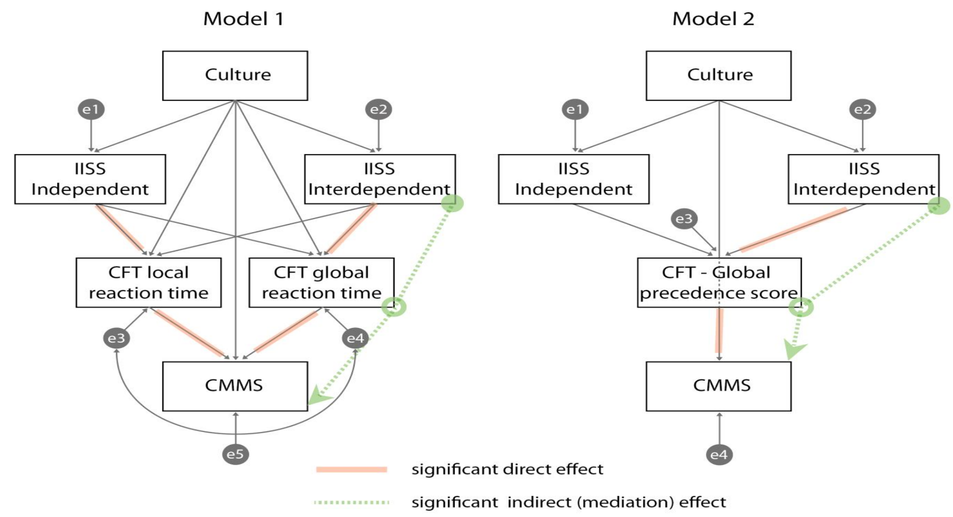

Figure 11 Path analysis models – Model 1 (left), Model 2 (right)

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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5 Research Methods, Procedures and Tools for the Study of Visualizations

In the research of visualizations, it is necessary to take into account the specific nature of a given topic with respect to the research procedures employed. Visualizations cannot be understood as simple graphic stimuli and examined in isolation at the level of visual perception. Visualizations are always carriers of meaning and automatically engage higher cognitive processes and functions. If this key aspect is not reflected in the research design and inadequate procedures are used, the researcher obtains results that only account for the influence of the graphic properties of the visualization. But the fundamental quality of visualization, which is the ability to carry and communicate information, is completely neglected. An example could be research on cartographic symbols using a simple "visual search paradigm". If the participant is not familiar with the logic of the legend and searches for cartographic symbols without any knowledge of the context, then the performance is only indicative of the graphical quality of the symbols and does not take into consideration the semantic level. To investigate the cognitive processing of visualizations, it was necessary to design suitable methodological procedures and corresponding research tools.

A key moment for effective research when working with 2D visualizations was the development of the original software. The paper called "The Hypothesis Platform: An Online Tool for Experimental Research into Working with Maps and Behavior in Electronic Environments", presents a tool that was designed from the outset to enable working with complex visualizations. It allows for the creation and administration of a whole range of tasks, from simple "visual search" or "memory recognition" tasks to more complex and interactive tasks. It is possible, for example, to draw lines or polygons (See 4.4) or to work with interactive maps (WMS). The platform makes it possible to create research batteries containing different types of tasks and items. From questionnaires, to static or interactive visualizations, to performative psychological tests that are used to determine the level of cognitive functions or to identify personality traits (See 3.1, 3.2, 4.1, 4.3, 4.4).

The article "EyeTribe Tracker Data Accuracy Evaluation and Its Interconnection with Hypothesis Software for Cartographic Purposes", describes, among other things, the interconnection of the Hypothesis platform and an eye-tracker, and describes a procedure combining a mass online data collection using the Hypothesis tool, and simultaneous small-scale individual data collection using an eye-tracking system. The research procedure was later further elaborated and referred to as "extensive-intensive research design" (see 3.1).

Besides the unique Hypothesis platform, a number of tests have been developed and standardized for research purposes. In the article "ImGo: A Novel Tool for

Behavioral Impulsivity Assessment Based on Go/NoGo Tasks", the ImGo test for measuring impulsivity levels is presented, which was evaluated specifically for cross-cultural research purposes. Other tests for measuring the analytic-holistic cognitive style were developed on the Hypothesis platform and evaluated, among others, for the purpose of research on cross-cultural variations when working with visualizations; these are described in Lacko et al. (2021, A Preregistered Validation Study of Methods Measuring Analytic and Holistic Cognitive Styles: What do We Actually Measure and How Well?).

The focus of the visualization research has been proceeding from 2D visualizations, through PSEUDO and REAL 3D, to fully immersive virtual environments. This area also required new research methods and tools to be developed. The article Ugwitz et al. (2019), Spatial Analysis of Navigation in Virtual Geographic Environments, outlines the possibilities of using eye-tracking and motion analysis in research on individual differences or cognitive style. The topic was subsequently further elaborated with emphasis on the utilization and analysis of eye-tracking data in the context of navigation in the paper by Ugwitz et al. (2021), Eye-Tracking in Interactive Virtual Environments: Implementation and Evaluation). In the paper "Toggle Toolkit: A Tool for Conducting Experiments in Unity Virtual Environments", a tool is presented that enables researchers to create interactive research designs in virtual reality using conditional bindings. Participant's action can trigger different responses from the environment. The tool has been used, among others, in research on building evacuation and with regard to the use of graphical evacuation plans (Snopková et al., 2021).

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

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), 407.

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.

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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

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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.

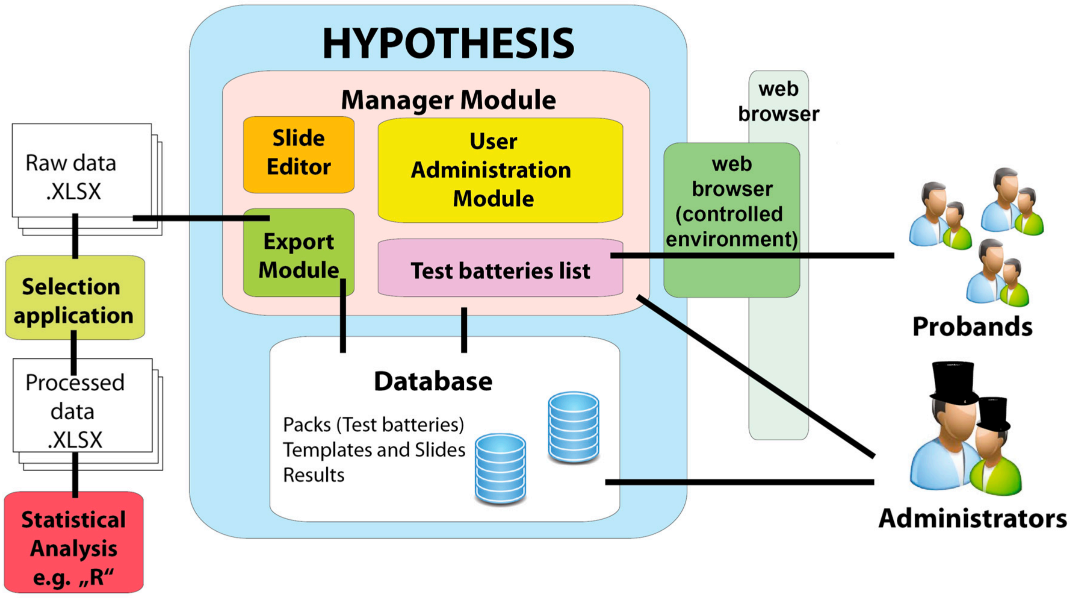


Figure 1. Basic functional components of the Hypothesis platform (modified and extended from Štěrba et al. [42]): The first part, Database (see Section 4); the second part, Module Manager (see Section 2.4) and Export Module (see Section 2.4.4), Administration Account (see Section 2.4.1) with the Pack 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).

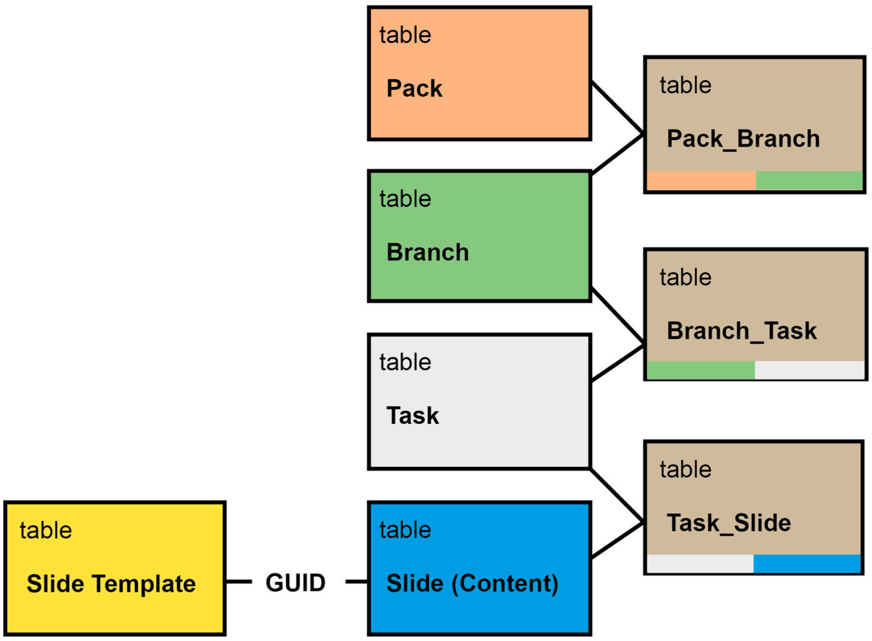


Figure 2. The content of Slide, Task and Branch Tables is associated with a higher level in the hierarchy through the following intermediary tables: Task_Slide, Branch_Task and Pack_Branch.

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.

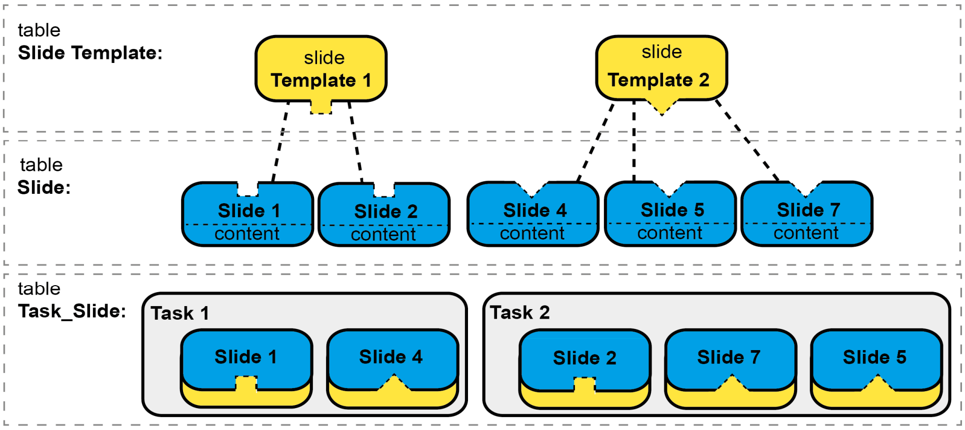


Figure 3. Database tables with hierarchical relations between Slide Templates, Slide Contents and Task slides. The slide template table contains Slide Templates defining the character of Slides. Linking of Slide Templates to Slide Contents is ensured by GUIDs. Typically, several Slide Contents are linked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

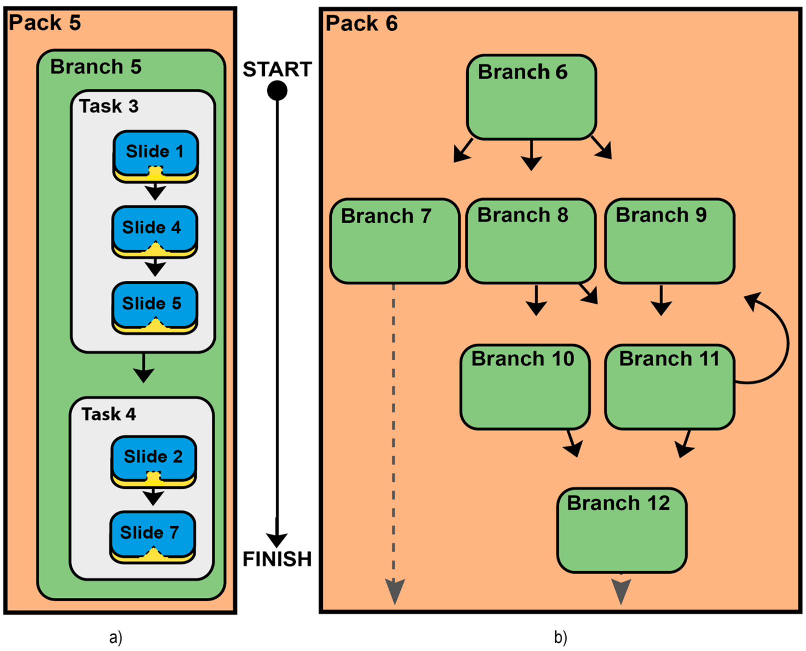


Figure 4. (**a**) Structure of Pack No. 5 with only one branch (5). The branch contains two Sections (Tasks) (3 and 4) with several linearly arranged Slides; (**b**) Pack No. 6 with multiple branches.

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).

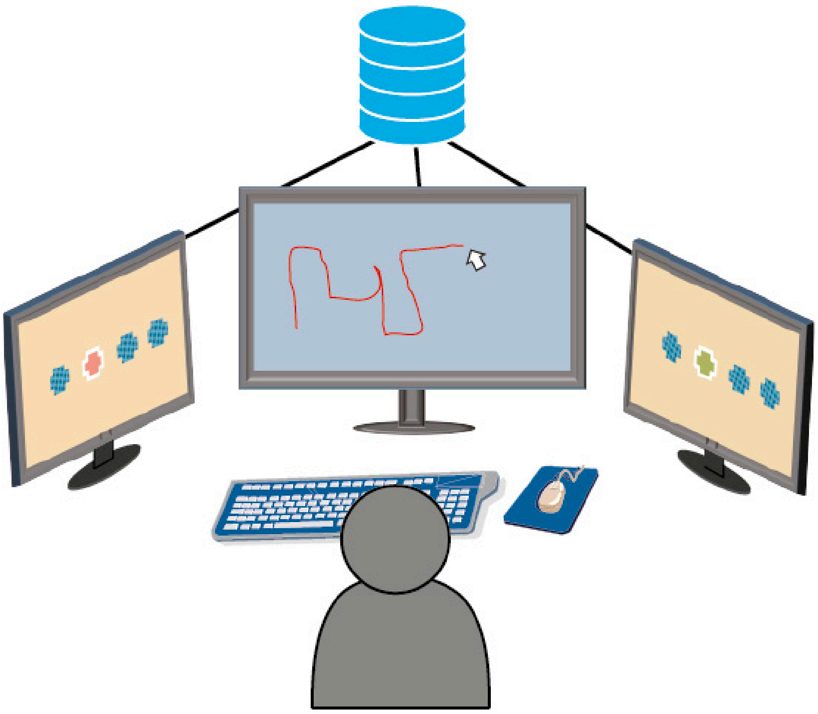


Figure 5. Multi-task mode scheme: while completing a primary task displayed on the central, mouse-operated screen (Master Pack), the participant uses keyboard to react to target stimuli presented on peripheral screens (Slave Packs).

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].

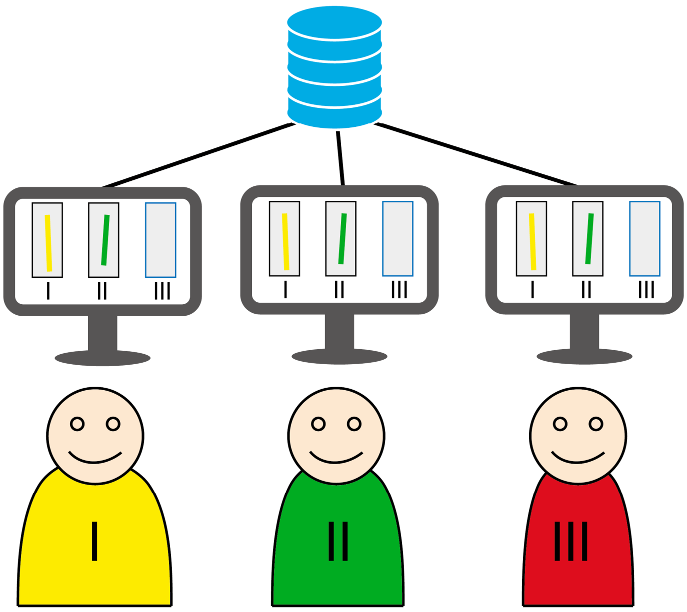


Figure 6. Use of the Multi-player Mode in a computerized adaptation of Asch conformity experiments. First, all three participants were simultaneously shown an identical object; then, they were asked to estimate its size by drawing a corresponding line. The line was then displayed to all the participants.

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.

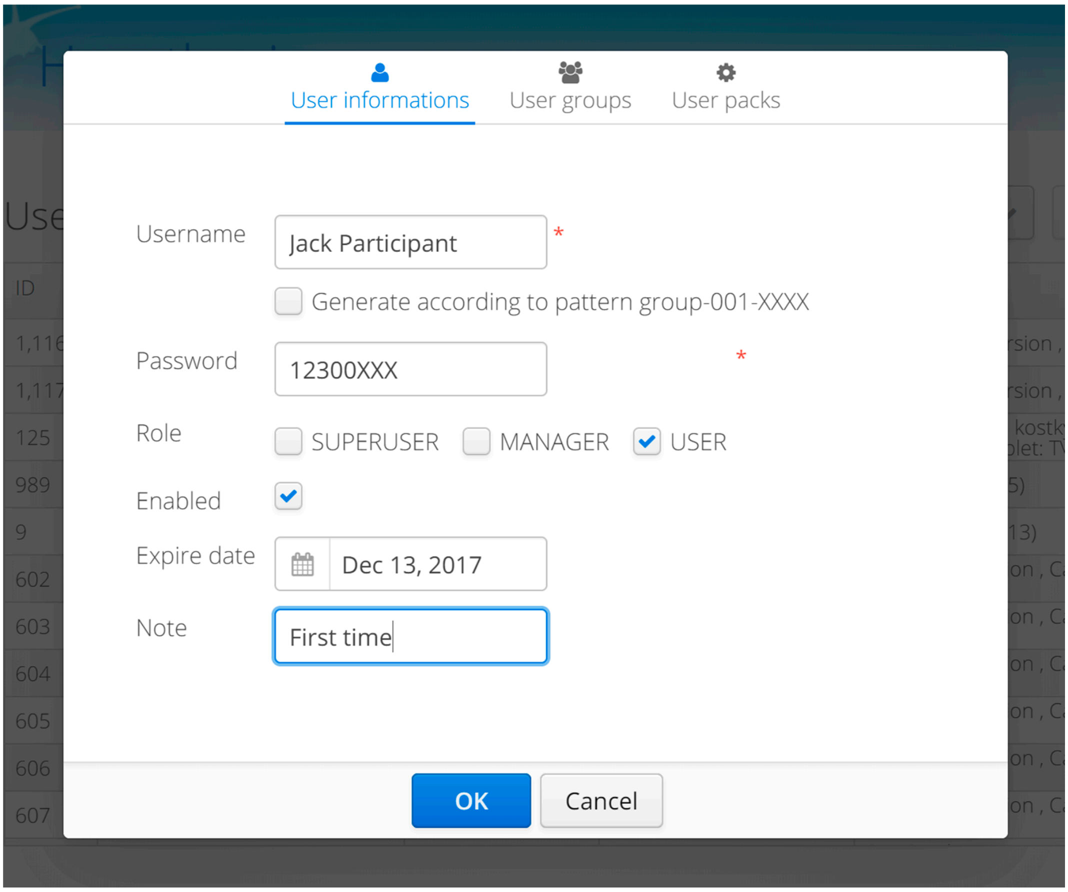


Figure 7. Sample Administrator Account. Editing of a new user account.

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).

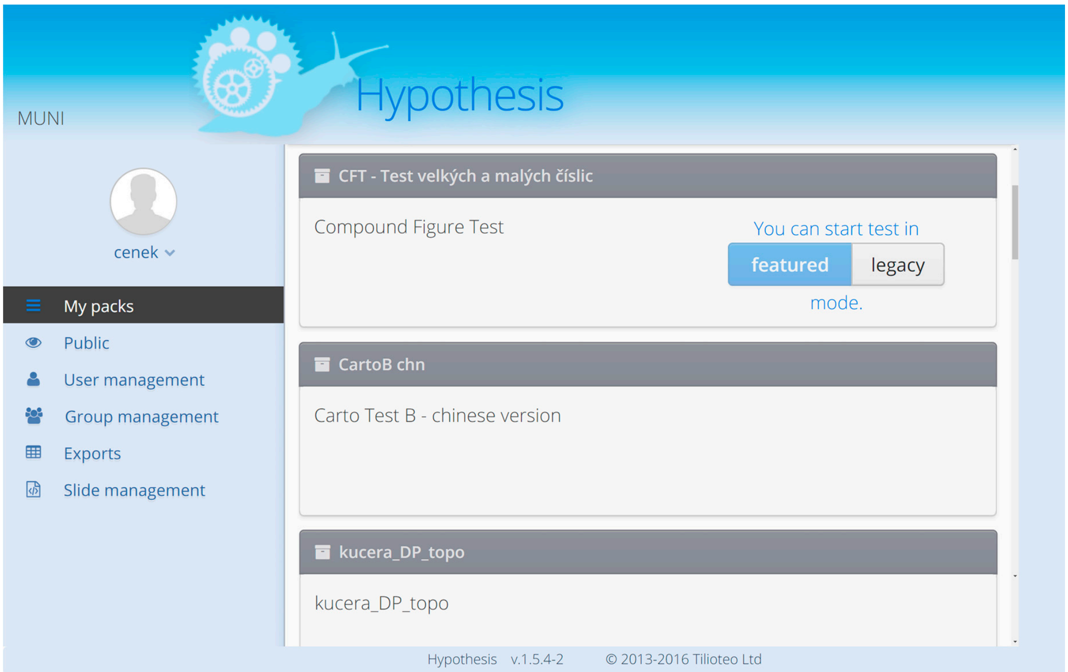


Figure 8. Opening of a Pack in a controlled (featured) or standard (legacy) mode.

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.

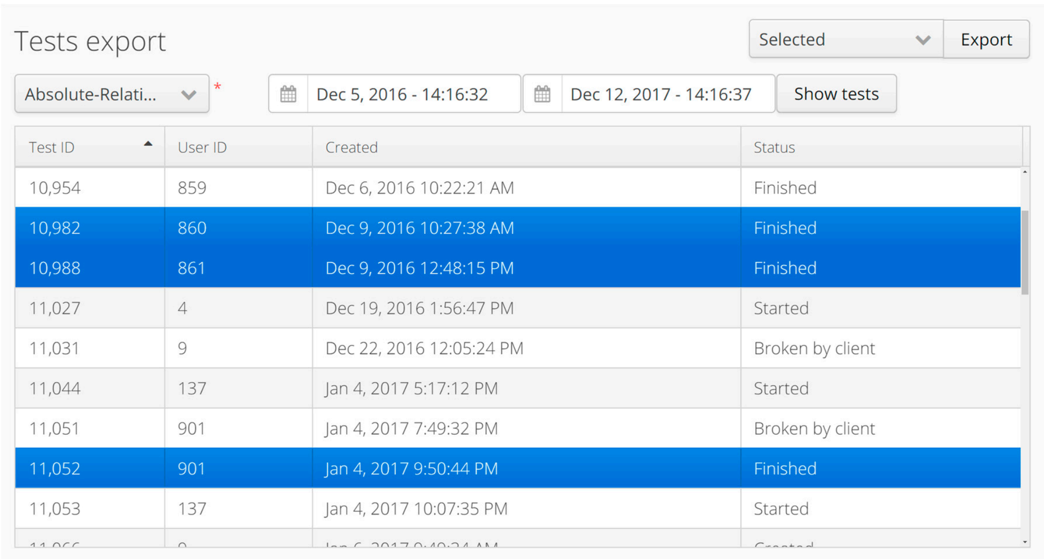


Figure 9. Export Module with finished tests (marked).

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].

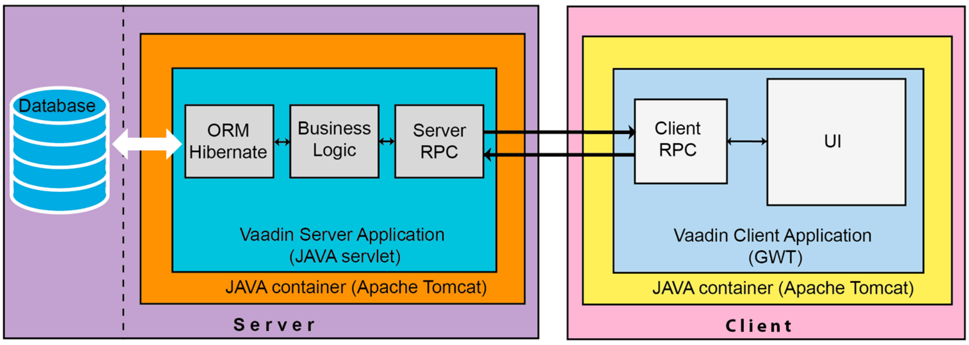


Figure 10. Scheme of the technical structure (adapted from Šašinka et al. [20]).

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).

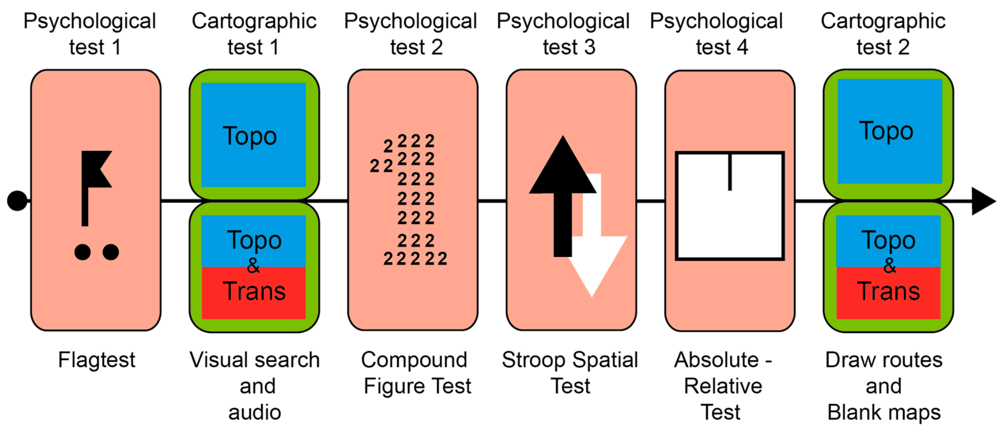
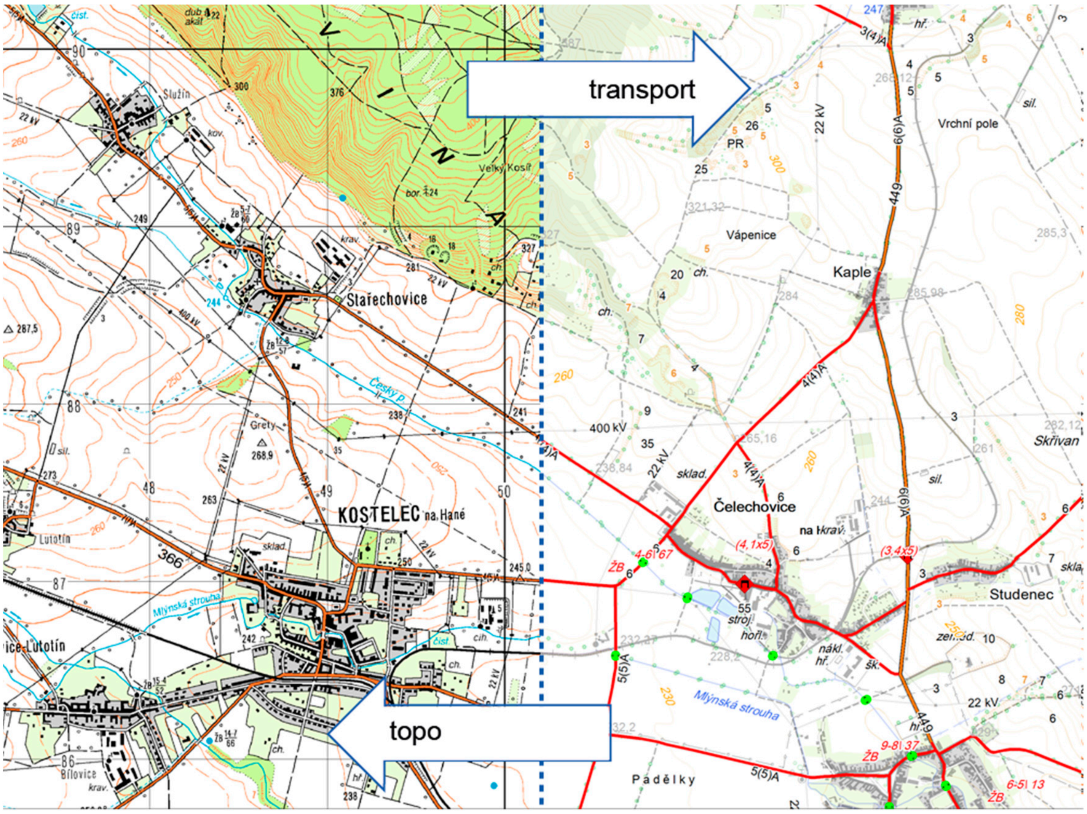


Figure 11. Scheme of the whole experimental design (adapted from Kukaňová [84]).

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).



a) b)

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.

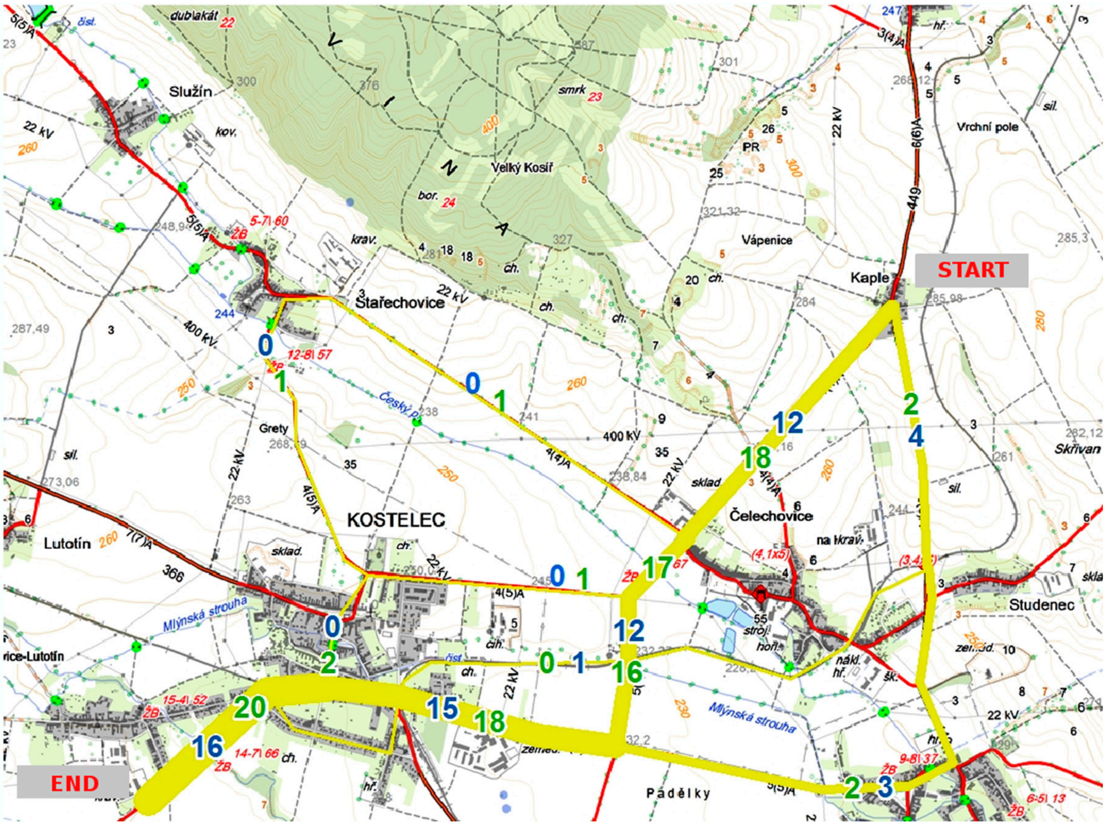


Figure 13. Yellow lines (**thickness**) express frequency of the routes chosen by the experimental group (**green digits**) and control group (**blue digits**) together. Data from both groups are presented at once in the transport map.

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.

Conflicts of Interest: The authors declare no conflict of interest.

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

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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.

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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

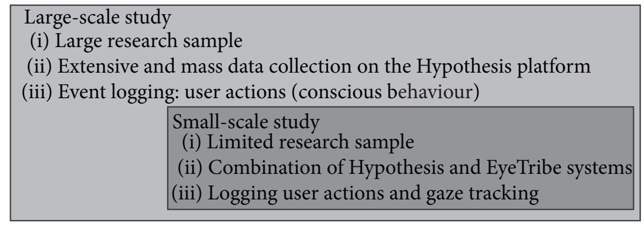


Figure 1: The combination of large-scale and small-scale study.

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

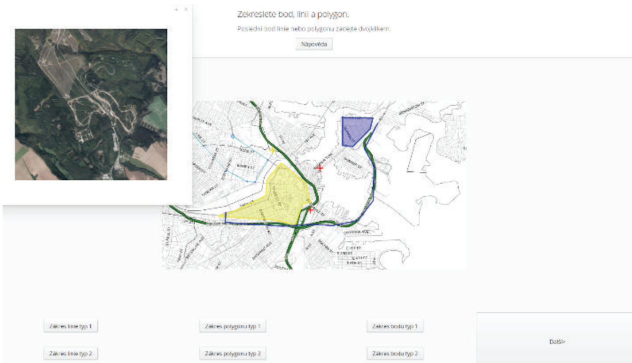


Figure 2: Example task on WMS interactive map. The user indicates the requested objects, draws lines, and marks out target areas by polygons. In the example shown, the user called up an orthophoto map in a dialogue-window. All the actions including the drawn point coordinates, lines, and polygons are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

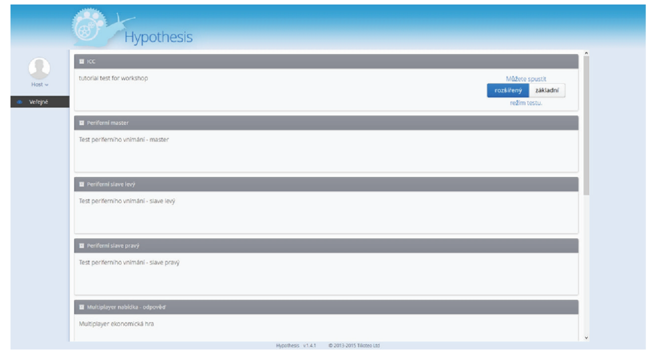


Figure 3: Management module in the Hypothesis platform. The user can launch the available tests in two modes: (a) legacy (launches in a normal browser) and (2) featured (launches in a controlled mode in SWT browser). The manager and the superuser have an extended access and can unlock the tests, create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

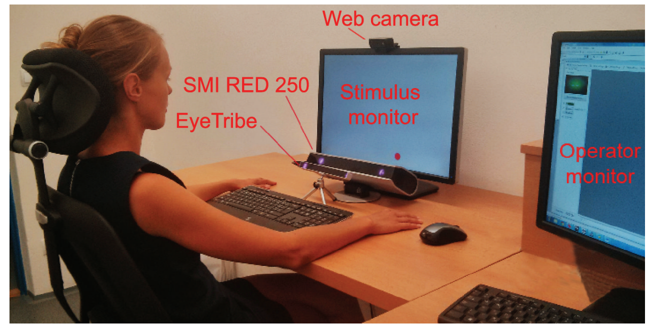


Figure 4: Laboratory setting for EyeTribe and SMI accuracy comparison.

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].

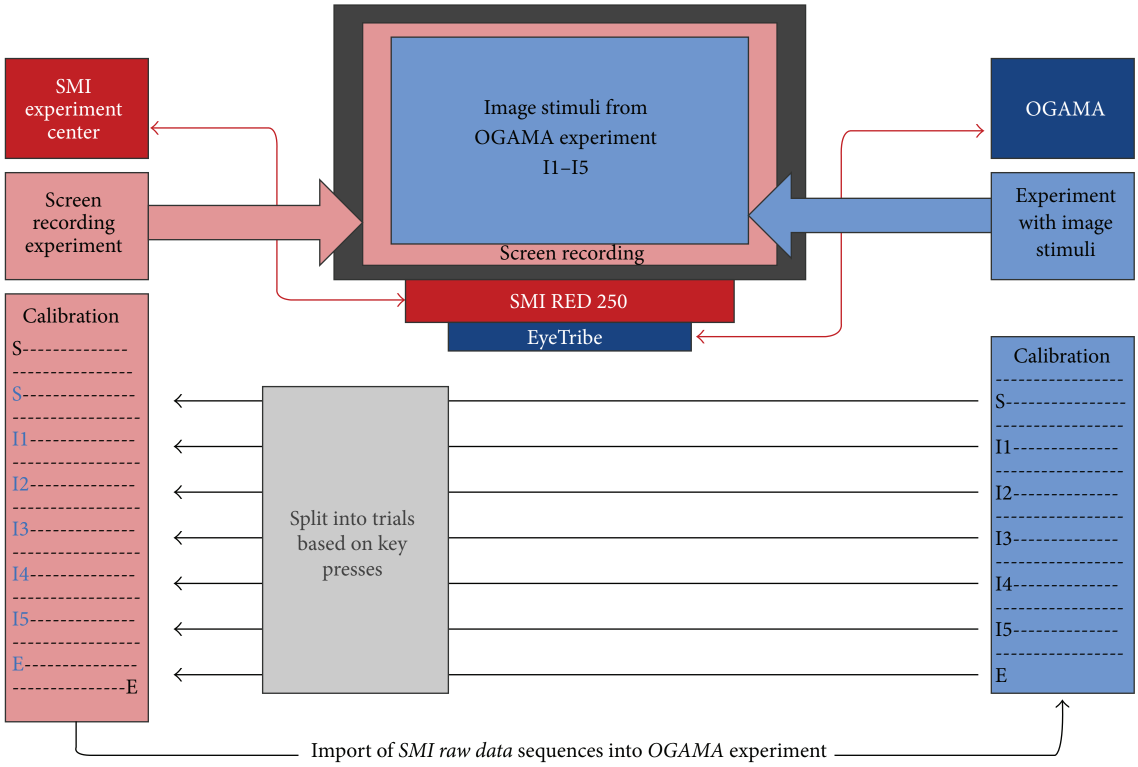
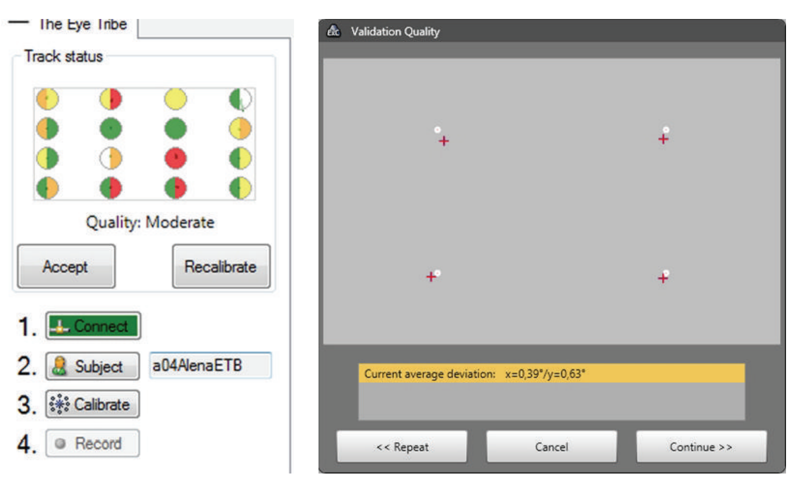


Figure 5: Diagram of concurrent eye-movements recording with SMI RED 250 and EyeTribe.



(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

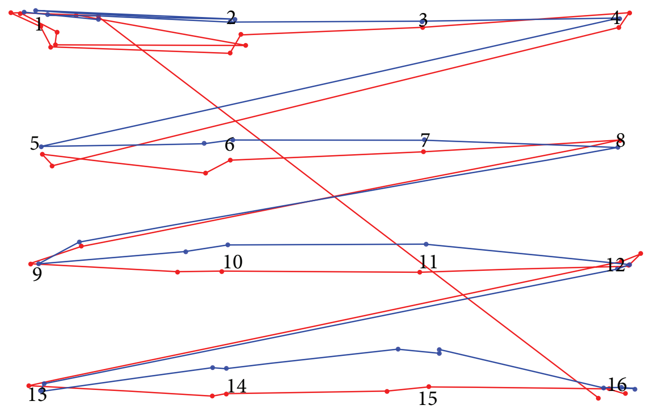


Figure 7: Comparison of recorded eye-movement data from participant P03 in Slide 2 from EyeTribe (blue) and SMI RED (red).

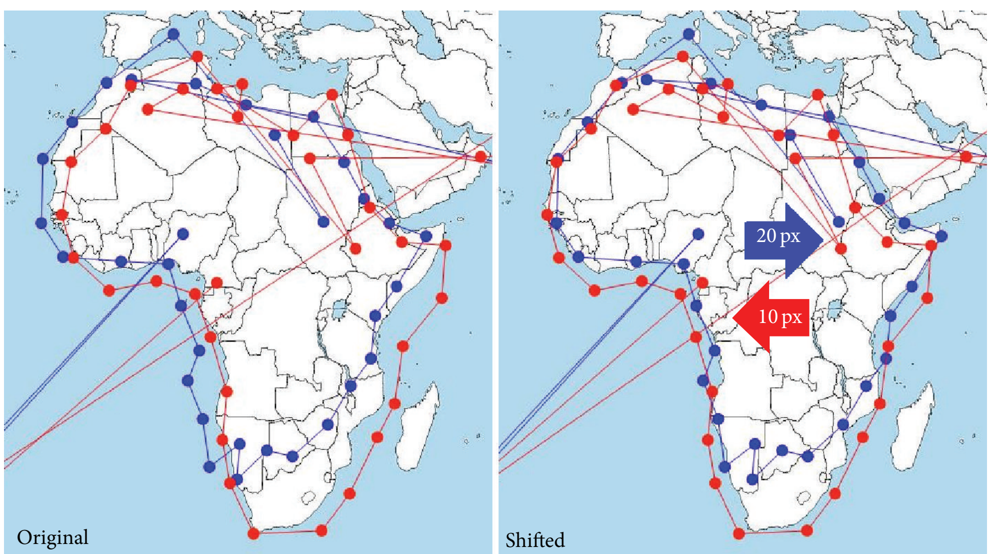


Figure 8: Comparison of recorded eye-movement data from participant P03 in Slide 6 from EyeTribe (blue) and SMI RED (red).

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

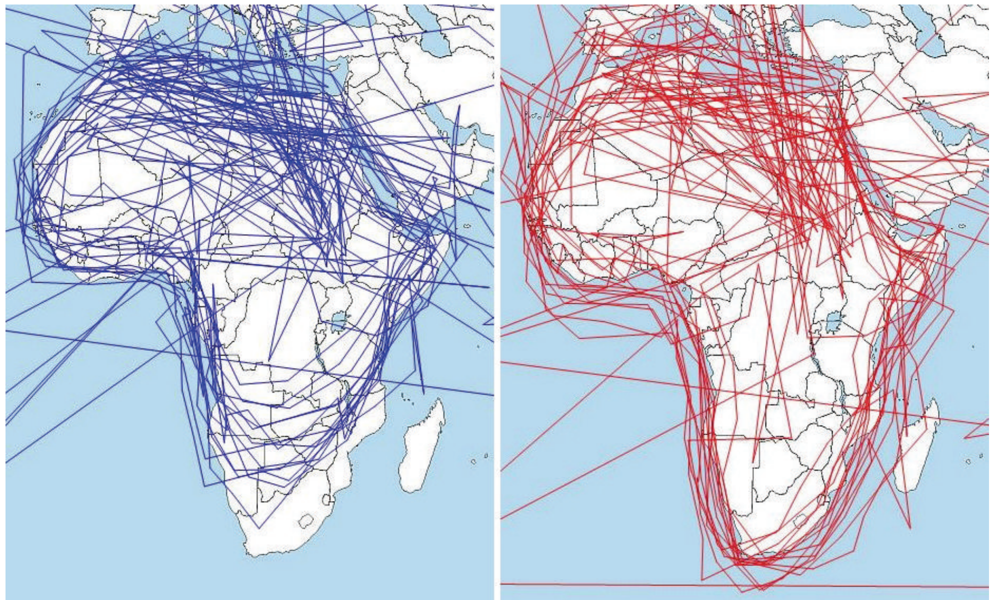


Figure 9: Problems with data recorded by EyeTribe (blue) at the bottom of the stimuli in comparison with SMI data (red).

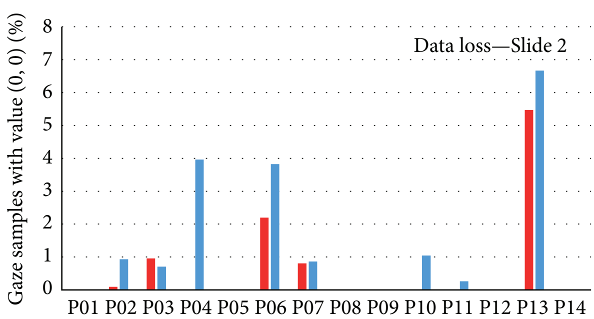


Figure 10: Comparison of data losses of fourteen participants during observation of Slide 2. Red bars represent SMI RED 250; blue ones represent EyeTribe tracker.

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

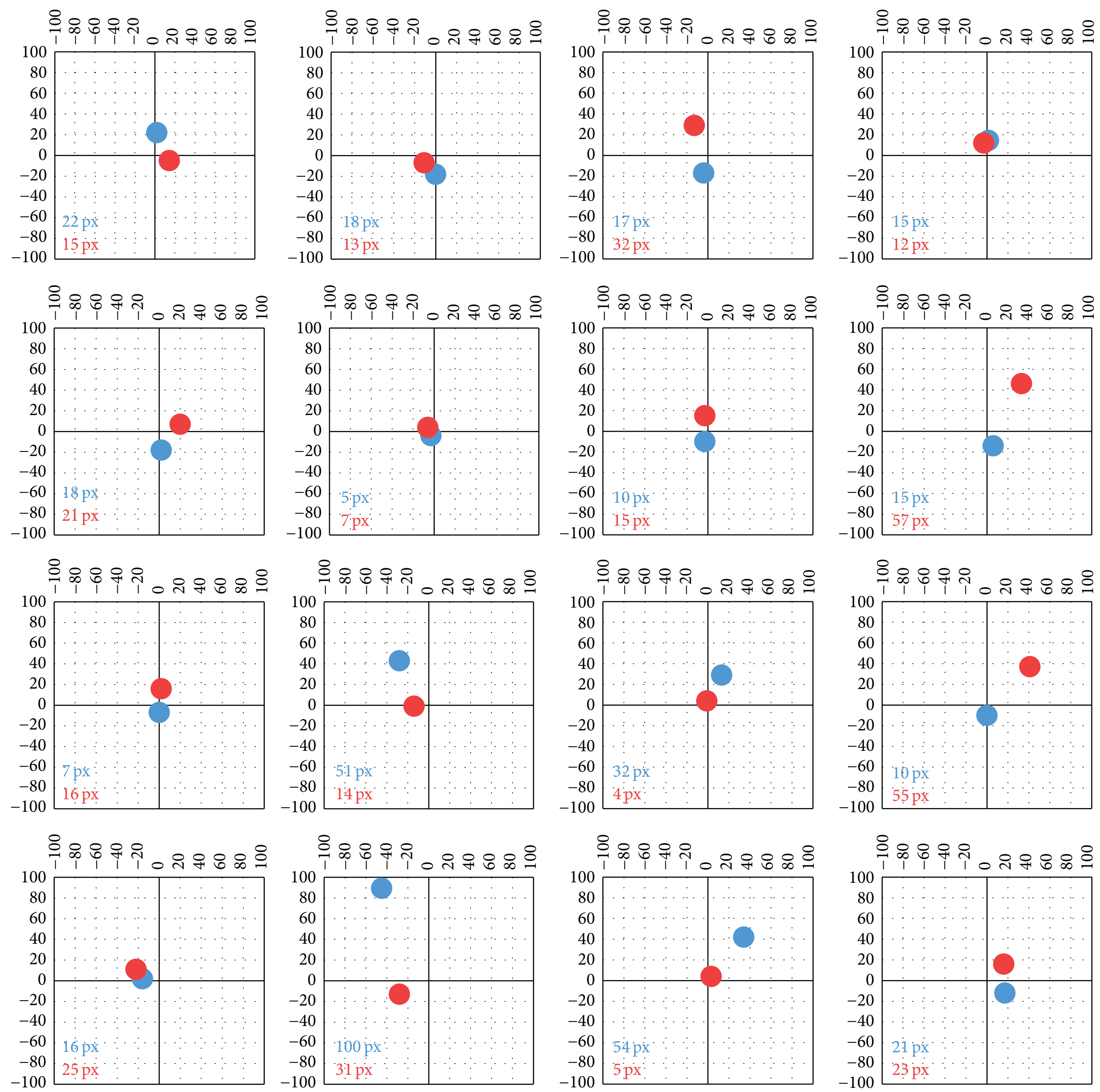


FIGURE 12: Comparison of fixation positions in Slide 2 for fourteen participants. Distance from the center of the image shows fixation deviation in pixels. EyeTribe data are displayed as blue dots; SMI data are displayed as red dots.

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.

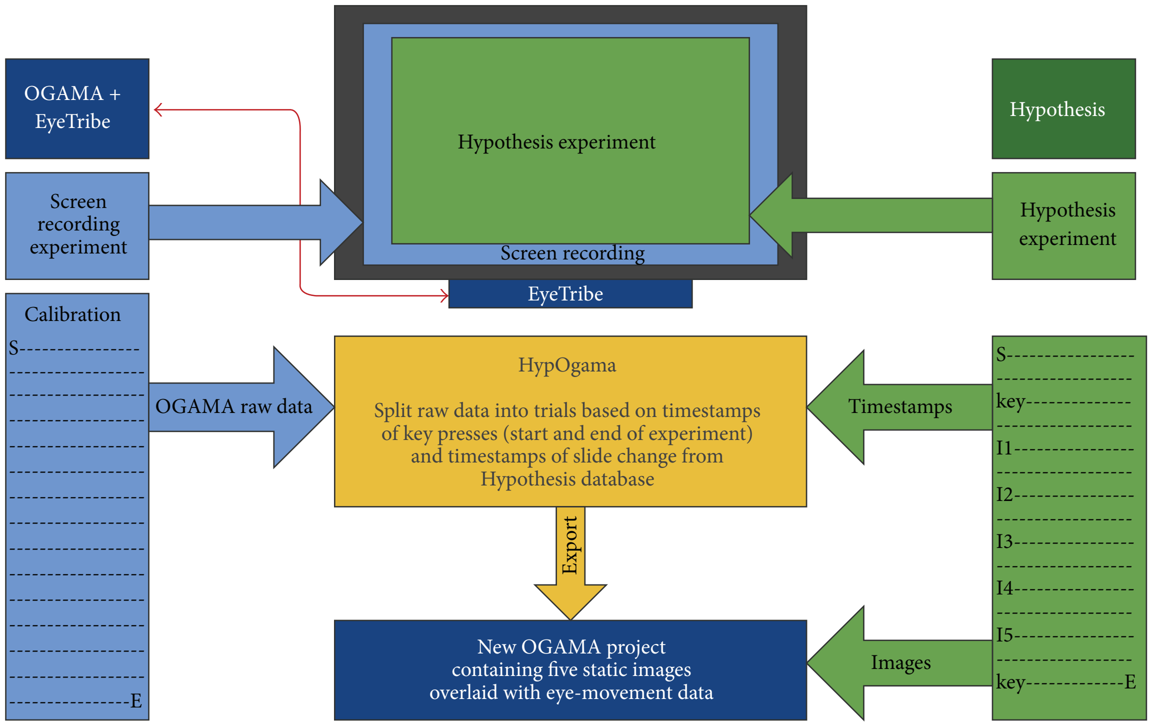


FIGURE 13: Process of splitting recorded data (screen recording) into trials with the use of HypOgama web application.

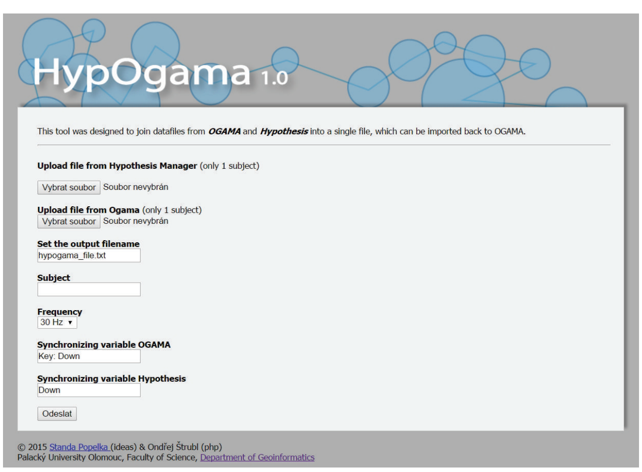


FIGURE 14: Environment of HypOgama web application.

(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,

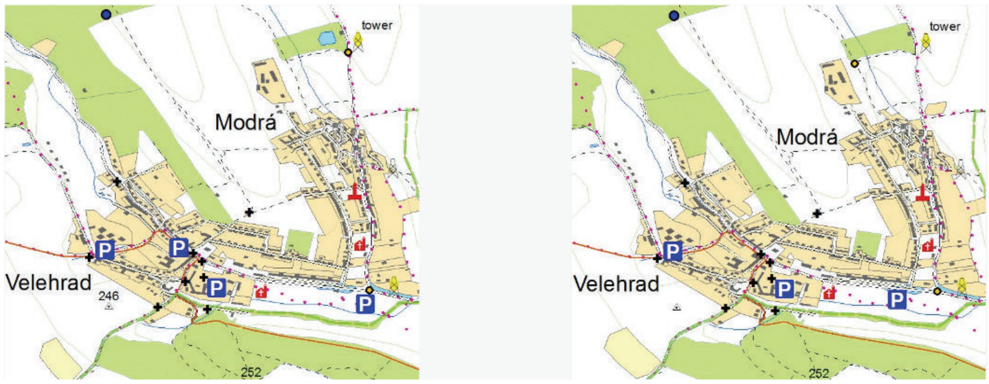


Figure 15: Example of stimuli—the first pair of topographic maps.

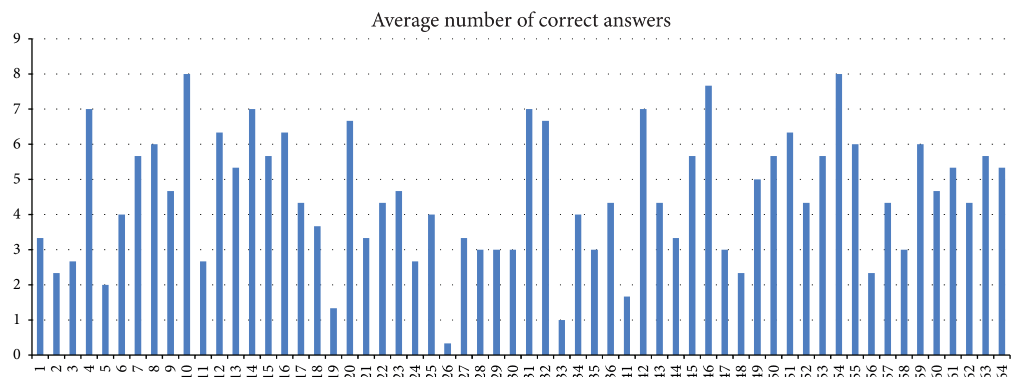


Figure 16: An example of results from Hypothesis. An average number of correct answers for each of the participants.

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

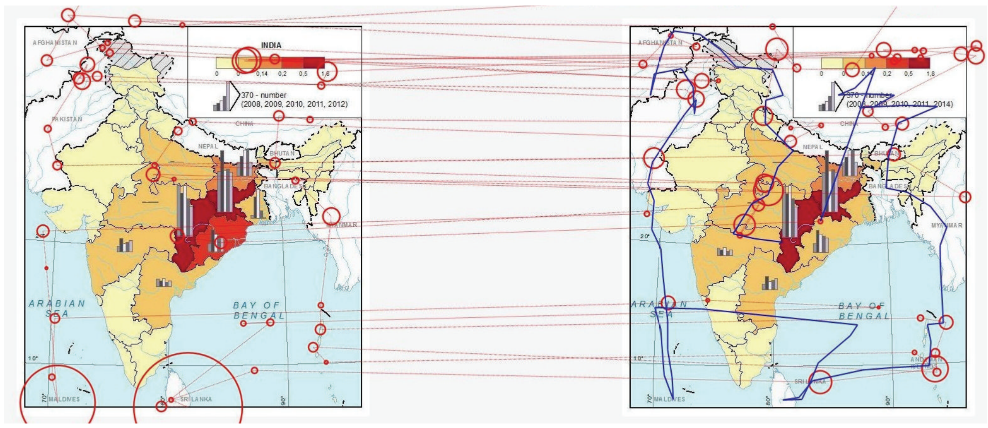


Figure 17: Example of eye-movement data recorded during the Hypothesis experiment. Circles represent fixations; blue line on the right is a mouse trajectory.

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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5.3 ImGo: A Novel Tool for Behavioral Impulsivity Assessment Based on Go/NoGo Tasks

Šašinka, Č., Lacko, D., Čeněk, J., Popelka, S., Ugwitz, P., Řádová, H., Fabianová, M., Šašinková, A., Brančík, J., & Jankovská, M. (2021). ImGo: A Novel Tool for Behavioral Impulsivity Assessment Based on Go/NoGo Tasks. Psychological Reports, 00332941211040431.

Abstract

This manuscript aims to present a novel behavioral impulsivity test ImGo, which is suitable for impulsivity assessment in the general population. A series of three studies was conducted to validate its psychometric qualities. In Study 1 we describe the principles of ImGo and verify its test-retest and split-half reliability and its convergent validity with an impulsivity self-report scale and Stop Signal test. In Study 2 we re-analyze the convergent validity of ImGo with a Stop Signal test and examine the potential relationship between ImGo and oculomotor inhibition measured by an Anti-Saccades test. In Study 3 we present a robust research with a large sample size and investigate the discriminant validity of ImGo with tests of other related cognitive and executive processes. Backed by our findings from these studies we can safely claim ImGo is a powerful tool with a good level of reliability (both test-retest and split-half) and validity (convergent and discriminant). Its potential lies in its use in diagnostic and research practice of experts from various countries as the test has already been translated to 9 languages so far. The open-source Hypothesis platform, on which the ImGo test is running, provides the option of both individual and group testing in laboratory conditions as well as remotely through an internet browser.

The text of the article is not included in the thesis for licensing reasons.

5.4 Toggle Toolkit: A Tool for Conducting Experiments in Unity Virtual Environments

Ugwitz, P., Šašinková, A., Šašinka, Č., Stachoň, Z., & Juřík, V. (2021). Toggle toolkit: A tool for conducting experiments in unity virtual environments. Behavior research methods, 53(4), 1581-1591.

ABSTRACT

This article presents and offers Toggle Toolkit, which is an original collection of Unity scripts designed to control various aspects of interactive 3D experiments. The toolkit enables researchers in different fields to design, conduct and evaluate experiments and include interactive elements in immersive virtual environments. This was achieved by using the internal functionalities of the Unity engine and solutions of our own design. The structure of Toggle Toolkit allows triggers and toggles to be allocated to existing virtual objects and throughout the Unity scene. Once a trigger is executed (with a pre-described action, such as colliding with a virtual object, pressing a key, gazing at an object, etc.), the toggles associated with the trigger are activated and then change the attributes or behaviors of linked objects. All interactive behavior is logged and made available for further statistical analysis. Examples of applications in research are presented and discussed. The Toggle Toolkit's utility lies in its simplicity and modularity. The Toolkit was especially produced for experimenters with few coding skills and high customization requirements in their experiments. The tool is freely available for use in research and can be enhanced with custom scripts. A video tutorial is provided to facilitate use of the tool. The paper aims to not only introduce beginners to experimentation with VR but also offers more experienced researchers who are potentially interested in using and adjusting the features the Toolkit a deeper insight into its structure.

The text of the article is not included in the thesis for licensing reasons.

6 Reflections in the perspective of the Theory of Probabilistic Functionalism

6.1 The Lens Model as an Explanatory Framework

V Previous studies have examined how recipients extract information from various external representations, also taking into account individual (See 3.1, 3.2), as well as cross-cultural variations (See 4.2, 4.3, 4.4). The effect of the form of visualization has been investigated at different levels of cognitive processes. Different studies have been conducted comparing the use of monocular and binocular depth cues in relation to the medium (See 2.2, 3.2), and perceptual studies (See 4.2) in which the effectiveness of visual search was investigated in relation to the size and shape of the symbol with a limited effect of the semantic component. In similarly designed perceptual studies (see 4.3), the semantic component was already integrated. Regarding the complexity of the cognitive processes involved, much more complex are those studies that focus on the interpretation of graphically encoded information, either of a single variable or of multiple variables simultaneously (See 2.1, 3.1). The next level of complexity is represented by tasks in which the process of reasoning plays an important role, and which also involve motor activity (See 3.2, Herman et al., 2021). Finally, at the symbolic top of the hierarchy in terms of complexity of the research topic, is group work with a complex visualization or information system that provides both a wide range of visual cues and opportunities for interaction (See 3.4). At this level of complexity, both perceptual and motor or executive aspects have to be taken into account, and at the same time, everything has to be put into a social context where communication between individuals and goal-oriented collaboration take place. The question arises whether the main research topic, which is the communication of graphically encoded information and its cognitive processing that is influenced by many contexts and that can be studied from the micro level of elementary visual perception to the macro level of information communication between live and artificial systems, can be covered by a single theory. I believe that such a universally applicable theory exists and can be, after partial modification and elaboration, applied to all levels of the addressed issue.

I will try to embed the research topic in its entirety in the Theory of Probabilistic Functionalism of Egon Brunswik and his followers (among others Hammond, Nystedt, Lusk, Stewart, Scholz) and describe the involved cognitive processes and behavior of an individual using the concept of the Lens Model. Brunswik's Lens Model, as part of the Theory of Probabilistic Functionalism (TPF) according to Scholz (2017), enables to explain phenomena at the elementary level of visual perception, as well as at the complex level of teamwork, it has been gradually elaborated by other researchers and therefore there are now different variants of the model (e.g., Hirschmüller et al, 2012, Lusk and Hammond, 1991, Hammond et al., 1966). An important step in its development is Nystedt's model (1972) which emphasizes the existence of an individual's personality structure and the cognitive representation of the external situation based on this structure. Also, Lusk and Hammond (1991) in their hierarchical Lens Model further emphasize the boundary between objectively existing cues and subjectively perceived cues, which are in the system further linked by organisms to second-order cues (Kostroň, 1997), the so-called precursors. Finally, Hammond (Hammond et al., 1966, Dhami and Mumpower, 2018) in his Triple-system Lens Model, extends the theory into the area of interpersonal learning and conflict.

Using the core Theory of Probabilistic Functionalism, the Lens Model, I will try to put the aforementioned studies in a theoretical framework, as well as further adapt the Lens Model and elaborate it with the emphasis on the aspect of cyclical interaction with the environment – through intentional search for complementary information (cues), on communication and collaborative activity between actors. I will also emphasize the aspect of subjective availability of possible actions or means of an individual. In this perspective, the Lens Model integrates, among others, Neisser's perceptual cycle and models of Information Behavior (Godbold, 2006), or Dervin's (2003) "sense-making approach" and Wilson's models (Wilson, 1999 and 2000). Yet, at the same time, it should be emphasized that I do not consider other actors in the model only as a potential information source completing the number of available cues, but rather I think of collaboration as an activity through which original judgments can emerge that go beyond the capabilities of individual actors. The communicated perspective of a phenomenon (a working hypothesis) from one actor to another may trigger the activation of contents and principles in the other actor that he or she did not originally consider when evaluating the phenomenon. By engaging his or her knowledge, the second actor iterates and advances the topic in further communication even for the first actor. There is not only an exchange of information occurring, but above all, the way of thinking about the phenomenon is being developed as part of the dyadic interaction. The universality of the Theory of Probabilistic Functionalism is an essential aspect for its use in the context of the presented research topics. The theory makes it possible to describe the cognitive processes involved in decoding graphic symbols, and at the same time, at the level of higher cognitive processes, it describes reasoning about complex phenomena, also with regard to individual or cross-cultural variations, including in the context of group work. Although Brunswik (1952) himself used the Lens Model as a metaphor or didactic aid, I argue that for instance at the level of deliberative processes and decision-making, the Lens Model (or modified versions of it) can be used as a well-rounded explanatory framework that has the capacity to predict the phenomena under investigation (Kaufmann et al., 2013).

One of the cornerstones and the mechanisms of the Lens Model is the distinction between the environmental cues available to the individual, and the distal phenomenon (criterion) to which the individual draws inferences (see Fig. 1). A distal phenomenon is for example an estimate of the height of a person, and a cue then the size of the object projected onto the retina. The size of the image on the retina is naturally not a sufficient cue to determine the actual height of the observed person, and other cues must be included in the judgment, such as estimating the distance from the observer based on the available depth cues. Different cues refer to a distal criterion to different degrees (ecological validity) and are utilized by the individual to different degrees (utilization validity).

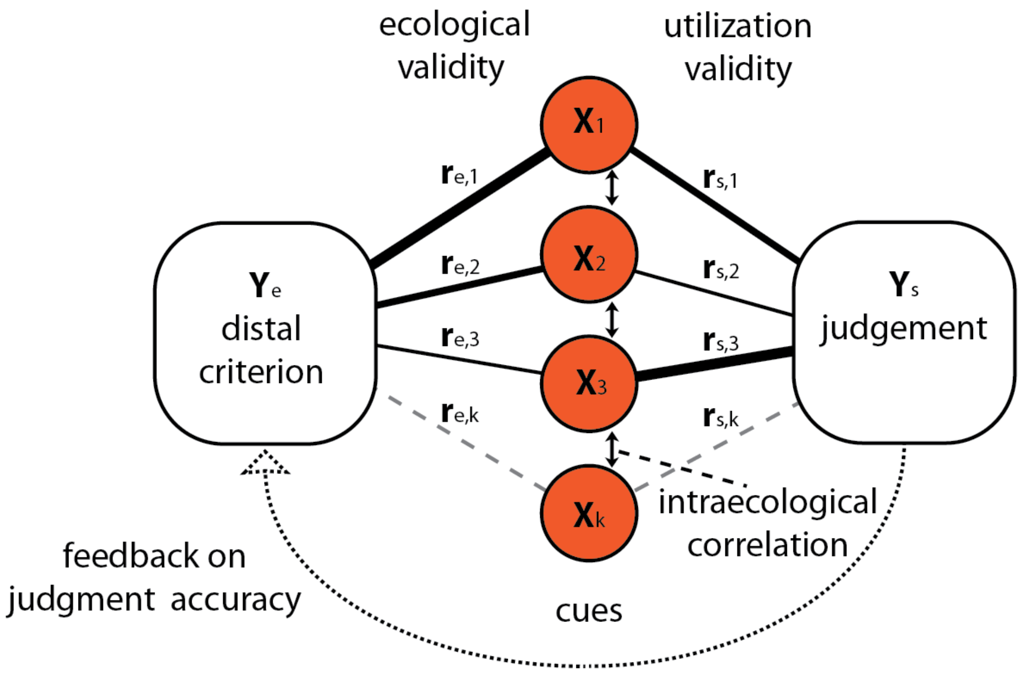

Fig. 1: The classic Brunswik's Lens Model (Adapted from Cooksey, 1996); Coockey called it a double-system design.

The judgment about the distal criterion may be final or may be a working assumption that needs to be refined. An example of a final judgment might be the physician's determination of a diagnosis based on symptoms, followed by the selection of available means of treatment (see Fig 2). By analogy to the perceptual phase, available means vary in the degree to which they are actually related to the considered phenomenon or goal. For example, the means validity of the use of antibiotics is low if it is intended to be a means to treat a viral infection. A distal goal in the case of a non-final working judgment about a possible bacterial infection could be to try to obtain additional cues to refine the diagnosis. The means would be then, for example, the use of a CRP (C-Reactive Protein) test. The subsequent process of perception, planning and behavior is elaborated with respect to the extension of the Lens Model by, e.g., Hoffrage (2018).

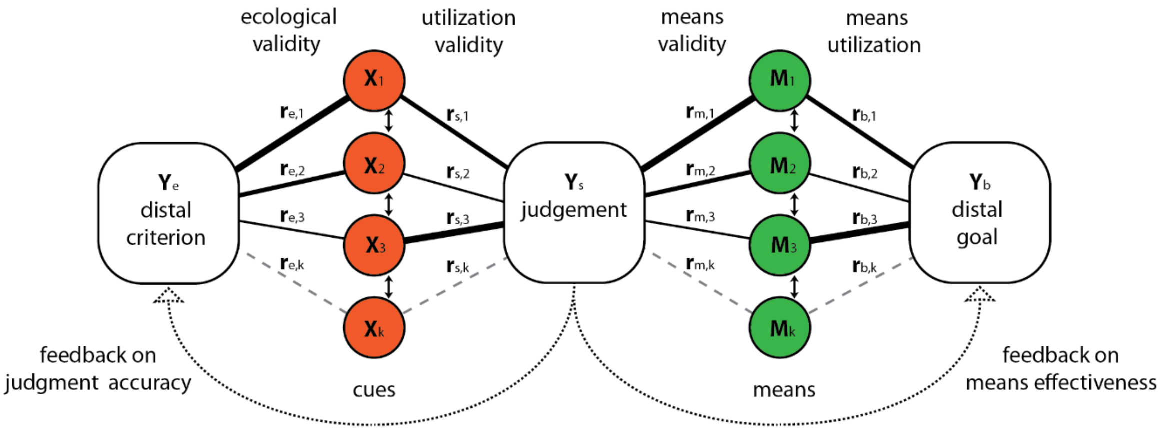

Fig. 2: The extended Lens Model (Adapted from Leary, 1987, Kostroň, 1997)

Another adaptation of the Lens Model (Hammond, 1965) describes interpersonal learning and conflict. The model is extended to include another person who is in the same situation and has the same cues at his or her disposal. However, the two persons may come to quite different judgments because they might form a different hierarchy of cues.

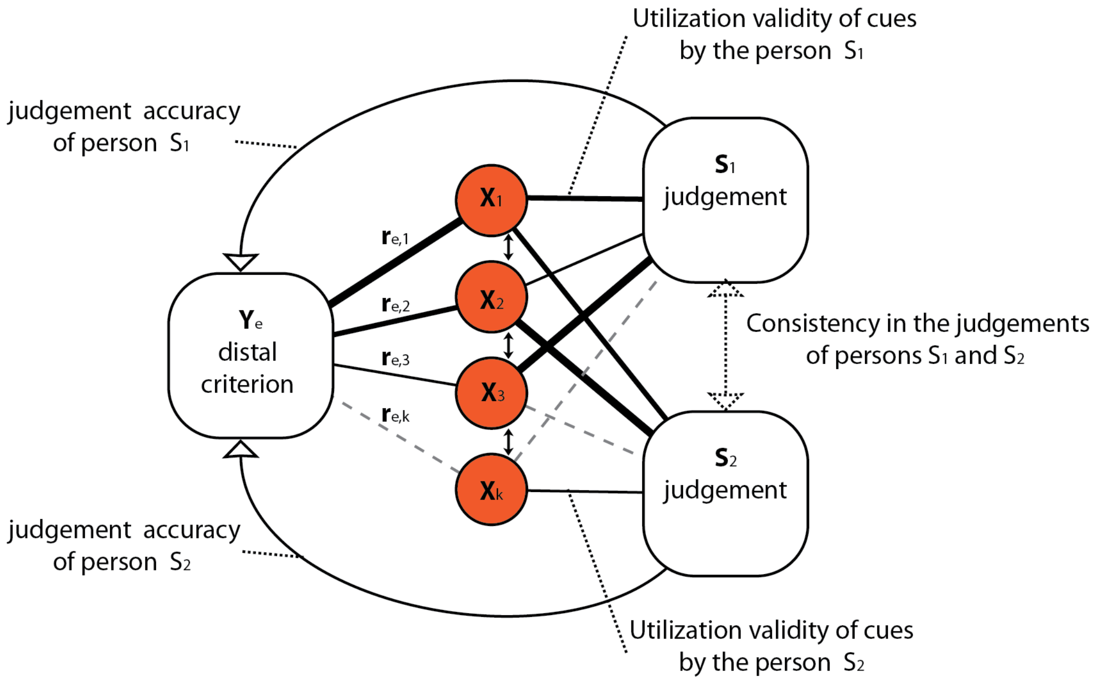

Fig. 3: The Triple-system Lens Model (Hammond et al., 1966, adapted from Cooksey, 1996)

In the following section, I will show on selected examples that the TPF and the Lens model overarch and describe the processes for all of the aforementioned studies on visualizations. Several studies have been devoted to the impact of the medium which compared REAL and PSEUDO 3D visualizations in different types of tasks. In the terminology of TPF, a REAL 3D visualization offers additional binocular depth cues when compared to PSEUDO 3D. Egon Brunswik himself built his theory on experiments investigating, among other things, the perception of three-dimensional environments and depth estimation (e.g., Brunswik, 1944), and could thus illustrate the notion of "vicarious meditation". An individual bases his or her estimates on cues that are often mutually substitutable. This also applies for three-dimensional perception, since in a particular situation an individual has a variety of monocular or binocular (two-dimensional) cues based on which a three-dimensional perception is made (see Fig. 4). In the case of 3D visualizations, different types of cues are also used to determine the distal criterion (distance/depth). Studies investigating the differences between REAL and PSEUDO 3D, i.e., between visualizations with present or absent binocular cues, do not clearly show conclusive conclusions in favor of the stereoscopic medium. In terms of TPF, the results can be interpreted as follows: PSEUDO 3D visualizations offer a sufficient number of alternative monoscope cues to compensate for the absence of stereoscopic cues and to draw conclusions about three-dimensional phenomena with the same effectiveness.

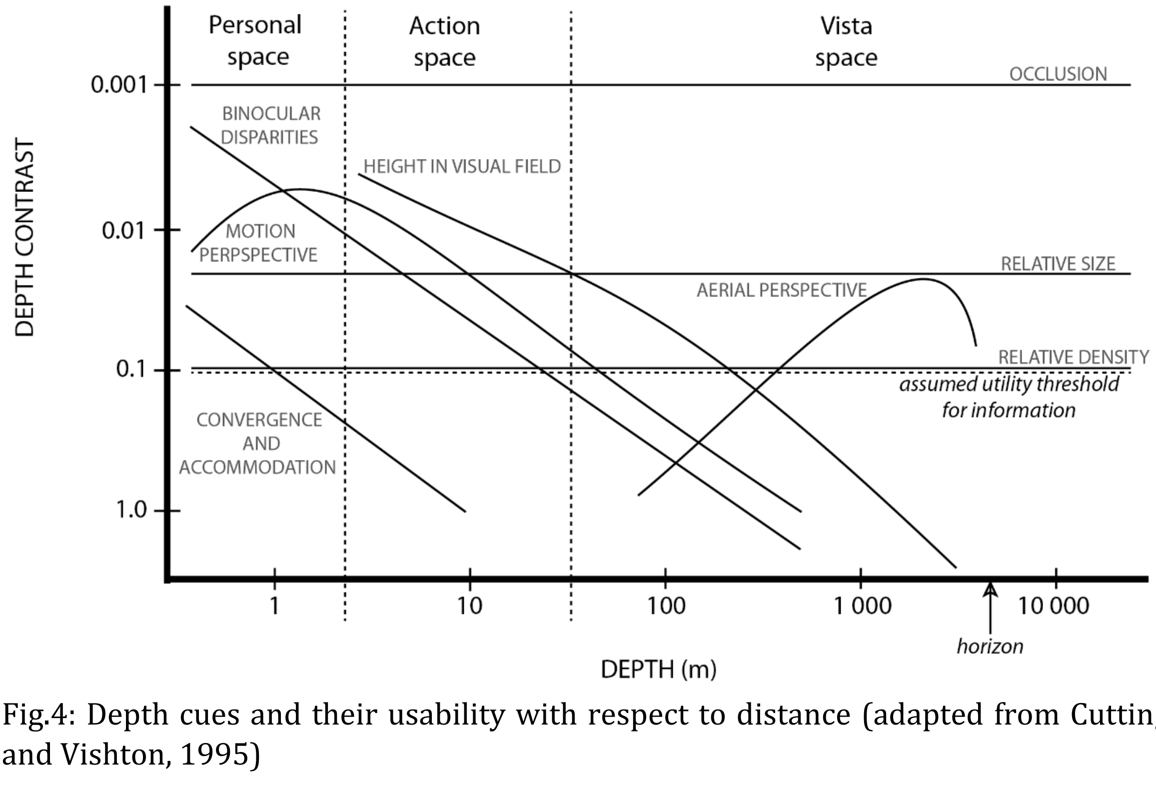

Fig.4: Depth cues and their usability with respect to distance (adapted from Cutting and Vishton, 1995)

In addition to the sensory phase, cognitive processing of visualizations has a following motor phase. The oculomotor activity must already be understood as an activity of an individual who purposefully searches for further cues to complete the final judgment on a static visualization. In case of interactive visualizations, the individual is directly provided with an interface and various means to refine his or her judgment. For three-dimensional geovisualizations, the typical operators are zoom, rotation and pan. In fact, these tools replace the movement of the person in the terrain and allow them to view the model from different perspectives. In addition, while moving the model, the individual also obtains a dynamic cue of motion parallax. The findings of the studies presented here have already demonstrated repeatedly the benefits of interactive environments, which are, in comparison to static visualizations, more often reflected in more accurate judgments.

Another type of studies presented here, those based on the visual search paradigm, works only with 2D visualizations. Can we also in this case use the concepts of TPF for the description of the investigated phenomena? Scholz (2017) argues that even though Brunswik did not develop his theory with respect to neurobiological mechanisms in his time, it can be meaningfully reflected and applied with regard to current biophysical and neurological models. In the context of tasks aimed at visual search for cartographic symbols, for example, it seems possible to meaningfully apply Brunwik's concept of the molecular or molar level of perception, which is also closely related to the functionalist conception of cognition. The functionalist foundation is the idea that the cognitive apparatus and processes are adapted to the structure of the environment so that the organism can exist within it effectively. It is then no surprise that TPF finds its application in engineering psychology and HCI, etc. (e.g., Jha and Bisantz, 2006), since one of the main tasks is to design systems in such a way that the cognitive apparatus of an individual acquires information in a desirable way and is able to deal with it effectively. Goldstein (2006) elaborates on the concept of molecular and molar perception and uses the notions of micro-mediation and macro-mediation. Micro-mediation (molecular level) refers to the left side of the Lens Model (Fig 1) and the degree (ecological validity) to which the proximal cue relates to the distal criterion. For example, how the size of the image of an object on the retina relates to the actual size of the object. Macro-mediation (molar level) refers to the central response of the organism and describes the use of proximal cues in judgment. It is the organism's long-term experience with its environment that creates stable learned patterns in cue utilization. These patterns enable the organism to select from the available cues those that proved successful in the past, and also to make effective estimations (judgments) based on defined intercorrelations. For example, a cue of the object size on the retina can be combined with a cue of eye convergence and/or height in the visual field to estimate the actual height of a figure (Fig 4). Map point symbols are often designed with regard to their visual saliency, so that they appear as focal figures in the visual processing of the whole map. The use of more prominent colors as opposed to the map background, for which rather subdued colors are used, or the use of clear and distinguishable shapes allows the human cognitive apparatus to detect potentially semantically important phenomena already at the sensory processing stage of visualization. This is examined in particular in studies (4.2, 4.3) that address the effect of symbol attributes – proximal cues in TPF terminology – on perceptual organization (Stachoň et al., 2013).

Another type of studies presented here (2.1, 3.1, 4.4) already works with map symbols mainly as carriers of meaning. In this perspective, a map symbol can be understood as a proximal cue referring to a distal directly unobservable criterion. The width of the line represents the capacity of the path (3.1), or the color lightness represents soil depth (2.1) or uncertainty (Šašinka et al., 2019). One graphical variable always represents one phenomenon. Identifying the level of a particular phenomenon in a particular location is only one operation for which maps are used. More often, the goal is to infer other phenomena from the variables presented. Information on capacity and road passability, together with an estimate of the length of each route, is used to make judgements and choices for the most appropriate detour (3.1). Alternatively, information about avalanche risk and uncertainty (or the reliability of the information) can be used to consider which skiing locations are still feasible for skiing in terms of an acceptable level of risk. A location with a presented low avalanche risk but high uncertainty (low reliability of the information) may be by someone found risky. The choice of a particular form of visualization can have a major impact on the extent to which a particular proximal cue (map symbol) is perceived and used to form a judgment. For representing the avalanche risk and uncertainty of given data, the hue of the color and its lightness, respectively, is used in intrinsic visualization, whereas for extrinsic visualizations, the lightness of the color is used for the risk and the size of the dots for uncertainty (Šašinka et al., 2019). For high avalanche risk and minimal uncertainty, dark blue and small circles are displayed (Fig 5, Extrinsic 1). When uncertainty changes, the dark blue representing the risk remains the dominant visual cue, and the size of the circle increases (Fig 5, Extrinsic 2). For the intrinsic method, a clear red is used for maximum risk and minimum uncertainty (Fig 5, Intrinsic 1). However, when uncertainty increases, the whole symbol changes to light pink (Fig 5, Intrinsic 2). The representation of the phenomenon in terms of the degree of visual saliency ceases to be dominant and also loses its natural warning character with regard to the associativity of the symbol. Thus, the form of visualization can directly influence to what extent cues are used in concluding judgments.

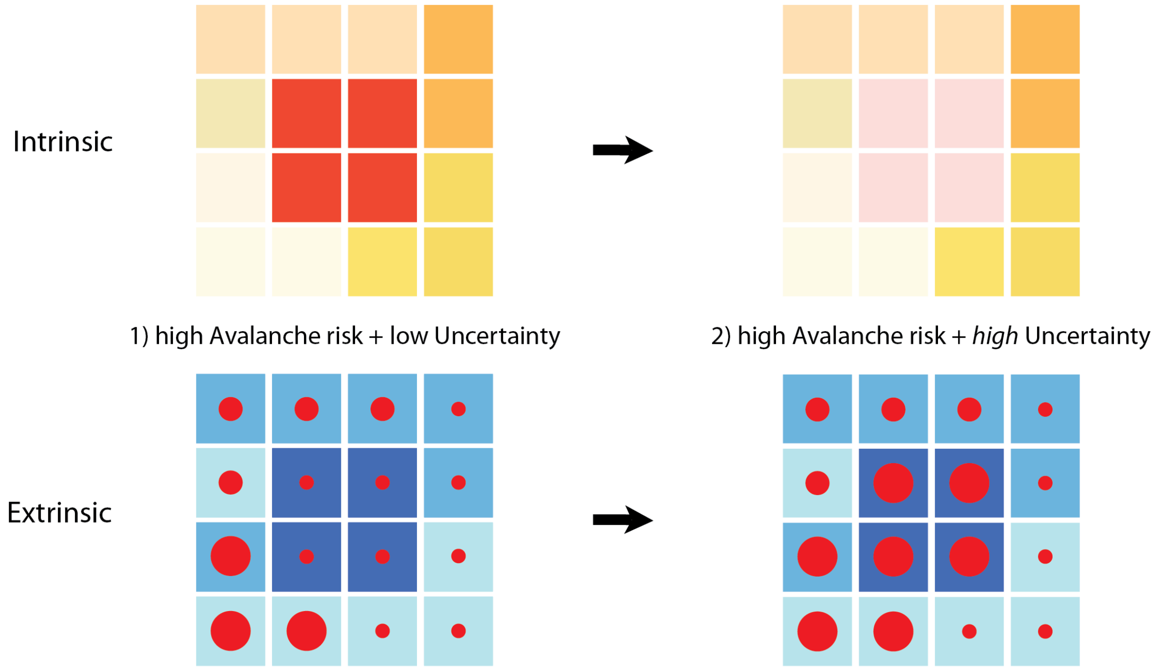

Fig. 5: Intrinsic visualization (above) and extrinsic visualization (below); the visualization are information equivalent and the four areas in the center represent the maximal level of avalanche risk. On the left, the minimum value of uncertainty is represented, whereas on the right, the uncertainty level is already at its maximum.

An important research issue pervading various visualization themes, is the impact of individual (3.1-3.3) and cross-cultural differences (4.2-4.4) on cognitive processing. In the perspective of TPF, the studied phenomena can be described using the Triple-system Lens Model (Hammond et al., 1966). Depending on their personality-cognitive characteristics, different individuals may process visualizations differently in an identical task, having the same proximal cues at their disposal. Different cognitive settings, that is also called cognitive style, lead to distinct cognitive processing of the visualization and the whole task. Individuals with a distinguished analytic cognitive style may pay more attention to individual symbols, their attributes, and place more emphasis on their mutual differentiation. They may subsequently build their judgments on partial cues but with an emphasis on their clarity and congruence. Holistically oriented individuals, on the other hand, may focus more on the relationships between variables, on the overall character and similarity, and neglect partial inconsistencies in their reasoning and instead emphasize common characteristics and features (4.4). Differences may be caused by habitual strategies and heuristics, as well as lower or higher ability to process a particular form of visualization (3.1, Šašinka et al., 2019). In the terminology of the Lens Model and TPF, different individuals not only use proximal cues to different extent to form judgments about distal criterion, but also use the available means in different ways. The strategy may be precisely to purposefully look for differences in discrete parts of the visualization, or, on the contrary, to look for continuity and trend across the visualization. Thus, the use of different strategies necessarily leads to gaining more and distinct additional clues and to different results.

The processing of visualizations by several persons can take place in parallel and completely independently, or in groups with targeted collaboration. Collaborative work using visualizations – though a special type of activity – is not uncommon. Quite the opposite. A significant part of the activities is done in groups and one of them is, for example, strategic planning, whether in the context of urban development or military operations. In addition to the fact that different actors use the available proximal cues in different ways, it is the direct interaction and communication between participants that occurs in collaborative work. In the communication process within the group, individual cues or working hypotheses and considerations are evaluated and during the next iteration, previously evaluated cues may be granted a new value (utilization validity) or correlations between cues may be redefined. An example would be a collaboration in immersive virtual reality (3.3), where the work group is making judgements about the terrain relief based on a contour map, and determining which objects are at risk of flooding on the basis of available variables. One of the actors presents the assumption that river flows must pass through a valley (not everyone is familiar or aware of this fact) and thus is explicitly naming a given proximal cue, giving it a potential importance and setting it into correlation with other cues, such as contour lines.

6.2 Adaptation and advancement of the Lens Model for the purpose of collaborative work with visualizations

In the previous chapter, it was discussed to what extent various research topics can be described in terms of TPF and the Lens Model. The original TPF and Lens Model focused more on the perceptual phase, and even though the importance of the behavioral phase itself was postulated from the very beginning, it received notably less attention. The following section aims to elaborate the TPF and Lens Model in a way that reflects the specifics of cognitive processing of visualizations, especially with respect to collaborative problem solving. The modified Lens Model will be demonstrated using an example of working in a collaborative immersive virtual environment - CIVE (3.3), even though the described principles are of a more general nature. The activities in this artificial environment are equivalent in their nature to those in a normal environment. But the artificial environment makes it possible to fully control sensory inputs and log and measure all behavioral activities, including eye movements. In CIVE, the subject moves as a virtual avatar, having a user interface through which they interact with visualizations (models, 3D maps). At the same time, they can see other collaborating persons, respectively their avatars, and can interact with them verbally or with gestures and additional tools (laser pointer). The aim of group work with the model (3D thematic map) can be, for example, to detect structurally affected regions (see distal criterion), and thematic layers (map symbols) represent proximal cues (e.g., unemployment, education, loss of large employers, transport services, etc.). In the TPF terminology, actors have means at their disposal, can interact with the visualization (zoom in, turn thematic layers on and off, use spatial operators to detect correlations, for instance, highlight areas with high values of two or more phenomena), observe the activities of other avatars, or intentionally interact with them.

The fundamental aspect of the Lens Model is, in my view, the emphasis on the cyclical nature of cognition and motor activity as an integral component of perception. I believe that the Lens Model should be looked at through the prism of Neisser's cycle of perception. The moment an individual forms a working judgment about a distal phenomenon in the first iterative cycle, a schema is formed (in Neisser's terminology) which then directs the attention and guides the choice of available means. By means we always mean the individual's activity, e.g., visual exploration (eye movement) or locomotion and direct interaction with the environment. By changing the focus of attention, the individual gains a cue for the sensory apparatus that was already available in the environment, or by a direct action and manipulation of the environment setting (e.g., bringing up a new thematic layer in the model), the individual changes and obtains a completely new cue. These activities in the environment are intentional and are used to gain cues in order to modify the schema (judgment). The motor activity, means utilization, is as important for the forming of a schema (judgment) as the proximal cue utilization itself (utilization validity). Brunswik uses the term "vicarious mediation" to explain the organism's adaptation to the environment, which he characterizes as a complex causal texture containing entities and other entities representing the former ones (Tolman and Brunswik, 1935). The available entities (cues) are substitutable in the formation of a judgment (Brunswik, 1952), and a certain redundancy allows for the identical judgment to be reached even when using different cues. By analogy to this, an organism can use different means to achieve a one selected distal goal. Brunswik (1952) refers to this phenomenon as "vicarious functioning".

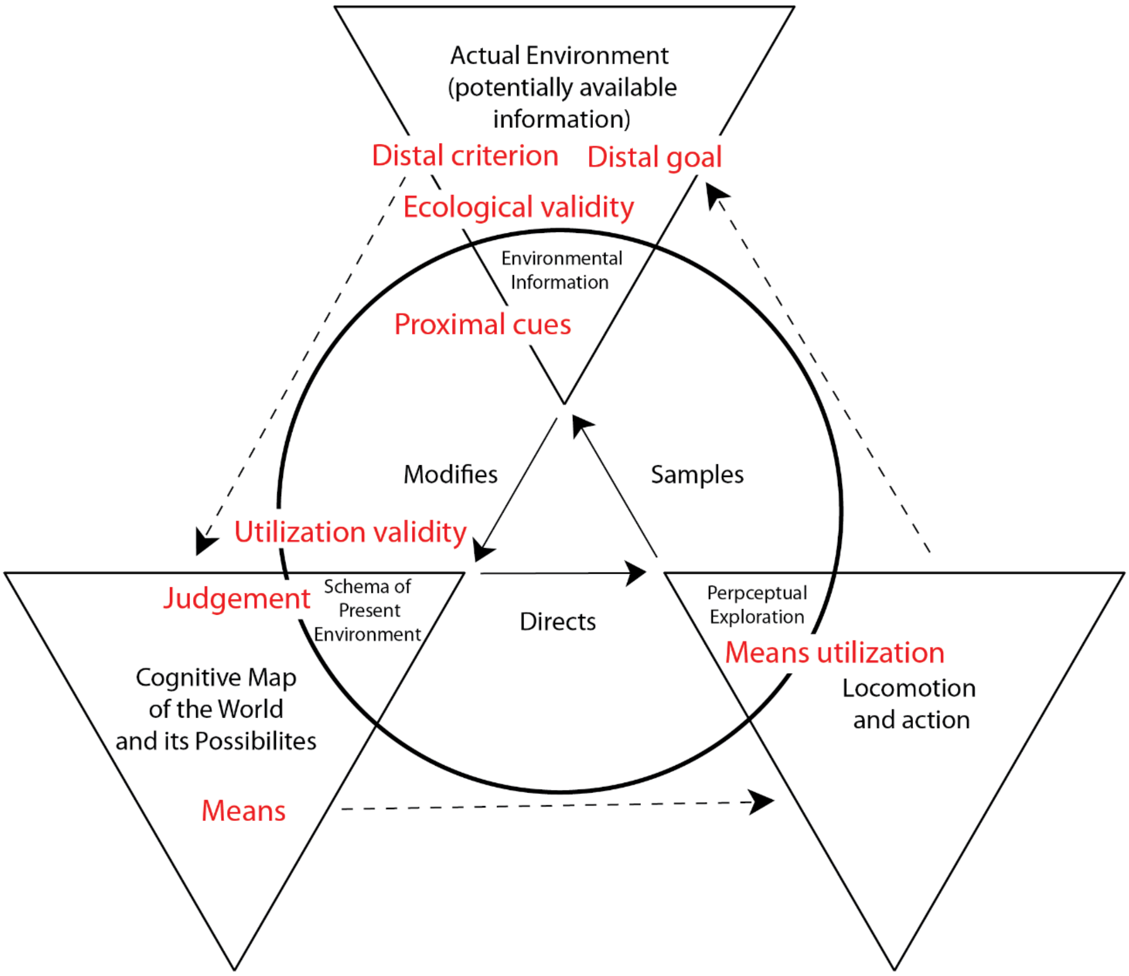

Fig. 1: Combining Neisser's perceptual cycle (Neisser. 1976) and Brunwik's Lens Model; (adapted from Salmon et al.,2018)

A certain limitation of cognitivist approaches is the focus on the individual and the way information is processed, and in turn, less emphasis on the context in which the activities under investigation are happening. In some other fields, such as information science, the same phenomenon is investigated from a different point of view. Borko (1968) states that "Information science is that discipline that investigates the properties and behavior of information, the forces governing the flow of information, and the means of processing information for optimum accessibility and usability". Information science has a close relation to the system approach as it investigates phenomena at the level of the individual or the interaction between individuals, as well as at the level of organizations or artificial systems. Wilson (1999) distinguishes different levels of how individuals interact with information. He uses the term "Information Behavior" to refer to all behaviors of an individual that involve active or passive reception and use of information, from watching advertisements to face-to-face communication. He distinguishes between "Information Seeking Behavior", i.e., the intentional search for information in order to meet a specific goal, and "Information Searching Behavior", which is a micro-level of information behavior. It comprises both mouse-click type activities when interacting with a computer or cognitive operations (e.g., applying a certain heuristic). "Information Use Behavior" then represents the incorporation of the information into the knowledge base of an individual. In his model (1999) of information behavior, Wilson takes into account, among other things, environmental or demographic variables that influence the whole process. He also uses terms such as self-efficacy (Bandura, 1997, Blatný, Jelínek and Osecká, 2007) and social learning theory (Bandura, 1986, Bishop and Bieschke, 1998) in information processing. Thus, the emphasis is also on the non-cognitive, social aspects that influence the way information is processed. A representative of the socio-cognitive stream in information sciences is Hjørland (2002), who emphasizes that concepts, information needs and information structures, as well as relevance criteria are shaped in discourse communities. From the perspective of the Lens Model, it is then necessary to take into consideration an individual's experience, both social and cultural-historical, which determines their cognitive structures. Different experience can lead both to preference for different information sources and to use of different cognitive strategies. In her sense-making approach, Dervin (1992) describes a situation in which an individual finds himself facing a gap between their understanding of the world and their experience in the world. To overcome it, a bridge can be built, for example, by obtaining new information. But if the gap is too large, then, in turn, it might be desirable to avoid new information, e.g., because of emotional risk – the fear of increased uncertainty (Chatman, 2000). It is then necessary to insert another element into the equation of the Lens model, for example the requirement to preserve the integrity of the individual which may outweigh the requirement to refine judgment. Information science theories also deal with Zipf's (1949) principle of least effort in the process of information gathering. Whereas in the case of proximal cues, the individual considers only their relevance to the distal criterion, in the case of means, the individual must also evaluate the possible availability or cost of the means. Bates (2005) states that people in information behavior prefer easily available information resources to high

quality information resources that are more difficult to access or process. If we apply this principle to Dervin's sense-making approach, we conclude that individuals are satisfied with and make sense of a state of knowledge that is easily attainable..
In the following diagram (Fig. 2) – a modification of the Lens Model – an attempt is made to illustrate and highlight those aspects of cognitive processes that play an important and specific role when working with visualizations in the context of collaboration.

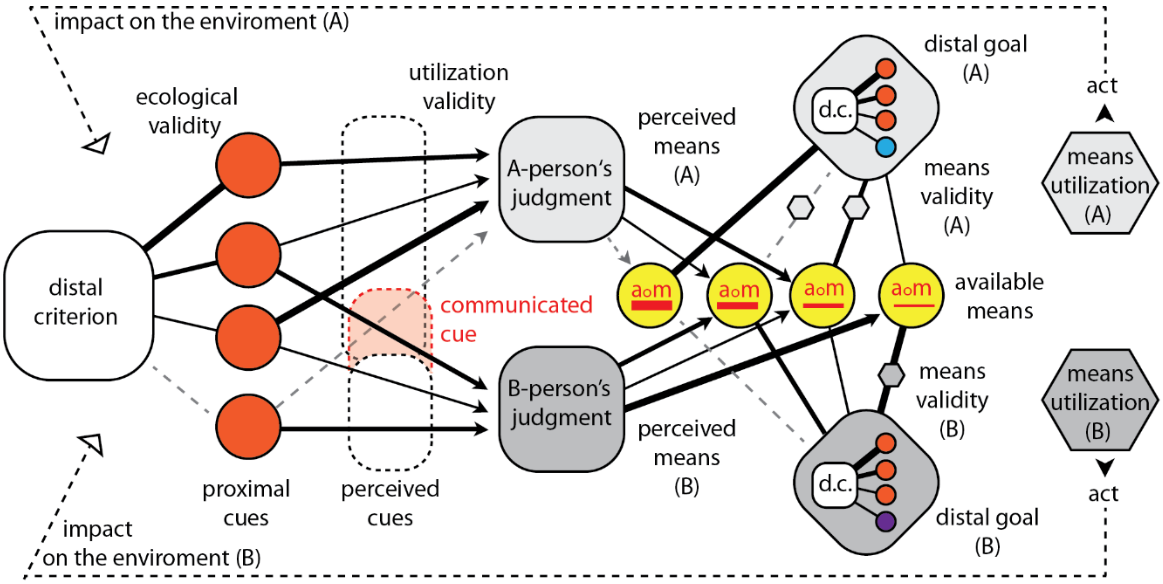

Fig. 2: The modified Lens model, which highlights the individual aspects of group work in the processing of visualizations

For better understanding, the key aspects are described using phased graphics. The diagram below (Fig. 3) highlights the difference between proximal cues and perceived cues. A perceived cue is one that is not only available to the sensory (memory) apparatus, but can also be evaluated as a cue by the individual's current cognitive structure. That means that two different individuals in the same situation decoding the same visualization may not have the same number of cues available. The thickness of the lines represents the hierarchy of the use of cues, the dashed line represents the non-utilization of a cue for making a judgment.

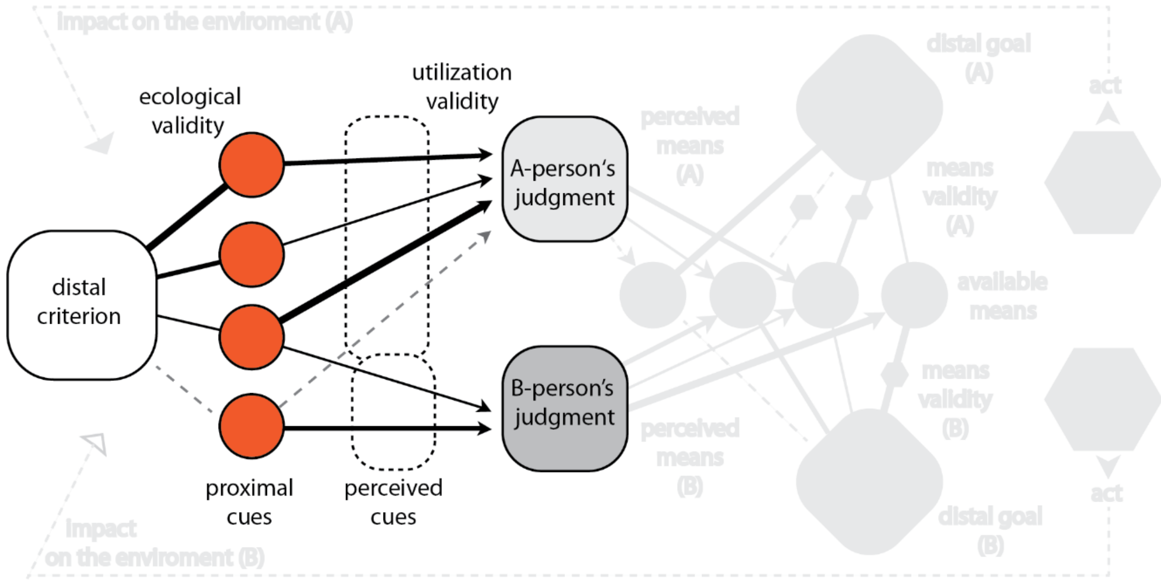

Fig. 3: The modified Lens Model – proximal vs. perceived cues

The first formed judgment, the working hypothesis, leads to a definition of a distal goal. In the example in diagram 4, this is to get an additional cue that would enable us to refine the judgment about the distal criterion in the next iteration. For the chosen distal criterion, the situation offers available means to achieve it. By analogy to proximal and perceived cues, a distinction must be made between available and perceived means that the individual is able to understand as means. Another attribute is the perceived availability of means, or economic cost. It is valid that the individual subjectively perceives some actions as more demanding. Examples include the use of the zoom function to zoom in on a detail of the model (visualization) or the observer moving closer to the model itself. At the same time, the principle of vicarious functioning (Brunswik, 1952) applies, where different means lead to the same distal goal.

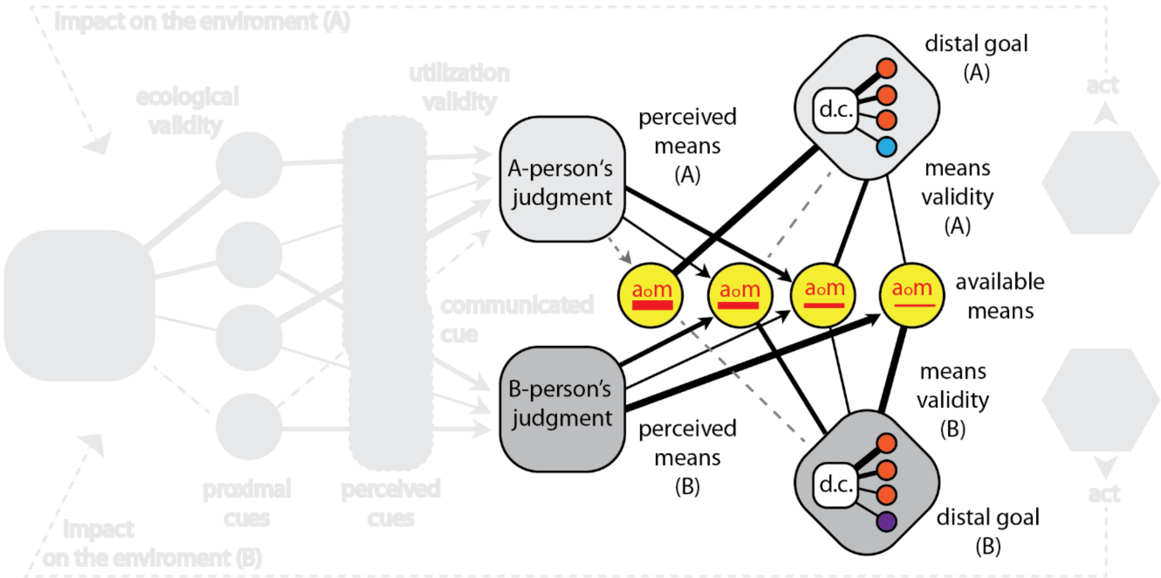

Fig. 4: Modified Lens model – hierarchy of available means in respect to chosen distal goals

After selecting the distal target and considering available resources, the actual behavior – action – takes place (Fig. 5). This can include oculomotor movements or changing the viewing position of the model, as well as actual intervention, manipulation with the environment (model), for example activation of another thematic layer. The selection of the means to be used is represented by a hexagon. It should be noted, however, that even if the means used do not lead to the intended distal goal, an unintended change of setting with respect to the distal criterion may lead to recalling of other relevant proximal cues.

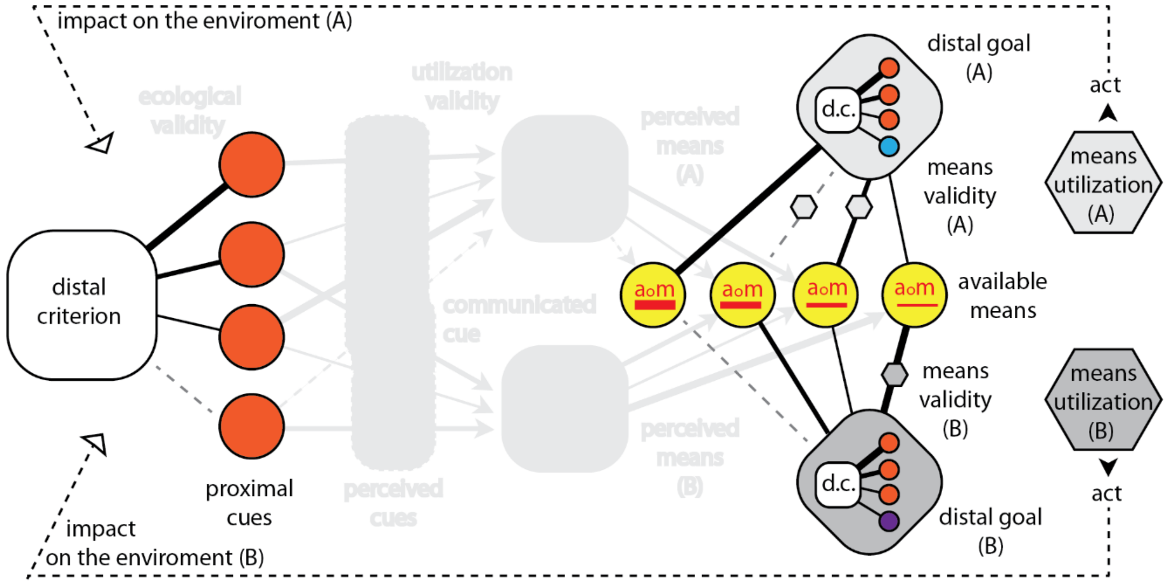

Fig. 5: The modified Lens Model – individual's action and the impact on the environment

A specific case of distal goal or behavioral choice in the context of collaborative work is focused communication and discussion of the problem, i.e., of the distal criterion and the available cues (Fig. 6). First, the participant may act as a source of new cues for the other person. Another case is a situation in which one participant purposefully clarifies to the other participant the presence and relevance of an available proximal cue. Such focused discussion leads to creation of a cognitive structure in the other participant that allows for the perception of the cue and its involvement in judgment forming. The discussion can equally be focused on evaluating the importance of individual cues or their degree of ecological validity. In this perspective, it is no longer simply a matter of adding cues, but a synchronized activity of making, expressing and sharing working judgments and developing them.

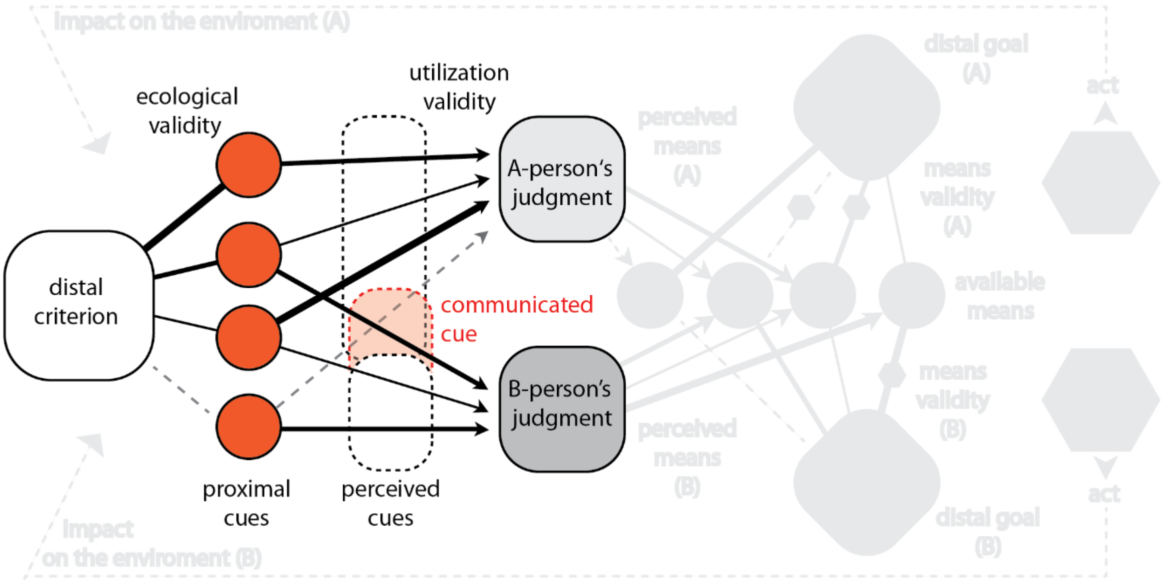

Fig. 6: The modified Lens Model – gathering new cues through the communication with another participant

The aspect mentioned last, targeted communication between individuals and information sharing, also indicates a fundamental characteristic of visualizations. Visualizations, as a form of information communication, are always a social act..

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