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# When the display matters: A multifaceted perspective on three-dimensional visualization of geographical data

--Manuscript Draft--

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# When the display matters: A multifaceted perspective on three-dimensional visualization of geographical data

**Short title: When the display matters**

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## Abstract

This study explores the influence of stereoscopic (real) 3D respectively monoscopic (pseudo) 3D visualization on the human ability to reckon altitude information in static and dynamic 3D geovisualizations. A two phased experiment was carried out to compare the performance of two groups of participants, one of them using the real 3D and the other one pseudo 3D visualization of geographical data. 61 psychology students were tested with respect to their efficiency at identifying altitudes of the displayed landscape. The first part of the experiment was designed as non-interactive, where static 3D visual displays were presented; the second part was designed as interactive and the participants were allowed to explore the scene by adjusting the position of the virtual camera. The investigated variables included accuracy at altitude identification, time demands and the amount of the participant's motor activity performed during interaction with geovisualization. The interface was created using a Motion Capture system, Wii Remote Controller, widescreen projection and the passive Dolby 3D technology (for real 3D vision). The real 3D visual display was shown to significantly increase the accuracy of the landscape altitude identification in non-interactive tasks. As expected, in the interactive part were differences in accuracy flattened out between groups due to the possibility of interaction, with no other statistically significant differences in completion times or motor activity. The increased number of omitted objects in real 3D condition was further subjected to an exploratory analysis.

*Keywords*: 3D vision; geovisualization; real 3D visualization; pseudo 3D visualization; stereopsis, kinetic depth effect; human-computer interaction

## Introduction

With the growing use of 3D technologies in many areas such as, geology, oceanography, meteorology, teaching geography, virtual tourism, documentation and preservation of cultural heritage, urban and transport planning, noise mapping, 3D cadastre [1-9] and others, the usability of 3D visualizations is increasingly discussed. The importance of 3D visualization of geographical data increases also in other fields such as crisis management and air traffic control (ATC), which represent areas motivated to secure user-friendly ergonomy and design of the human-machine interfaces [10, 11]. Creating a user-friendly interface preventing human errors should be the highest priority in user interface engineering; at the same time the type of information depiction is the key factor influencing the processing of visual stimuli. In this study we compare two types of 3D visualization - real (stereoscopic) 3D and pseudo (monoscopic) 3D - in order to find out how people process and evaluate 3D geographical data; in addition, we analyze their task-solving strategies.

Previous studies focused on the differences between real and pseudo 3D visualization of geographical data in relation to e.g. the estimation of distances [12], identification of similarities in 3D networks [13], spatial navigation [14] or military and disaster situations [15]. Based on the results of our previous exploratory study [16], we created a new experiment to clarify the benefits and limits of alternative 3D geographical visualizations at identifying the altitude. In addition, to provide complex view on issue of 3D visualizations, we explore the static and interactive forms of such visualizations.

## Real 3D and pseudo-3D visualization and geovisualization

The monoscopic pseudo 3D visualization (also called weak 3D visualization; [12]), is displayed perspective-monoscopically on a flat media, e g. computer screen [17]. Pseudo-3D visualization offers only monocular depth cues for the identification of spatial features in the environment (e.g. linear perspective, relative size, interposition, texture gradient or kinetic depth effect). On the other hand, real (or “strong”) 3D visualization [12] uses both the binocular and monocular depth cues and provides stereoscopy [17]. In the real environment, stereoscopic vision – stereopsis means that we see slightly differently by each eye – helps people to better discriminate the distances and depths. In the virtual reality, the Real 3D visualization simulates monocular visual depth cues as well as one of the binocular depth cues, which is called binocular disparity [18]. The stereoscopy in real 3D is usually ensured by the use of a specific peripheral device such as 3D glasses. Due to the stereoscopy, the real 3D visualization offers more visual cues to detect the spatial features of the virtual display; especially the ability of altitude identification is expected to be enhanced in real 3D [19, 20]. These two different types of 3D visualization are considered to be computationally non-equivalent [21], i.e. demanding different cognitive processing despite the fact they both depict the same content (information). Supported by neuroscientific researches, the cognitive processes such as working memory and attention are increased in virtual 3D viewing, which indicates the cognitive processing of more incoming data in 3D visualization [22].

Studies on 3D visualization show enthusiasm on the one hand and certain doubts on the other, especially with respect to the user-friendly human-computer interaction. Some studies view interactive 3D visualization as an effective way of presenting geographic data and explaining the complex processes and various phenomena that occur in real environments [23]. Other studies consider 3D technologies as a promising tool for the future of advanced 3D cartographic products [24, 10]. Weber et al. (2010) [25] and Hirmas et al. (2014) [3] focus on the possibility of using 3D geovisualization when teaching geography; Bleisch & Dykes (2008) [26] describe the utilization of 3D geovisualization for planning mountain hikes and evaluation of 3D hiking maps. Zanola et al. (2009) [27] propose and evaluate the utilization of real 3D visualization in urban planning. On the other hand, the limits of 3D visualization using motion and binocular visual depth cues are reported, such as increased time needed for solving the tasks, or visual discomfort [12, 28-30]. As highlighted in Plant & Stanton (2012) [31], the relevant features influencing the process of perception should always be considered in relation to the phenomenon of human error, which can be influenced by the 3D visualization type.

## Non-interactive and Interactive Level of Perception

Within this study, it is necessary to distinguish between a non-interactive and interactive level of 3D perception. Non-interactive perception is represented by looking at the static perspective views without possibility to actively change the point of view. The interactive type integrates perception and manipulation with the geographical content to reach a given spatial objective; therefore, the operator’s performance is much more dependent on the participant's searching strategy and on a specific motor activity when solving the task. The issue of interactive visualizations was explored in some previous studies [32] suggesting that interactivity does not necessarily enhance task performance if the needed information is immediately visible/available, no matter if obtained actively or passively. However, with respect to the previous theories [33], the proximal visual cues we perceive to catch and understand reality are chosen from the wide spectre of possibilities. Contextual issues such as visualization type or available control device matter in this choice. In this study, the different types of 3D visualization with different number of visual cues are expected to induce different motor activities of participants. To explore separately both visual and motor aspects of interaction with 3D visualizations, we divided the experiment into two parts (Experiment 1 and Experiment 2). The aim is to compare the effectivity of alternative types of 3D visualization in static and in dynamic tasks (see Fig. 1). In the whole experiment (Exp. 1 and Exp. 2), participants' ability to identify the relative vertical position of the objects in the scene was investigated. Participants were given the virtual geographical terrain, where were placed geometrical objects of different colors and participants were asked to order them according to their altitude. All the primary test views of the geographical terrains were perspective (i.e. oblique) views. In both phases of the experiment (Exp. 1 and Exp. 2), participants dealt with ordering of the geometrical bodies in the terrains.

*Experiment 1* was designed as a non-interactive variant where the stimuli were static perspective views. The aim of the non-interactive Experiment 1 was to explore the assumption that different types of 3D visualization of geographical data are perceived in a different way. The influence of 3D visualization type was explored, with focus on visual perception only. In the static, non-interactive virtual environment, the binocular disparity provided by 3D glasses was expected to increase the participants' ability to identify the altitude features of the terrain [19] in shorter time.

*Experiment 2* was designed as an interactive variant, with the participants being able to navigate the interactive 3D visualization by adjusting the position of a virtual camera. With such a navigation, the missing cues of binocular disparity in pseudo 3D were expected to be compensated by the *kinetic depth effect* [34, 35] and therefore the accuracy in altitude identification was expected to be the same in both conditions. However, increased amount of navigating actions (motor activity) was expected in pseudo 3D group as a compensation for missing binocular disparity. This increase of motor activity in pseudo 3D was expected to correspond with longer task-solving times. Crampton (1992) [36] suggested, that mental efforts should be enhanced in the pseudo 3D condition due to missing binocular depth cues and people in real 3D would solve tasks more easily, but with the risk of omission (not finding) of some important aspects in the scene, as suggested in previous studies [16]. In the Experiment 2 was possible that participants could miss some objects in the scene, so the number of omitted objects was measured.

## Methods

The two phased experimental design consisted of a series of tasks measuring the ability of participants to identify the correct altitude arrangement of objects in a three-dimensional geographical terrain. The experimental tasks were alternated with filler tasks to prevent the testing period to become monotonous and to keep the participants focused and well-motivated for the experimental tasks (see Fig. 1).

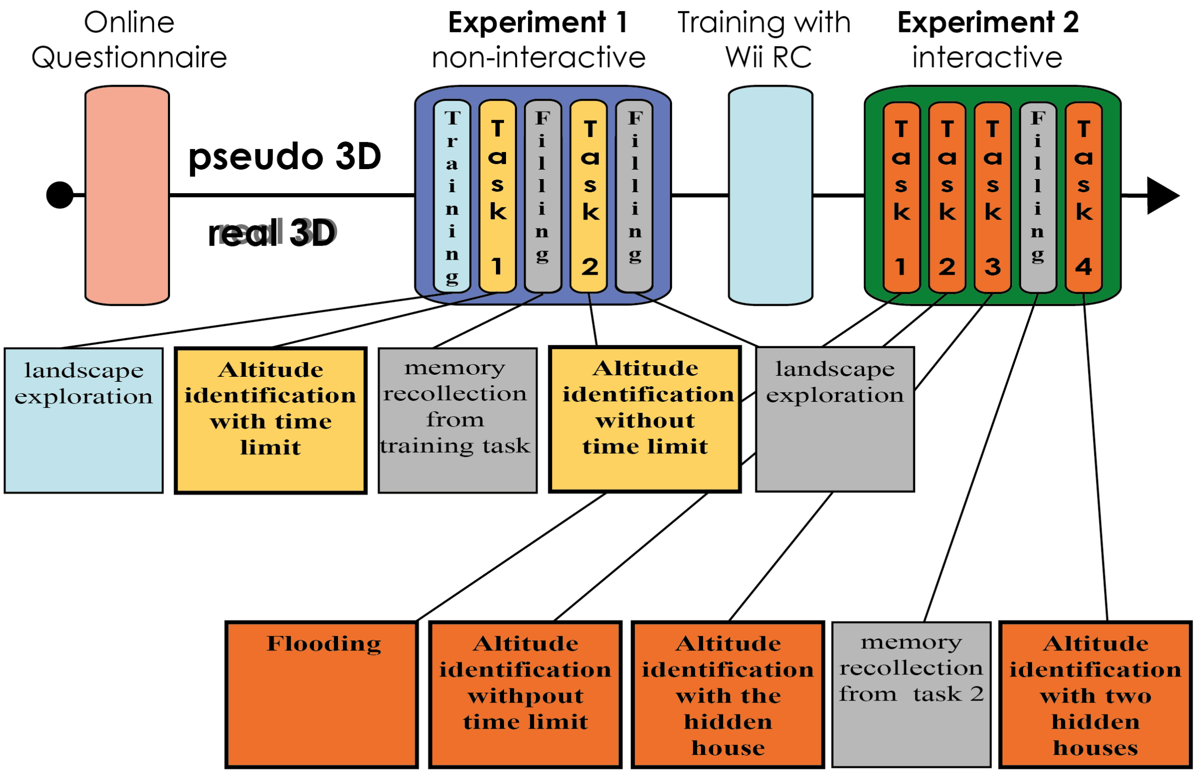


Fig. 1: Schema of the Experimental Design

## Used technologies and geographical data

The test arrangement was designed exclusively for the purpose of the present study. Real 3D display was created using a wavelength-multiplexed stereo system utilizing a pair of projectors and a set of passive (filter) glasses. Pseudo 3D display was created with one of the projectors operating in the classic (2D) display mode. See Jorke et al. (2009) [37] for more details about display modes.

Because the participant's motor activity (namely the types of actions used for navigating the terrain) in interactive Experiment 2 was measured, we avoided using the typical control devices such as computer mouse which could enhance a stereotypical behaviour within participants. A wireless handheld Wii Remote controller (RC), originally designed for a Nintendo game console, was used as a basis for the interaction. The Wii RC has motion tracking capabilities, but the precision and reliability of the movement detection is rather low and there is a risk of adverse effects on the users' performance. Therefore, we also used an optical Motion Capture system "OptiTrack" by NaturalPoint for tracking the position and orientation of the Wii RC. This solution provides significantly higher quality of tracking in terms of resolution, speed and reliability. The combination of Wii RC and an "OptiTrack" system enabled more natural 3D movement patterns, thus ensuring high user comfort. The above was possible due to more (namely three) degrees of freedom (DoF) available in comparison with the usual PC mouse, which provides 2 DoF [38]. With respect to embodied cognition approach where the cognition is considered to be body based activity as well as subjected to the situational contexts [39-41], the 3 DoF and free 3D movement enabled participants to carry out natural and interface-dependent patterns of movements when controlling the visualizations.

The interactive part (Experiment 2) was displayed using the VRECKO software system. VRECKO is an open-source modular software which has been continuously developed by the Human-Computer Interaction (HCI) Laboratory at the Faculty of Informatics at the Masaryk University since 2003. VRECKO was programmed in C++ using the OpenSceneGraph library (see more details at http://vrecko.cz). A set of modules for the visualization of geographical data was developed and implemented by Tisovčík (2014) [42]. For the passive part of the experiment (Exp. 1), a new, single-purpose and easy-to-use application was developed at the HCI Laboratory for the creation of experimental tasks, display of textual and graphical data and recording of the answers and task solving times.

Digital terrain models (DTM) were used as a main input for creating 3D geovisualizations. A fourth-generation Digital Terrain Model of the Czech Republic (DTM 4G) was acquired by airborne laser scanning (ALS) and processed to ground resolution 5 x 5 metres. DTM 4G is now being distributed by ČÚZK (Czech Office for Surveying, Mapping and Cadastre). The collected point clouds were imported as text files directly into the VRECKO software where continuous terrains were created. Used DTMs were from different parts of the Czech Republic (mainly the Giant Mountains and Bohemian Paradise) and they were for the testing visualization covered by a corresponding orthophoto. Some data (from the area of Bohemian Paradise) has been transformed by multiplying (2x) the vertical values, in order to highlight the relatively small variation in landscape altitude. The processing of data for interactive visualization in the VRECKO system is described in more detail in Tisovčík [42]. The terrain data used in the passive part (Experiment 1) were also processed and exported using the VRECKO system and then pre-rendered using a Cinema 4D software. The participants were not familiar with any of presented terrains.

## Participants

The participants were 61 volunteers (students of psychology) recruited from the Department of Psychology at Masaryk University (42 females (F) and 19 males (M); age 19-31, m=23.24, sd=2.609). The data were collected in May/June 2015. The participants were recruited via e-mail, social networks and personal contact. Before the testing, all the participants were asked, using a questionnaire, about their experience with 3D visualization. All of participants had some previous experience with 3D visualization applications, but none of them had an experience with the interaction with 3D geographical data as used in this study. The participants were divided into two groups (real respectively pseudo 3D visualization) with an equal proportion of males and females in each group, in order to balance out the suggested differences between males and females in spatial orientation tasks [43]. The experimental conditions (including lighting conditions and other environmental factors) were identical for both conditions. All participants had normal or corrected to normal vision and had no motor/movement limitations. All the participants agreed with the experimental procedure and participated voluntarily, with the open opportunity to withdraw from the testing at any time. All of the participants were rewarded with small gifts after finishing the test battery. Before the testing, all the participants were told to pay attention to the spatial distribution of objects in the tasks. They were instructed that correctness in answering was more important than the speed, but also that their completion time would be recorded.

## Experiment 1 — non-interactive part

### Task and Stimuli

To find out whether there is a general effect of 3D type on visual discrimination in altitude tasks designed in VRECKO, we prepared an experiment with non-interactive stimuli. The non-interactive Experiment 1 was fully computerized; the participants were answering with the use of a conventional optical mouse. The Experiment 1 consisted of 2 test tasks (the first containing 15 and the second 20 items; see Fig. 2). In addition to the two tasks, the testing procedure contained a training task and filler tasks (see Fig. 1). In every task there was a written instruction presented on the screen which preceded the given set of items.

### Content

### Task 0 — Training

The training task was placed at the beginning of the test battery for the participants to get acquainted with the testing design and controlling features. The training task required the participants to explore the presented landscape with geometric bodies randomly placed in it. Afterwards the participants were asked to answer several questions using a computer mouse so they could learn how to answer.

### Task 1

The first task consisted of 15 items - 15 scenes showing 3 cubes of different colours placed onto the terrain models. Different coloring was used as most simple method for identification of specific cube. The first 5 scenes were shown for 5 seconds, the next five for 4 seconds and the last 5 were exposed for 3 seconds. The participants were instructed to determine the order of the cubes according to their altitude. After the exposition, the participants indicated the order of the cubes by matching the colored squares with appropriate boxes (see Fig. 2). Correct identification of all the three cubes was scored 2 points; one correct answer was scored 1 point and 0 points were given if no answer was correct.

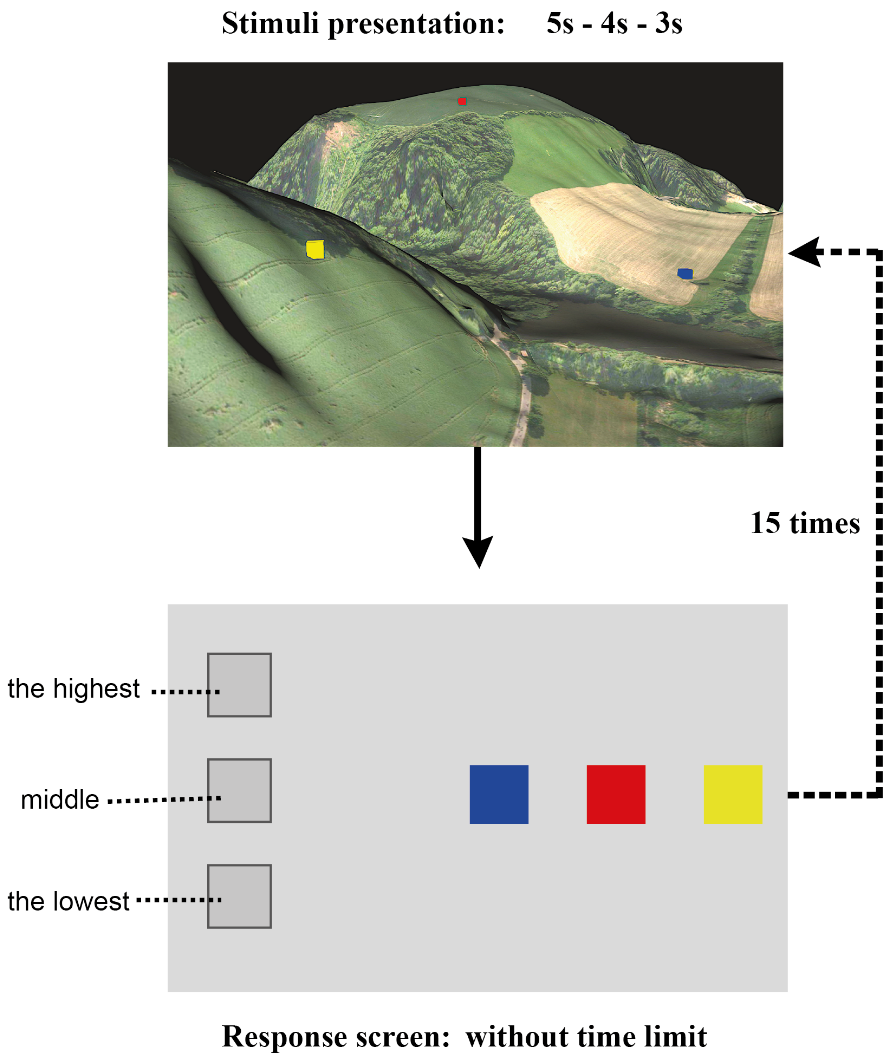


Fig. 2: The Example of Task 1, Experiment 1

**Task 2**

The second task comprised 20 items - 20 scenes showing 3 cubes of different colours placed on the terrain (see Fig. 3), but, contrary to Task 1, there was no time limit. The participants were asked to identify the order of the cubes according to their altitude. After being certain of their answer they ended the exposition and indicated the order of the cubes by matching the colours with appropriate. Identifying the correct position of all the three cubes was scored 2 points; one correct answer was scored 1 point and 0 points were given if no answer was correct. The accuracy and the completion time (when identifying the altitude until the participants were sure about their answer) were measured.

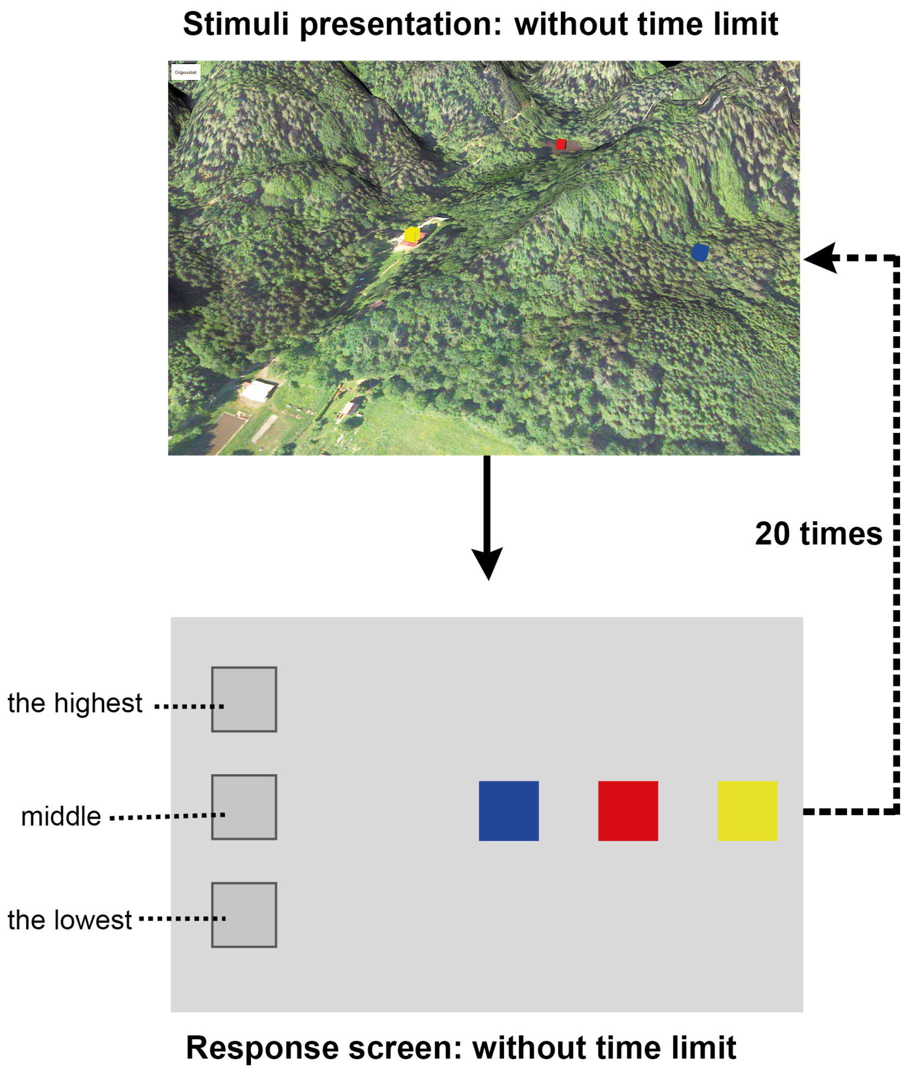


Fig. 3: The Example of Task 2, Experiment 1

## Results — Experiment 1

The total number of participants included in the data analysis was 61 (42F/19M). There were 28 participants in the pseudo 3D condition and 33 in the real 3D. Due to the relatively small number of participants we used non-parametric methods to analyze the data. All the collected data were analyzed using the IBM SPSS program, version 22.

### Task 1 — Altitude Identification with a Time Limit

*Accuracy* The real 3D users (cumulative score; m= 20.38; med = 21.00; sd = 1.90) were not found to be significantly better than the pseudo 3D group (cumulative score: m = 19.75; med = 20.00; sd = 2.23) at identifying the altitude within the set time limit ($U = 525.5$, $p = .352$). See the cumulative accuracy scores of real and pseudo 3D groups in Fig. 4.

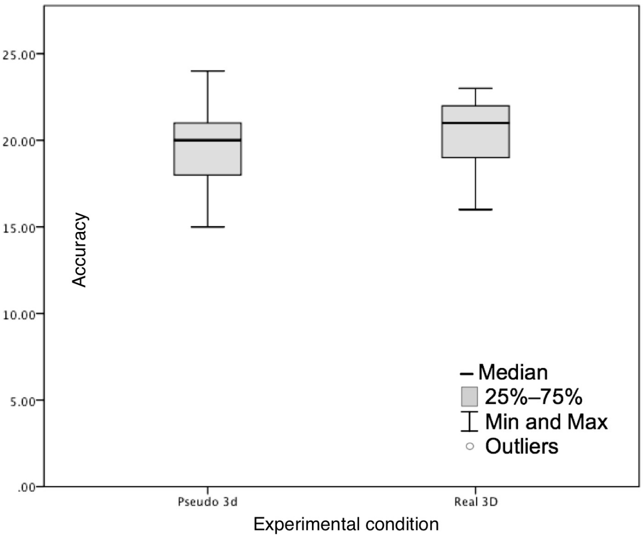


Fig. 4: Differences in Accuracy (cumulative score) for Experiment 1, Task 1

**Task 2 — Altitude Identification without Time Limit**

*Accuracy* The real 3D participants (cumulative score: m= 30.54; med= 31; sd= 3.04) performed significantly better than the pseudo 3D group (cumulative score: m = 27.11, med = 27.5, sd = 3.57) at identifying the altitude without a time limit. The results were found to differ significantly (U= 690.5, p = 0.001). A comparison of both groups with respect to accuracy is shown in Fig. 5.

*Completion Time* Using the Mann-Whitney U Test for independent samples, no significant differences in total completion times were found (U = 391; p = ,304) between the pseudo 3D group (cumulative score: m = 339.96; med = 327.97; sd = 113.90) and the real 3D group (cumulative score: m = 310.86; med = 306.05; sd = 88.70).

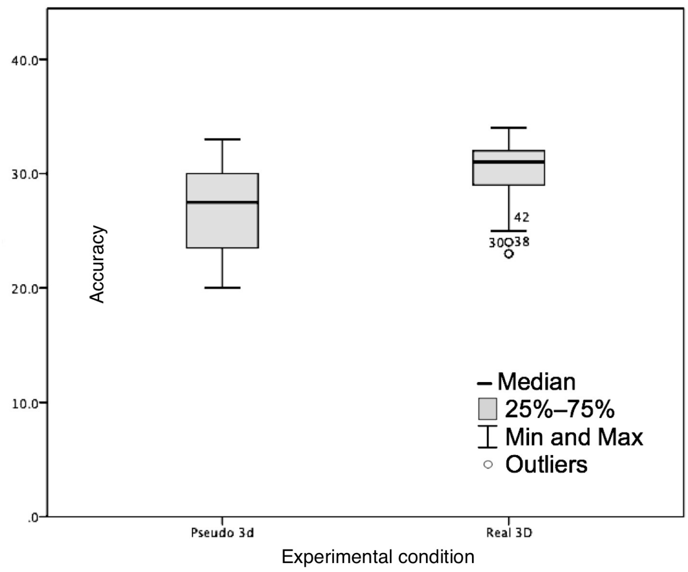


Fig. 5: Differences in Accuracy (cumulative score) for Experiment 1, Task 2

# Experiment 2 — interactive part

## Task and stimuli

Identification of the altitude of objects in a non-interactive display is different from active searching process in an interactive display. In the second experiment, participants were asked to identify the correct altitude order of several geometrical bodies in a scene during interaction with the 3D model. In order to thoroughly explore the information searching process, we made the experimental tasks more complex; the participants needed to interact with 3D visualization of geographical data to obtain more information and to be able to solve the tasks. The test battery consisted of four complex ordering tasks (schema of Experiment 2 is shown in Fig. 1). The number of tasks was limited by the long time needed to solve each of the tasks. There was no time limit imposed, therefore, participants could thoroughly explore the scene to find the correct answer. Each task was preceded by verbal instructions. The answers were verbally reported by the participant to the experimenter and noted down for further analysis. The participants' motor activity was recorded by the VRECKO software.

The investigated variables included the correctness, completion time, the number of omitted objects and the amount of motor activity participants performed. The motor activity included navigating in interactive 3D visualization through adjusting the position of a virtual camera (the virtual point of view). Changes in the position and rotation of this virtual camera were recorded at 60fps (*frames per second* ). From these raw data, a file including all motor actions of all the users was created. Data about each motor action include: type of action (dragging, orbiting or zooming with a virtual camera), starting time of the action, duration in milliseconds, total sum of movement of the camera and total sum of rotation of the camera. Any change in the virtual camera position was considered, no matter the duration. Four variables were measured: (1) correctness rate; (2) searching activity during task-solving; "motor activity" which was calculated as the sum of all motor actions of a user for a particular task; (3) task-solving times and (4) the number of omitted objects in the scene.

**Content**

**Task 0 — Training**

The training task was placed at the beginning of the test procedure to flatten out the possible differences in Wii RC skills between the participants. The participants were instructed about how to control their actions with the Wii RC and then asked to practise control of a training map for 5 minutes. After the training, the testing was launched.

**Task 1**

In Task 1 the participants were asked to rank the presented buildings (located near a lake) based on the level of risk of their flooding. The buildings were marked by colours and there were 6 of them. Every correctly identified position was scored 1 point.

**Task 2**

The second task required the participants to order 7 geometric bodies according to altitude. The participants were asked to rank the geometric bodies from the lowest-placed one to the highest-placed. Every correctly identified position was scored 1 point.

**Task 3**

In the third task, the visual display contained 4 houses standing near the lake. Three of them were visible on the first sight and the fourth was out of the primary camera scope. Again, the participants had to order them according to altitude. Every correctly identified position was scored 1 point.

**Task 4**

In the last task, the participants were asked to order the objects in the scene according the altitude, but this time two of the objects were hidden in the terrain – not visible on the first sight. The total number of objects was 6; see Fig 6, bottom right. Every correctly identified position was scored 1 point.

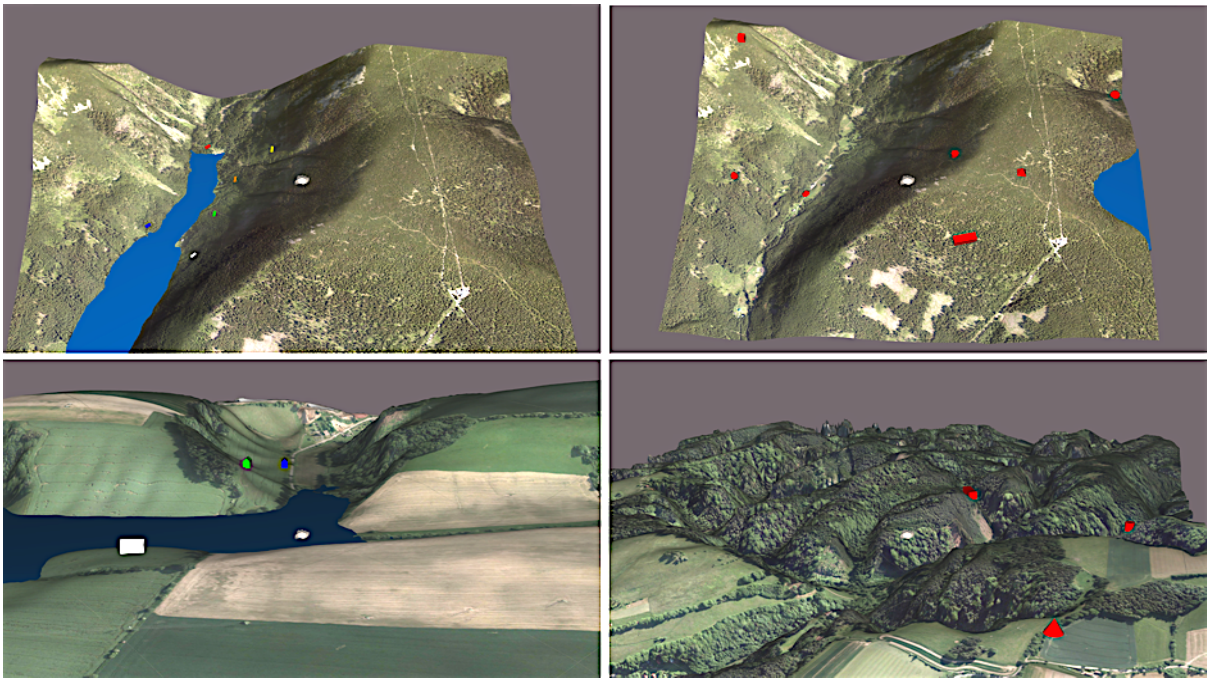

Fig. 6: Experiment 2 - Examples of tasks initial view (Task 1 — top-left; Task 2 — top-right, Task 3 — bottom-left, Task 4 — bottom-right)

## Results — Experiment 2

Only 56 participants (37F/19M) of the total number of 61 participants were included in data analysis; 4 participants had to be excluded due to technical reasons (4 participants from the real 3D group got lost in the 3D virtual space, they were not able to finish the task and gave up, so their data had to be excluded from the data analysis); 1 participant withdrew from the experiment. There were 27 participants in the pseudo 3D group and 29 participants in the group working with the real 3D. The data were analyzed using the IBM SPSS. Due to the relatively small number of participants, non-parametric methods were used to analyze the data.

### Tasks 1 - 4

With respect to the interactive tasks 1— 4 (flooding, altitude identification, flooding with the hidden house, altitude identification with two hidden objects), no significant differences were found in completion time, accuracy, motor activity or omission rate between the pseudo 3D and real 3D conditions. All the features of interaction with the virtual 3D geographical context were similar for both groups (see Table 1).

| | | Task 1 | | Task 2 | | Task 3 | | Task 4 | |
|---|---|---|---|---|---|---|---|---|---|
| | | Pseudo 3D | Real 3D | Pseudo 3D | Real 3D | Pseudo 3D | Real 3D | Pseudo 3D | Real 3D |
| **Response time (s)** | m | 70.00 | 72.24 | 135.22 | 102.38 | 91.44 | 93.31 | 171.85 | 153.59 |
| | med | 68 | 60 | 92 | 95 | 78 | 81 | 142 | 150 |
| | sd | 35.28 | 38.62 | 92.97 | 52.03 | 52.83 | 46.97 | 102.26 | 79.86 |
| | U | 393.5 | | 477.5 | | 408.0 | | 464.0 | |
| | p | 0.974 | | 0.471 | | 0.787 | | 0.652 | |
| **Accuracy** | m | 4.33 | 3.83 | 3.48 | 3.76 | 2.63 | 2.69 | 3.85 | 3.93 |
| | med | 6 | 4 | 3 | 4 | 2 | 2 | 4 | 4 |
| | sd | 1.96 | 1.67 | 1.19 | 1.75 | 1.47 | 1.29 | 1.88 | 1.41 |
| | U | 323.0 | | 430.5 | | 396.0 | | 400.5 | |
| | p | 0.242 | | 0.507 | | 0.937 | | 0.879 | |
| **Error Rate** | m | 0.04 | 0.07 | 0.07 | 0.14 | 0.00 | 0.00 | 0.26 | 0.52 |
| | med | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | sd | 0.190 | 0.258 | 0.267 | 0.351 | 0.000 | 0.000 | 0.526 | 0.790 |
| | U | 404.0 | | 416.5 | | 391.5 | | 449.5 | |
| | p | 0.599 | | 0.444 | | 1.000 | | 0.230 | |
| **Motor Activity** | m | 227.44 | 251.86 | 346.41 | 231.48 | 349.56 | 453.38 | 497.48 | 292.17 |
| | med | 139 | 248 | 220 | 119 | 200 | 279 | 263 | 201 |
| | sd | 256.34 | 180.26 | 391.69 | 250.15 | 365.11 | 515.043 | 567.94 | 264.32 |
| | U | 454 | | 331 | | 450.5 | | 313 | |
| | p | 0.305 | | 0.321 | | 0.333 | | 0.198 | |

Table 1: The Experiment 2 – Summary of the Results

## Exploratory Analysis

### The Issue of Interactivity

Although there were no statistically significant differences between the real and pseudo 3D groups with respect to omissions, total number of omissions was consistently higher for the real 3D condition (see Fig. 7). The above was true despite the fact that all objects in Task 1 and Task 2 were visible on the first sight. The real 3D users were more prone to omit important aspects of the scene. These results are in accordance with a previous study by Špriňárová et al. (2015). Within Task 3 we encountered the floor effect and no differences were found. However, as seen in Fig. 7, the omission rate was considerably higher among the real 3D group. Although the differences in the omission rate between the Tasks 1, 2 and 4 were not statistically significant, the propensity of the real 3D participants to ignore some aspects presented in the scene remains an issue for further research as it could be considered from the human factors point of view [44].

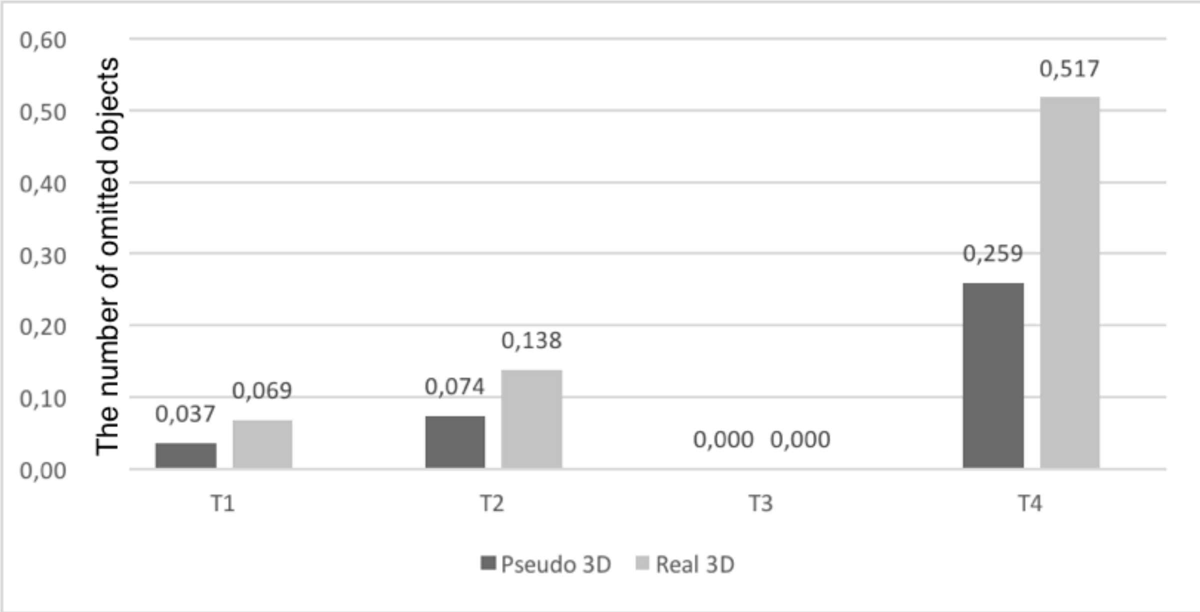


Fig. 7: The Average Number of Omitted Objects in Tasks 1- 4, Experiment 2

The increase in total motor activity invested into searching among the pseudo 3D group (Task 4, see Fig. 8) might have been surprise-related; during the testing, we observed that more participants in the pseudo 3D condition noticed during manipulation with the 3D visualization that there were hidden objects in the scene which were not noticed on the first sight. The pseudo 3D participants were surprised that the scene contained more objects than what was visible on the first sight and they searched for other possibly hidden objects, just to be sure. The analytical searching process (e.i. the systematic sequential searching) was activated by the non-standard situation while the real 3D participants contented themselves with the first available answer.

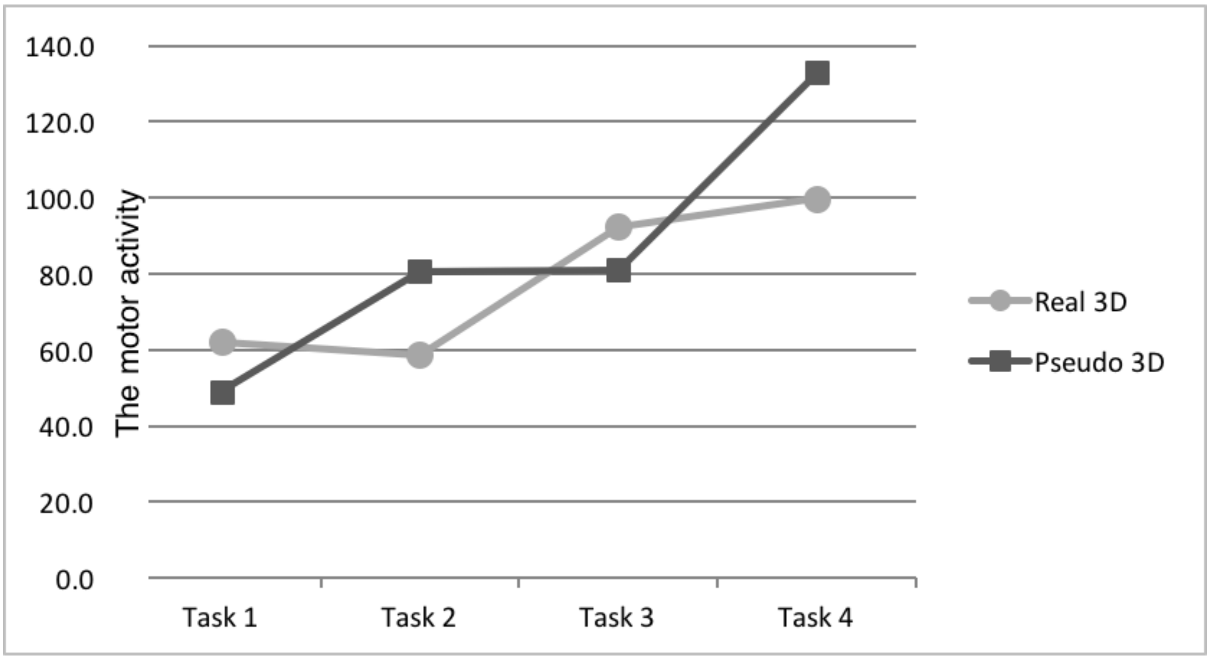

Fig. 8: Total Motor Activity in Tasks 1- 4, Experiment 2

**Action-type Analysis**

In order to gain a better insight into the participants' motor interaction with the UI, we analyzed the interaction with respect to the three specific types of action performed in the virtual interface (dragging, orbiting, and zooming). Fig. 9 shows almost identical movement patterns for both groups of participants with respect to the training task, which was preceded by instructions. For the testing period, however, the strategies of the real 3D and the pseudo 3D groups slightly differed, although in general the patterns of actions in both conditions were similar. Although there is needed more precise research on motor interaction with interactive geovisualizations, within this study there was found no relation between specific type of 3D visualization and general pattern of navigating motor activity (see in Fig. 9).

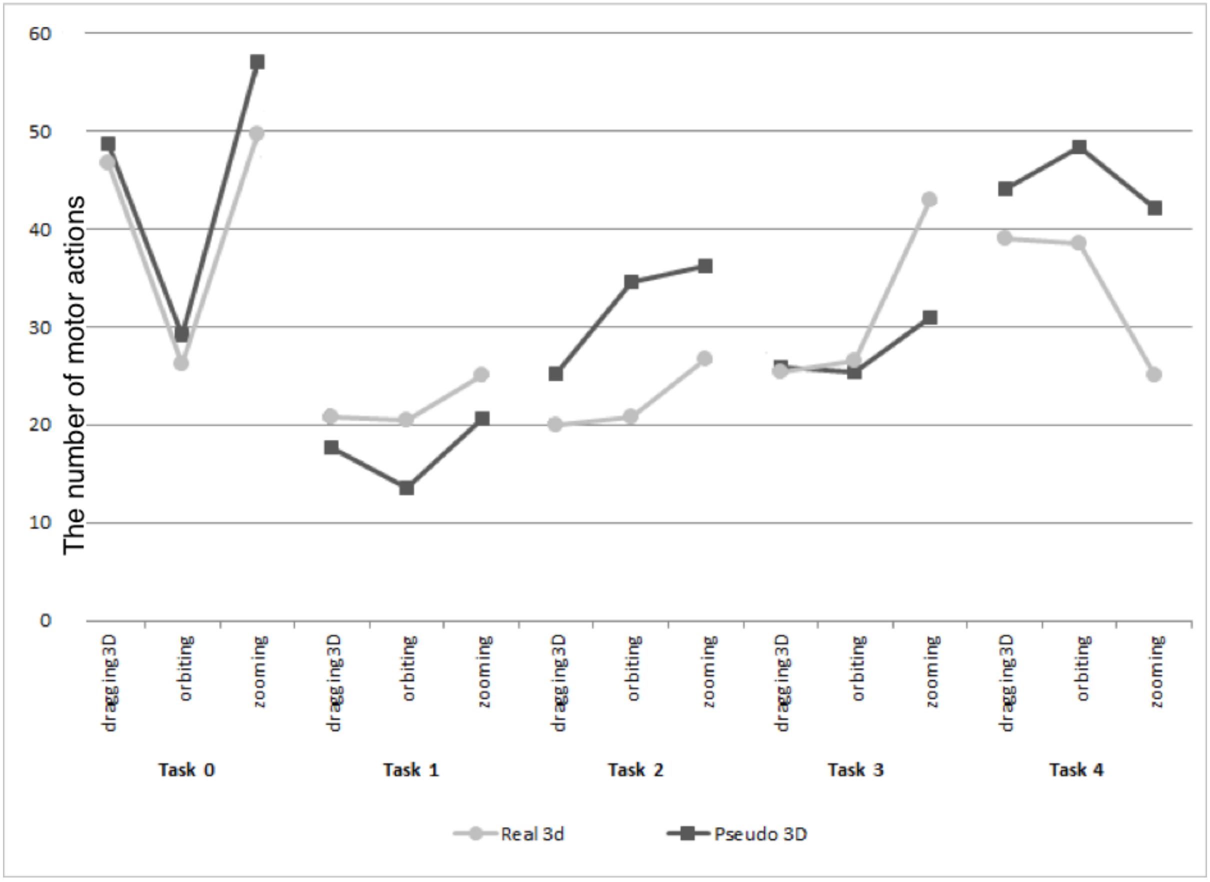


Fig. 9: Detailed Analysis of Motor Activity In Tasks 1- 4, Experiment 2

## Discussion and Conclusions

Based on results of the data analysis, we found strong evidence that real 3D condition enriched with stereoscopic binocular depth cues resulted in better spatial identification in non-interactive (i.e. static) 3D geographical visualizations (Experiment 1). The importance of binocular disparity in visual perception was emphasized e.g. by Landy et al. (1995) [20] and Qian (1997) [19]. The above effect was present in altitude-identification in non-interactive tasks without time limit, where the real 3D participants significantly outperformed the pseudo 3D group. We can assume that in Task 1 the above mentioned effect was cut off by the effect of time pressure. The completion times in Task 2 were found to be the same for both conditions. This evidence opposes the previous suggestion about the operator's general tendency to spend more time with evaluating the spatial features of pseudo 3D visualizations [16]. The suggestion was based on Crampton's claim (1992) [36] that a two-dimensional content must be mentally transformed into a three-dimensional form and thus is bound to require more mental operations. We can summarize that our expectation about better altitude identification due to binocular disparity included in real 3D visualization was verified. We assume that this effect arisen due to the presence of binocular depth cues in real 3D visualization tasks where more visual cues were available to participants to help them with the detection of spatial data. Binocular disparity can thus be viewed as enhancing the perception of spatial distribution in static geovisualizations.

In the interactive 3D visualizations as they were used in Experiment 2, the missing binocular cue in the pseudo 3D condition was expected to be compensated by the interaction with 3D geovisualization. According to the results from Experiment 2, the interactive nature of the scene can offer enough compensation for the missing binocular depth cue thanks to the kinetic depth effect [34] provided by manipulation with the visual display, as earlier discussed by Bingham and Lind (2008) [45] or Rogers and Graham (1982) [46]. A pseudo 3D user who interacts with the dynamic geovisualization can reach the same information about the spatial distribution of the scene as the real 3D user, but with the use of different visual cues. However, due to differences in number and quality of visual cues included in these alternative ways of 3D visualization, the real 3D group and the pseudo 3D group were expected to differ in the way participants handled the geovisualizations to reach the correct solution (e.g. time demands or motor activity performed when navigating the scene). In this matter our results showed no differences between the two groups. The task-solving speed and accuracy were found to be on the same level for both 3D conditions. The amount of motor activity, which was supposed to be an indicator of enhanced exploring/processing of the visual display, was found to be the same for both groups in the interactive subsection and no significant differences were found. The comparable amount of motor activity performed by the participants from both groups can be explained by the concept of affordance [47], which is an intrinsic property of an interactive 3D visualization; thus, navigating of the visual display occurred spontaneously in both conditions and the tasks were solved with approximately the same amount of motor activity, because participants navigated (moved) the 3D visualizations spontaneously in both conditions.

The increased tendency to omit target objects in the relatively simple tasks, which was observed in real 3D group (Experiment 2), should be mentioned. As participants were asked to order bodies in the interactive 3D visualizations according to their altitude (Experiment 2), the real 3D users persistently omitted (didn't noticed) some of those bodies, although without statistical significance (tasks 1, 2 and 4). Such omissions speaks for computational nonequivalency as discussed by Larkin and Simon (1987) [ 21] and can be explained from more than one point of view. The influence of such phenomena as fidelity of the display [48], immersion and presence as the "feeling of being in VR" [49], which could affect the choice of visual cues [33] included in the scene, should be discussed within the further research.

Considering the above, the issue of 3D geovisualization still remains quite ambiguous. It seems clear that real 3D vision can enhance the ability to detect the altitude dimension in static 3D geovisualizations, on the other hand its advantages disappear when the 3D visualization is interactive. The interactiveness including kinetic depth cues can offer the satisfying amount of visual cues for accurate spatial identification in the pseudo 3D visualization. However, as geovisualization is frequently used in many applied areas, the results suggest that the real 3D visualization in comparison with pseudo 3D can increase the risk of omitting some of the important aspects of the exposition in interactive tasks (which could be classified as human error [44]). This should be considered as a crucial aspect in the human-computer interaction issues, especially for the areas where any human error might endanger lives or property [50, 51]. Above mentioned issues are a challenge for further software optimization and upcoming research.

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18. 10. 2016

Dear Sir or Madam,

I wish to submit an original research article entitled "When the display matters: A multifaceted perspective on three-dimensional visualization of geographical data" for your kind consideration. We believe that this manuscript is appropriate for publication in Open Geosciences because it matches the specific focus of your journal in the field of geoinformatics, geovisualization, geographical data depiction and interaction with it. The paper reports the results of two experiments regarding the judgements of altitudes in projected (pseudo 3D) and stereoscopic (real) 3D geovisualizations.

In this paper we present the original user interface designed to capture interaction with the 3D virtual geovisualizations. The interface was developed within multidisciplinary collaboration at Masaryk University between psychologists, geographers and programming experts. With the use of Motion Capture system and the software platform VRECKO we compared whether the accuracy in altitude identification and motor activity of users in real 3D visualization differed from those using pseudo 3D when exploring virtual terrains.

The paper "When the display matters" brings insight into hitherto ambiguous opinions about 3D visualization and offers the answers for previously stated questions. We found a strong evidence that the real 3D visualization enhances accuracy in the altitude identification in static 3D geovisualizations. In interactive geovisualizations the advantages of real 3D disappear due to possibility to navigate such visualizations. The results are significant with respect to many applied areas, such as directly geo-related domains (geography, geology etc.) as well as beyond (e.g. crisis management, aviation) where the 3D geovisualizations are considered to be the promising technology for the future development.

Open Geosciences focus covers issues discussed in presented study. We believe, that not only cartographers but also human factors experts and researches using the various kinds of modern technology for measurement of human behavior would be interested in presented study. The application potential of 3D technology and Motion Capture technology is widely discussed and within our research efforts we find it necessary to broaden this field as much as possible.

We have no conflicts of interest to disclose. Please address all correspondence concerning this manuscript to me at jurik.vojtech@gmail.com. Thank you for your consideration of this manuscript.

Hereby I confirm that this work is new, original and has not been published elsewhere, nor is it currently under consideration for publication elsewhere.

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Sincerely,

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