BEHAVIOR ANALYSIS IN VIRTUAL GEOVISUALIZATIONS: TOWARDS ECOLOGICAL VALIDITY

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Abstract
The huge technological leap in recent years brought extensive possibilities of hypotheses testing in immersive virtual environments (VE) and geovisualizations. Traditional research standards require well controlled experiments with strict setting to bring valid data about human behaviour. Unfortunately, such experiments testify in a limited way about complex processes of human behavior and cognition and it is not usually possible to transfer their conclusions into real life. For various reasons, experiments are often strictly narrowed to reveal particular point, however for the price of external and ecological validity losses. With the use of VE, people can relive authentic simulation in controlled environment, providing ecological validity as well as huge deal of data, infinite options of experimental stimuli and simple customization and administration. In this paper we discuss the value added to virtual reality (VR) in the matter of ecological validity. We suggest procedures for behavioral analysis of interaction with 3D geovisualizations and outline possible applications.

INTRODUCTION

Cartography has traditionally reflected human needs when designing and developing cartography products (Koláčný, 1968; Slocum et al., 2001; Van Elzakker & Wealands, 2007; Fabrikant et al., 2010; Staněk et al., 2010; Griffin & Fabrikant, 2012; Popelka & Brychtová, 2013; Kubíček et al., 2017a; Svatoňová & Kolejka, 2017; Šašinka et al., 2017; and many others). Regarding this, cartographers adopted various methods from the field of behavioral science, especially psychology, to improve their methods and incorporate knowledge about human cognition into the process of creating maps. Applied research point of view is also reflected. In the field of psychology, a strong research methodology has been established during the last hundred years, which emphasised exclusively well controlled laboratory experiments exalting internal validity at the expense of ecological dimension of extracted knowledge. Despite all the benefits it has, such approach can offer only limited ways to help develop and evaluate cartographic products with all its features, and usually it lacks tools needed for the applied field. It is necessary to emphasize, that studying cognitive processes in laboratory experiments still represents state of the art in current psychology research. It is not possible to criticise current methodology, not bringing suggestions for further progress, so we discuss this issue within the following text.

In this paper we summarize arguments why and how research in behavioral sciences, including mentioned cartography/geography field, should go back to the real world phenomena issues when trying to answer questions it considers. We argue why methodology in behavioral sciences regarding geographical issues should be enriched with more complex methods engaging VR to better understand human behavior and interaction with cartographic products as well as general human-environment processes. In such constellation, VR offers great platform to provide stimuli on the one hand and it can effectively promote collection of behavioral data on the other. Finally we provide short user study conducted on various types of devices to demonstrate functionality of application, which allows precise and at the same time relevant data collection beyond the laboratory environment.

WHAT IS PRECISE DOESN'T NEED TO BE RELEVANT

The dispute between "precision" and "relevance" in measurement of human behavior is not a new topic. Labeled rather as external vs. internal validity in experimental design, this contradiction has been discussed since the beginnings of modern science era (Campbell, 1957; Campbell & Stanley, 1967). Well-controlled experimental designs can bring precise predictions about human behavior in specific conditions, however, unfortunately it usually lacks sense of relevance for the real life issues. Such relevance remains persistently on the spot, especially in regular everyday real-world issues which include human factors, e.g. map navigation (Svatoňová & Kolejka, 2017; Juřík et al., 2017), wayfinding (Liao, et al., 2016; McKenzie & Klippel, 2016), crisis management (Konečný & Reinhardt, 2010; Řezník et al., 2013) etc. One specific type of external validity is the ecological validity, which generally means the extent to which the conclusions of specific research can be generalized to the situations in which the studied phenomenon naturally occurs. Current research on human cognition and behavior is, especially in psychology and related fields, usually done in particular positivist tradition with strict experimental rules and tells us very little about what the real performance of the human would be in the physical world (this was discussed already by Brunswik, 1943). Brunswik then described research direction in psychology as "narrow-spanning problems of artificially isolated proximal or peripheral technicalities of mediation which are not representative of larger patterns of life". We have to critically reflect, that psychology reached this point, despite his prophecy. Studies conducted in real circumstances are usually criticised in rigorous journals for potential lack of internal validity. However, great thinkers like Brunswik (1943) or later Neisser (1976) anticipated and pointed out the limits of strict laboratory experiments. Neisser (1976) considered artificial stimuli used in experiments distant from real world phenomena. He widely discussed the relevance of the knowledge acquired in laboratory conditions, where he saw used stimuli as abstract, discontinuous, and only marginally real material. Almost four decades earlier, Brunswik realised, that with the infinite number of variables in the natural systems we can barely predict all the possible outcomes precisely and with the use of available scientific models, exact predictions are only guesses meeting reality with some level of probability. That was the reason, why in Brunswik's point of view, psychological science should be more likened to geography than physics (Hammond & Stewart, 2001). And in this metaphor we can also easily demonstrate existing intersection between psychology and geography. Human cognition has evolved and works with respect to specific environmental principles, it is shaped by the spatial rules and natural patterns and it is environmentally reactive, as discussed below. Therefore, research which is done on maps or currently geovisualisations, should respect basic environmental principles in the stimuli creation, which could make conclusions derived from the study more relevant.

From this point of view, traditional methodology used in behavioral science truly is quite impractical for cartography development and potential usability testing. Let's illustrate an example regarding map optimization. When a cartographer wants to optimize her/his map regarding matter of - let's say - visibility of symbols, s/he needs to create specific map symbol set. Every symbol in this set (regarding fundamental Bertin's work, 1967) may acquire specific shape, colour, size, texture and other features (variables). When we want to reveal suggested effect of colour on visibility, in traditional paradigm, we are allowed to manipulate only one variable (colour) and the rest of variables we need to keep constant. But the rest of the Bertin's features, when varied, dramatically change the nature of each symbol, regardless the colour. Since there is no unified theory speaking about mutual interactions of these various features in the map depiction, we cannot say what sense it will make to the reader. The best option to fully explore this issue would be to create and compare every existing combination of symbols regarding Bertin's variables. But such design is barely possible, because it represents thousands of combinations. Not only because of too many combinations, but also because true experiment has some other demands such as randomization (i.e. areas of interest in visual field should be varied within tasks), which should be taken into account. What more, in real world there are phenomena, which are mutually dependent and to some degree coexist. Also they can be equivocal, i.e. relating to couple more coexisting phenomena. Such phenomena usually occur together, but not as a rule. In this case, any randomization is not possible, because their interconnectivity or pattern can represent another clue for their identification. As Hammond & Stewart (2001) wrote, "the environment is a *causal texture* in which different events are regularly dependent upon each other"

… " and because of the presence of such *causal couplings* actually existing in their environments, organisms come to accept one event as a *local representative* for another event" (Hammond & Stewart, 2001).

Now, let's go deeper with the map optimization. Cartographers have to compromise between the size of the characters and information richness when creating the map. Ideally, they should design characters of similar size. However, some signs demands more space to be eloquent to reader than the other. Readability of the symbol is, like any other parameter, valid just and only within its specific context. Even with hypothetical research design, which would fulfil all the previous requirements, at this point, the background comes to play. Specific background (e.g. depicted terrain) also affect how the characters are going to be perceived. Perception of the map is of holistic nature. The specific area can lead or mislead user to specific perception or searching strategy and the content can be misinterpreted. Of course, we can explore background and symbols set separately, but their reunification in practice wouldn't be predictable, because it creates new, hitherto unexplored entity. And from cartographers' point of view, every terrain is almost every time unique. To compare, psychologists usually work with abstract stimuli in their experiments, where e.g. cross representing area of interest is just a cross. In cartography, a cross can represent hospital or a church and reader automatically incorporate this meaning into the process of visual searching, so he potentially associate it with either pharmacy or graveyard. A significant part of the visual/perception studies in behav. science are not considering any context/surrounding, which hugely affect process of visual perception (Todorović, 2010). Already Brunswik argued, that in the environment without context we cannot do such elementary thing as e.g. guessing sizes of the objects, because our guesses rely on the relative scales defined by surrounding etc. Simply said, searching for the ball on the rugby pitch is not equivalent to search for brown dot on the green computer screen. Regarding this, classical laboratory experiments are very limited in the way how we can apply their conclusions to practice. Therefore, when creating cartographic products, cartographers can rely only partially on existing research and possibly some fundamental findings about elementary cognitive processes, but they have to immanently engage their experience and intuition.

Brunswik jointly with E.C. Tolman advocated the idea, that cognitive processes in humans developed in consonance with their natural environment, which is possessing selective pressures (Hammond & Stewart, 2001). In the *theory of environment* they considered environment a predeterminant of specific cognition. That was the reason why they analysed environment on the first place as a "designer of thinking" and after that theorized about cognition. This was quite opposite to what was the regular practice those times. It is necessary to say, however, that research practice studying organisms separately from their environment persisted until these days. In this matter, Hammond & Stewart (2001) emphasized how important is the generalization of results from behavioral sciences into real life - thus he promoted relevance. To avoid low relevance of research conclusions, Brunswik suggested to replace sampling of participants with a representative sampling of situations and tasks. What is here meant by ecological validity, is the setting of the experimental environment. Natural environment provides information in probabilistic fashion (Hammond & Stewart, 2001). Signs can be valid or misleading, some of them are clearly unequivocal signs, and similarly, one can act various different ways to reach a specific goal. Existence of this natural 'mayhem' suggests, that experiments should "entail more than the variation of a single sign (isolated from all other variables), nor should signs be unequivocally related to significates; rather, they should entail probabilistic relations" (Hammond & Stewart, 2001). This lead Brunswik to the idea of *probabilistic functionalism* (Hammond & Stewart, 2001) and introduction of his *lens model* (see Tucker, 1964). Experiments regarding cartography or geovisualizations are usually used in practice and they need to be designed with high level of relevance (to be functional), so their testing usually adopts applied research paradigm. Applied research aims to test functionality of specific product in a specific context. Within applied research issues, however, some unique qualitative phenomena very often manifest, which were not expected before (e.g. human error/failure). Therefore, to ensure ecological validity, research setting must posses representativeness and naturalness, it must reflect naturalistic settings of the world. Research should represent true environment to promote actor's regular-basis behaviour (Schmuckler, 2001).

Despite the criticism from the ranks of psychologists and psychometricians, for the exploration of environmental issues (i.e. phenomena relevant in real world), scientists may find inspiration in different types of designs, which may refer to applied research, human factors and human computer interaction problematics. For example, MacKenzie (2013) advocates comparative evaluations approach, or looking for circumstantial relationships, which can testify about possible causalities. Authors of this paper don't suggest that researchers should forsake existing methods in behavioral research. However, we want to encourage researchers to consider expected outcomes of their studies and adapt research methods emphasizing relevance of study conclusions. Even for the price of going out of the lab, real world application demands to boost ecological aspect of the studies to maximum. The message of this paper is to promote modern tools, especially VR, as distinctly solving problems outlined above. VR technologies, when appropriately used, can not only increase representativeness of the experimental stimuli, but they can also compensate controlled laboratory environment without necessity of critical trimming of the experimental context/stimuli. Especially, regarding possibility to pick up data about whole process of human interaction with the task as discussed below, new possibilities of behavioral analysis open. As suggested in Brunswik *lens model*, people create personal hypotheses, which they constantly test by interacting with the environment and this interaction (including feedback) brings them to more or less successful action.

In classical experiment, the incorrect answer from navigation task on map can't tell us enough about what the map actually represent, because we don't know what led user to wrong decision. With the option of dynamical monitoring users' actions within interface, we can easily measure specific behavioral patterns to get better insight in what leads or misleads users in their trying.

VR AS A TOOL FOR MODERN BEHAVIORAL RESEARCH

Technological progress in VR technologies based on increasing computing power of graphics within the last 20 years (Singer, 2013) have brought extensive possibilities for behavioral and cognitive research. Lokka & Çöltekin (2016) mention, that e.g. in the matter of wayfinding, VR simulation can help to control unexpected situations and better control various factors affecting observed variables. Virtual worlds are not equivalent to the reality, however some researchers suggest there is a strong correlation between mental representations user induce from each of them (Richardson et al., 1999). E.g. various visual aspects depicted in VR (i.e. similarly as in reality) should be better remembered by users (Mania & Chalmers, 2001; Höffler, 2010; Borkin et al., 2013). It means that if we produce enough realistic VE, we can in general prevent lack of ecological validity. In VR conditions, simulation of the real environment is possible with quite high level of realism (Lin et al., 2015), movement freedom and precise tracking of actions, however with all benefits of laboratory research (see Fig, 1; or Loomis et al., 1999). Current trends in geosciences reflect the above mentioned arguments and e.g. Roth et al. (2017) suggested, that it is suitable to use more complementary methods simultaneously when collecting data (e.g. VR combined with eye-tracking technologies). Roth et al. (2017) claims that this can increase effectivity and validity and it can help to reach data of better quality. In VR, we can present any type of stimuli to the user, dynamically modify it and at the same time observe and measure his/her interaction with such stimuli. VR represent meaningful solution for providing satisfactory ratio of internal and external validity during the process of hypothesis testing, which was also reflected in previous research (Kattenbeck, 2015).

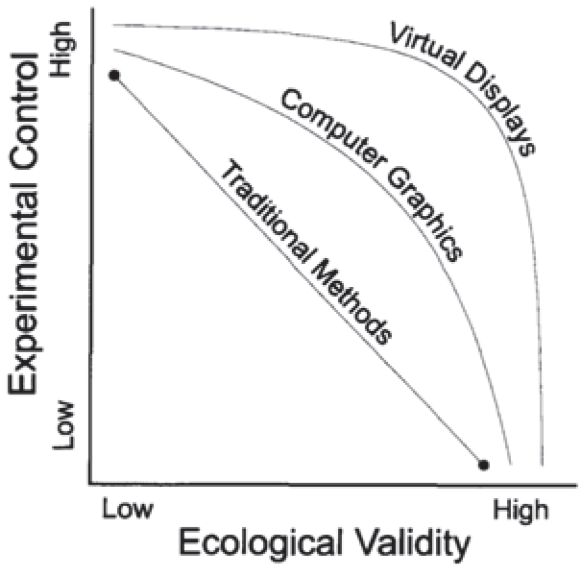

Fig. 1. Tradeoff between experimental control and ecological validity (Loomis et al., 1999)

Among what was written about VR we can find various taxonomies trying to describe VR. The key components of VR were described as (a) virtual world, (b) immersion (presence), (c) sensoric feedback and (d) interactivity (Sherman & Craig, 2003). Some existing taxonomies reflect to what extent VR corresponds with reality (Thurman & Mattoon, 1994). Brill (1994) designated systems: *Immersive first-person*, *Through the Window*, *Mirror World*, *Waldo World*, *Chamber World*, *Cab Simulator Environment* and *Cyberspace*. Jacobson (1993) distinguishes between immersive, projected and desktop systems. Let's further discuss VR possibilities from the technology-based point of view (Fig. 2).

Immersive VR

Immersive systems are usually providing strong feeling of being there in virtual world (presence) and they can be provided by specific kind of head-mounted display (HMD). HMD is a "helmet with glasses", that can transfer individual into the realistic 3-dimensional virtual space, where s/he is allowed to move freely with salient visual and haptic feedback. Such transfer has a great potential because user can easily forget about the test situation and provide natural patterns of behavior. HMD provide 3D vision by exposition of image separately for each eye (binocular disparity). Due to implemented movement detectors, user is able to look around freely in a VE and immersive simulation including wide range of activities can be easily done. Also, combination of HMD with some treadmill technology providing free movement in large virtual spaces can reveal important information about embodied aspects of human cognition, about process of decision-making in real-like environment and hence it has the potential to further promote ecological validity within experiment. Currently there are more versions of HMD commercially available. Until now, the greatest vitality was demonstrated in Oculus Rift or HTC Vive. Both of them have satisfactory level of visual quality and HTC Vive is enriched with room motion detector and 2 hand controllers. Its availability and relatively small spatial and technical demands classify this device as a very promising tool for human factors issues. Usability of this technology is however still disturbed by frequent user sickness while wearing it.

VR on large screens

VR can be easily projected on the large media screens or walls. In all these cases, the purpose is to visually surround user with the VR to increase level of her/his presence. So called CAVE (Computer-Assisted Virtual Environment, Cruz-Neira et al., 1992) is a good way to reach high quality resolution and fidelity for VR applications. This setting can provide fully immersive environment where user is not loaded with any peripheral device such as glasses or HMD. Unfortunately, it has quite high spatial and technical demands and it is not practical for massive data collection. Example of geographic research, using wide-screen 3D projection for VR emulation, was conducted e.g. by Špriňarová et al. (2015) or Juřík et al. (2017)

Desktop VR

These systems including web-based systems also represent a promising tool for exploration of user performance when interacting with geovisualizations. The great advantage of web-based systems is the possibility of mass user testing, without the necessity of data collection in the lab. Even for the price of lower presence, desktop systems open great possibilities for dynamical analysis of interaction patterns when using desktop applications (see for example or Kubíček et al., 2017b).

Fig. 2. Technologies for VR (HMD - left, CAVE - middle, desktop VR application - right)

All three types of VR systems allow tracking and recording of user movement in VEs and of overall interaction. What more, all three types of systems can be combined with another currently valuable technology - eye-tracker (e.g. Herman et al., 2017a). Web-based systems can use the JavaScript library WebGazer.js. Another actual trend in the development of VR technologies is the gradual interpenetration of these three above mentioned categories. For example, the web libraries for 3D visualization (X3DOM or Three.js) can be combined with HMD technology Oculus Rift. Regarding above mentioned arguments, we can conclude, that VR has and always will gain importance as a great evaluation tool for behavioral analysis and it will bring great deal on the account of ecological validity.

USER STUDY

To demonstrate how desktop VR applications can be used in the mass data collection, we designed a geo-application for easy use and with it we conducted a simple study. The main objectives of the user study were to:

- determine if ever and with what limits it is technically possible to conduct user testing of 3D geovisualization outside the laboratory conditions (with the use of devices which users regularly use),
- find out what is the return rate of test which is administered remotely,
- find out the most common hardware and software configurations that are used for further testing in these conditions and which could be included in the data analysis as relevant factors.

We used 3DmoveR (3D Movement and Interaction Recorder), which is an application for recording user interaction with virtual geovisualizations. It is based on combination of screen logging approach with online questionnaire engaging practical spatial tasks. Open web technologies, like JavaScript, jQuery, WebGL and PHP, were used for implementation of 3DmoveR. All recorded data about user interaction and responses were stored on server and could be later analysed. This testing tool and its variants have been used in several user studies in controlled conditions (Herman & Stachoň, 2016; Herman et al., 2017a; and Herman et al., 2018). For the empirical part of this study 3DmoveR version 2.0 was used. The main shift (compared to the previous version) lies in replacing the X3DOM library for rendering 3D geospatial data by the equally focused Three.js library. This change extends support for various types of devices (mouse-controlled desktop PCs, laptops with touchpads or tablets), and across a variety of operating systems and web browsers. In addition to better support on hardware and software, there are also other benefits of this change (e.g. automated stimuli preparation using open source GIS – QGIS 2.18 and Qgis2threejs plug-in). Application was fully interactive and users were allowed to move freely with 6 degrees of freedom (Fig. 3). The 3DmoveR 2.0 application is freely available to any interested person under a BSD (Berkeley Software Distribution) license.

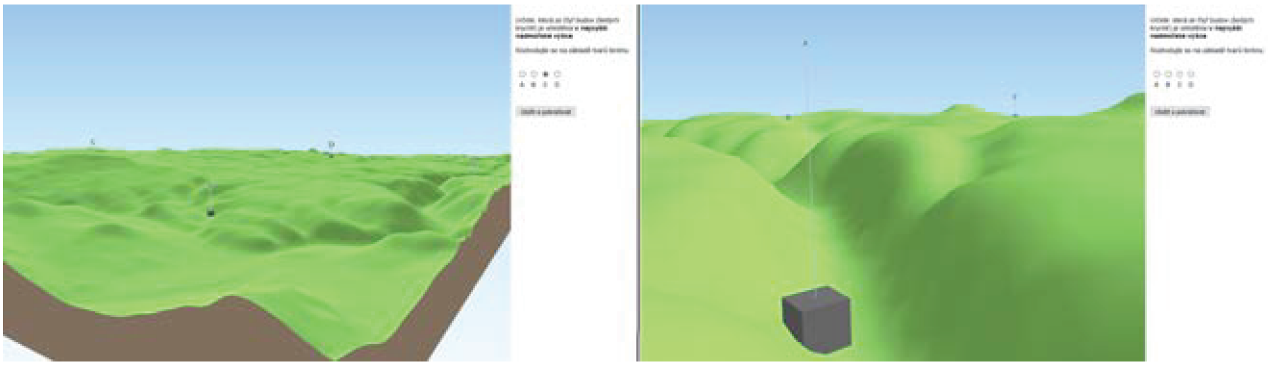

Fig. 3. Interactive 3D geovisualization as a stimuli in 3DmoveR 2.0 application

User study consisted of two short questionnaires and also one simple spatial task. First questionnaire was asked to be filled in before the spatial task and it investigated basic demographic data, users' experience with maps/3D geovisualizations, and data about hardware platform. Spatial task was set as identification task. Users were asked to choose one of four objects placed in the terrain, which lies in the highest altitude. Part of the information was recorded automatically (operating system, web browser, screen resolution, coordinates of movement in VE, user interaction when solving a spatial task, and reaction time – RT). Questionnaire presented after the spatial task interviewed about potential bugs or errors. The user test was published online (http://olli.wz.cz/webtest/3dmover2/remote_test_iccgis2018) and shared to potential users via Facebook.

Results

Participants

We began to analyse the preliminary results approximately one week after publishing our call on Facebook. Out of 35 total attempts to fulfil the test, 30 users went through the whole testing period and completed the assignment. There were 17 females and 18 males, age between 21 and 56 years. 4 users did not introduce their age. All participants reported that they worked daily with PC and majority of them (94 %) worked regularly with maps. There was distinctive variation of answers regarding their experience with 3D models, some of them work with 3D on a daily basis, some of them reported very low experience.

Software platform and settings

Most of the users completed test on personal computer or laptop, one participant used tablet and four participants used smartphones. This reflects operational systems used (74 % of users worked on Windows, 11% Android, 9% used different variants of Linux and remaining 6% used macOS) and web browser (71 % Google Chrome, 14% Mozilla Firefox, 9% different variants of Opera and remaining 6% other browsers - Internet Explorer and Safari). Screen resolutions varied considerably, but usual screen aspect ratios were (16:9 – 57 % and 8:5 – 29%). Majority of users (94 %) used display with colour depth 24 bites.

Reaction time

We were able to record reaction time in spatial task precisely. Users answered the asked question under one minute on average, but with quite wide variability (m=54.0s, med= 43.7s, sd = 34.2s). Users were only partially correct when solving the task (57 % have chosen correct object “C”), 40 % of participants guessed object “D” as in the highest altitude, which was placed almost as high as object “C”. With respect to the used hardware/software platform or any demographic data, no pattern in terms of affecting correctness of answer or RT was observed on this small sample.

Feedback on usage from users was very brief. All users, who completed the test (30), reported that they understood the instructions well, only one user complained about loading speed of 3D scene. One user reported troubles with controlling the app, and there was one user who reported problems with the layout of geovisualization on the screen, probably because he was not able to zoom out. This user was using a touch screen device (Android 7.1, Opera mini). We can draw conclusions, that for small mobile devices, better optimization (use so called responsive design) would be needed.

FUTURE WORK

We tested an elementary application on small research sample to see, if it posses any potential for massive data collection and also to test its limits and further possibilities. In this case, we chose a simple visualization and simple task. For the future implementation, regarding above discussed issue of ecological validity, more detailed geovisualizations are about to be tested with the particular focus on the human-device interaction process, possibly engaging big samples of users. Data reported above are going to help us to control conditions, but not for the price of laboratory isolation. Users would be able to perform navigational task in real environment (e.g. find particular meeting point in the city) or to conduct an advanced spatial task, like analysing spatial distribution patterns or spatial correlations with complex interactive 3D geovisualizations. More possibilities for customization of the application is visualised in the Fig. 4.

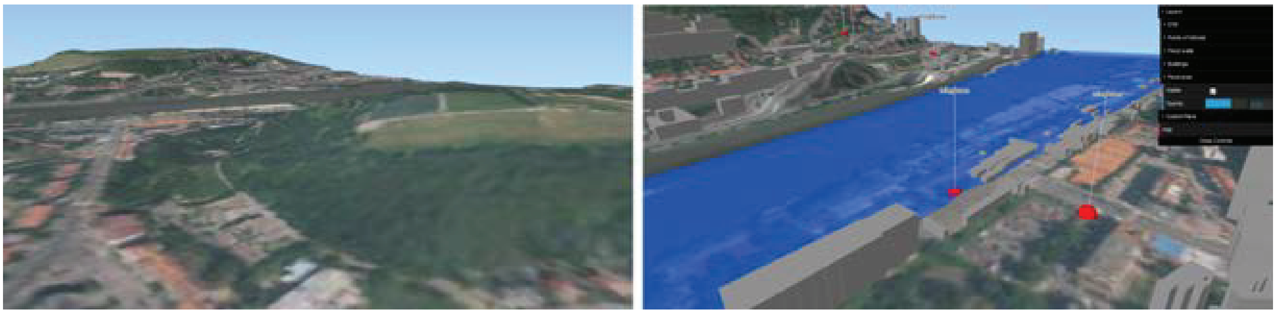

Fig. 4. Further examples of possible customization of test application (for more details see Herman et al., 2017b)

CONCLUSION

Within this paper we argued why ecological validity in the research of geo-related issues should be more emphasized. We suggested VR technologies applications as partially resolving contradictions in the matter of relevance and precision in the research of human performance on geo-related tasks. Finally, we submitted original practical example of the web-based VR application, on which we conducted simple user study as a demonstration of above mentioned arguments. The application was (next to standard RT and user performance) able to bring relevant data about various situational conditions, in which the users found themselves when they were solving the given task. This data can help researchers to set up following studies. What's more, applications 3DmoveR 2.0, which was applied in our user study, can be further optimized and customized for wider use and can be applied as a low cost valid tool for massive data collection, e.g. in navigational tasks in realistic VE.

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