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Interactive 3D geo-browsers, also known as globe viewers, are popular, because they are easy and fun to use. However, it is still an open question whether highly interactive, 3D geographic data browsing, and visualization displays support effective and efficient spatio-temporal decision making. Moreover, little is known about the role of time constraints for spatio-temporal decision-making in an interactive, 3D context. In this article, we present an empirical approach to assess the effect of decision-time constraints on the quality of spatio-temporal decision-making when using 3D geo-browsers, such as GoogleEarth, in 3D task contexts of varying complexity. Our experimental results suggest that while, overall, people interact more with interactive geo-browsers when not under time pressure, this does not mean that they are also more accurate or more confident in their decisions when solving typical 3D cartometric tasks. Surprisingly, we also find that 2D interaction capabilities (i.e., zooming and panning) are more frequently used for 3D tasks than 3D interaction tools (i.e., rotating and tilting), regardless of time pressure. Finally, we find that background and training of tested users do not seem to influence 3D task performance. In summary, our study does not provide any evidence for the added value of using interactive 3D globe viewers when needing to solve 3D cartometric tasks with or without time pressure.

Keywords: geo-browsers; map interaction; time pressure

Introduction

For several thousand years, static, hardcopy paper maps have been the state of the art for map-based decision making. Due to technical progress, such as the increase in processing power of computers, and the availability of user-friendly interfaces, recent years have seen a dramatic popularity increase of interactive maps. In particular, so-called 3D geo-browsers (Hruby et al. 2009), virtual globes, and 3D globe viewers have introduced the concept of fully interactive 3D maps to a wide, non-professional audience (Riedl 2006). Three-dimensional geo-browsers, such as GoogleEarth, NASA's World Wind, and similar efforts, provide users with the possibility to interact with the map display in various ways, such as panning, zooming, and especially, rotating and tilting in 3D (Schultz et al. 2008).

However, it is still unclear how people actually "geo-browse" (Peuquet and Kraak 2002; Abend et al. 2012), and whether these novel tools for interaction with the third dimension available in interactive geo-browsers and globe viewers are indeed efficient and effective for spatio-temporal decision-making (Fabrikant 2005). We know even less how people use map displays including 3D geo-browsers under varying decision-time constraints (e.g., under time pressure), and how time pressure might affect the quality of the map-based decision-making. This is surprising, as many map-based decisions in life are often made under time pressure, and thus time pressure is an important factor to consider for the efficiency and effectiveness of map-based decisions (Wilkening and Fabrikant 2011a).

In this paper, we try to shed light on these issues by means of a controlled experiment, in which participants have to solve 3D cartometric tasks of varying complexity using GoogleEarth, as one prototypical 3D geo-browser. We specifically investigate how often participants interact with a 3D geo-browser display, which tools they use when they interact, and which role time pressure plays in this context.

Related work

Already in the early nineties, Kraak (1993) envisioned state-of-the-art, interactive, virtual globes, featuring three-dimensional visualization capabilities and allowing "geometric map transformations such as rotation, scaling, translation and zooming to position the map in 3D space with respect to the map's purpose and the phenomena to be mapped" (p. 193). While several design considerations for 3D cartography have been made, and some empirical studies have focused on 3D cartography and visualization (e.g., Moellering 1980, and Kraak 1993), decision-making effectiveness or efficiency of human–map interactions with virtual globes or 3D geo-browsers has not been widely studied by cartographers.

In one of the first empirical studies, specifically investigating how people navigate in space with 3D geo-browsers,

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Abend et al. (2011) found that users tend to employ a mix of interaction tools for navigation. They also found that participants preferred to retain a North-up orientation of the map display, while users with 3D graphics software experience were more likely to tilt the view when navigating.

There is an ongoing debate to what extent people generally benefit from being able to interact with a (3D) visual display, with inconclusive empirical results. While studies on visual object recognition (Harman et al. 1999; James et al. 2002), or on the acquisition of spatial knowledge in a virtual environment (Peruch et al, 1995) have found significant advantages to providing interactivity to users, other studies were not able to detect any benefits of interactivity for navigating in desktop and virtual environments (Foreman et al. 2004; Melanson et al. 2002). There are even examples of studies showing that participants who were searching for structure in 3D data performed worse when provided with possibilities to interact (Marchak and Zulager 1992). In a study on user interaction with a 3D visualization for inferring and drawing cross sections, Keehner et al. (2008) have demonstrated that providing participants with active controls of the 3D display did not necessarily enhance people's task performance. Having participants passively watch a movie showing optimal display interaction by good task performers was already sufficient to improve task performance to a level that was equal to that of participants directly interacting with the 3D display. The results of Keehner and colleagues indicate that seeing task-relevant information might be more important in some task contexts, than allowing people to interact with a 3D display, regardless of whether this information is obtained actively or passively. From this discussion one might conclude that the open question is not whether interactivity is superior to static displays or not, but for which particular task contexts interactivity might be useful.

User characteristics (i.e., individual and group differences) can often play a crucial role for the success of display use, but this is typically overlooked in studies investigating the effectiveness and efficiency of map-based decisions with spatio-temporal displays. Various studies about the self-assessment of spatial intelligence have demonstrated that males tend to overestimate their spatial abilities related to map-reading tasks, while females often underestimate them (Furnham et al. 1999; Furnham 2001). This phenomenon has also been found for visual categorization with aerial photographs (Lloyd et al. 2002), and way finding skills (Pedersen 1999). However, we still know very little on how user characteristics and training might interact with the effectiveness and efficiency of spatio-temporal decision-making when using 3D geo-browsers.

Hegarty (2010) observes that "children learn world geography by flying over the earth using Google Earth" (p. 277), and that the development of 3D geo-browsers perhaps has stimulated a new interest in studying spatial thinking and the acquisition of spatial intelligence. In this context, Hegarty (2010) also mentions the influence of playing video games on spatial intelligence. While males seem to have significant advantages in mental rotation abilities (Linn and Petersen 1985; Voyer and Saunders 2004), gender differences in mental rotation can be reduced by playing video games for ten hours (Feng et al. 2007; Terlecki et al. 2008).

In another study, Cohen and Hegarty (2007) investigated correlations between spatial abilities and performance on 3D cross-section tasks with 3D displays. These authors found that participants with better spatial abilities were more likely to more effectively and efficiently interact with 3D visualizations.

Time pressure might be another factor to consider when investigating the effectiveness and efficiency of decision-making with interactive 3D displays. Clearly, decision-making will take more time when having to interact with a 3D map, compared to decision-making with a static 2D display. Researchers outside of cartography have shown that time pressure can have a negative effect on the quality of the decision-making such as, response accuracy (Maule and Edland 1997; Wickelgren 1977), and response confidence in decisions made without maps (Maule 1998; Maule and Andrade 1997; Smith et al. 1982). This is contrasted by empirical studies that find a positive effect of time pressure on the quality of human decision-making (Andrews and Farris 1972; Peters and O'Connor 1980). While only a few studies have focused on map-based decision-making under time pressure (Baus et al. 2002; Srinivas and Hirtle 2010), no prior study has specifically looked at decision making with 3D geo-browsers under time pressure.

The relationship between human response accuracy and response confidence has been investigated to assess the effectiveness or quality of decision making. Prior behavioral decision making research has repeatedly shown that people tend to be overconfident in their responses for various tasks (e.g.,Lichtenstein et al. 1982). In particular, it has been shown that human overconfidence is more pronounced for complex tasks, and that people who are generally more confident are also more over-confident in their responses. The relationship of (over)confidence, task difficulty, and response accuracy is discussed in detail in Klayman et al. (1999), for instance. Consistent with prior non-cartographic research (i.e., Levin et al. 2000), Fish and colleagues (2011) have found that participants asked to detect change in animated maps were generally overconfident in their change detection capabilities, but not very accurate.

Related own work

We carried out a series of experiments to investigate the effect of time pressure on map-based decision-making. In the first experiment on map use preferences (Wilkening and Fabrikant 2011b), we explored people's preferences for interaction tools typically available in interactive 2D and 3D maps. Participants (N = 155) were asked which interaction tools they would prefer to use for similar road selection tasks, but under different decision-time scenarios: an emergency response task under time pressure (TP), and an excursion planning task without time pressure (NTP). Participants had to rate their interaction tool preferences on a scale ranging from (1 "I would definitely not use the tool") to 5 ("I would definitely use the tool").

Collected preference ratings are summarized in Table 1 below. The ratings suggest that the 2D interaction tools (i.e., zooming and panning) are more preferred than the 3D tools (i.e., rotating and tilting), regardless of the time available to respond. Only for the tilting tool, preferences differed significantly between the two decision-time scenarios. People preferred to tilt the map display significantly less when under time pressure. Participants' open-ended responses such as "are just for decorative purposes", "should not be used", or "are rather toys" might provide reasons for the low ratings of the 3D tools.

In two follow-up experiments, we assessed the effects of time pressure on response accuracy and confidence in decision-making with 2D static maps. The first experiment focused again on a 2D road selection task (Wilkening 2010). We found that different response time limits affect response confidence more than response accuracy for the road selection task with static 2D maps varying in realism. In a third time pressure experiment, we asked participants to solve a 3D slope detection task using a combination of 2D maps showing elevation information; one showing contour intervals, two types of shaded relief maps, and one with classified slope information (Wilkening and Fabrikant 2011a). We find that time pressure had a positive effect on map-based decision making. Both overall response accuracy and response confidence follow an inverted U-shaped curve pattern, well established in the decision-making literature in psychology (Hwang 1994). That is, participants were most accurate and confident when under a moderate response time limit, while response accuracy and confidence decrease with more decision time available.

We then conducted expert interviews from the domain of 2D and 3D map-based decision making under time pressure, including helicopter pilots and ambulance drivers. Interviewed experts reveal that they rarely use 3D geo-browsers for their daily work, for several reasons, 1) because of the low spatio-temporal resolution of the available satellite images, 2) because the map data is too slow to load, and 3) because they are more familiar with paper maps, which they regard as sufficient for their everyday tasks. This lead us to empirically investigate if and how useful 3D geo-browsers are for spatio-temporal decision-making under time pressure.

Table 1. Interaction tool preferences (Standard deviations in brackets).

Tool	Average NTP	Average TP
Zooming	4.9 (0.5)	4.8 (0.9)
Panning	4.6 (0.8)	4.5 (0.9)
Tilting	3.4 (1.3)	2.7 (1.3)
Rotating	2.6 (1.3)	2.6 (1.4)

Empirical study

With the time pressure experiment we report below using a 3D geo-browser, we wish to investigate to what extent observed human–map interaction for spatial decision-making in a 3D context is in accordance with interaction tool preferences, as recorded in our first map interaction preference study. Another aim of this experiment is to assess to what degree time pressure might not only influence the type and frequency of human–map interaction, but also affect response quality. Within the context of behavioral decision research, time pressure can be considered as another source of uncertainty (Jungermann 2004; Mellers 2002), which can explain the quality of decision-making.

As little is known on the effect of user background and training in the geovisualization literature, we are also interested in studying how people's background and training might affect the quality of decision-making with a 3D geo-browser. A series of group difference and individual difference factors are of interest to us, such as whether people who are good "mental rotators", thus having high spatial competencies, might also rotate a digital map display more often, as previous work by Cohen and Hegarty (2007) suggests. A related question particularly relevant for 3D geo-browsers is whether participants who rotate paper maps when navigating in the real-world (Lobben 2004, 2007), would also rotate an interactive map display more often when navigating in a digital world, or how familiarity with video games might influence the efficiency and effectiveness of decision making with interactive 3D displays, as shown by several authors outside of cartography (Feng et al. 2007; Terlecki et al. 2008). Furthermore, we ask whether experienced 3D geo-browser users might also tilt the display more often compared to 3D geo-browser novices, as Abend et al. (2011) have shown. Finally, we wondered whether we could replicate higher male response confidence in task performance as found in various other studies (Furnham 2001; Furnham et al. 1999; Lloyd et al. 2002), including our own (Wilkening 2010; Wilkening and Fabrikant 2011a) with 3D map-use tasks in an interactive 3D geo-browser context. Based on prior work, our working hypotheses regarding individual and group differences can be summarized as follows:

1. People who are good mental rotators (and tend to have high spatial abilities), rotate interactive 3D maps more often.
2. People who rotate paper maps during navigation in the real world (and tend to have low spatial abilities) rotate interactive 3D maps more often.
3. People who often play video games (and tend to have improved spatial abilities) interact more with interactive 3D maps.
4. Males are more confident in their 3D map-based decisions, without being more accurate.

Based on the related work discussed earlier, one and two in the list above are competing hypotheses. In the following section we detail the empirical 3D geo-browser study.

Experiment design

This experiment followed a complete within-subject design, consisting of four cartometric tasks:

1. Identification of elevation at two given points.
2. Selection of the highest point along a given path.
3. Selection of the steepest slope based on three given locations.
4. Qualitative description of the terrain between two given points.

There are a series of reasons why we chose these particular tasks. First, we needed to use the same type of task for two different time constraint scenarios: one task in a time pressure situation (e.g., emergency response), and a second task in a condition without time pressure (e.g., excursion planning). The chosen tasks are similar in scope to the tasks used in the prior preference experiment (Wilkening 2011b). One of our aims was to be as consistent as possible with the prior preference experiment, in order to compare user preferences with their actual performance. Moreover, the tasks in this experiment needed to be particularly relevant for decision making with the third dimension. Finally, we aimed for an appropriate balance between ecological validity (i.e., believable use and interactions with a 3D geo-browser) and internal validity, including experimental control (i.e., comparison to prior studies and measurable outcomes).

We chose tasks with varying levels of complexity to explore how these might trigger different human–map interactions, and how tasks with varying difficulty might influence response accuracy and confidence as prior research suggests. The first three tasks are closed-ended, and they can be ordered from least (1) to most complex (3). We consider task 1 as the least complex in the above list, as participants are simply asked to read off height values at two given elevation points. For all other tasks, participants are asked to process several pieces of information before making a decision. For task 2: "highest point", participants have to first read off, and then compare the elevation information along the entire given route. This is why we believe that "highest point selection" is more complex than "elevation identification". The third task "steepest slope" has additional complexity, in that participants need to derive new information (i.e., slope) based on given data (i.e., elevation and distance) before making a decision. There are at least two possible strategies for doing this: Participants could tilt and rotate the map to visually inspect the slope at the three given points, and compare the derived slope information before making a decision. Alternatively, they could calculate the slopes at each of reference points, after inspecting respective height information (one start point and one end point for each of the three slopes), and then calculate the vertical and horizontal differences for each of the newly derived slopes. Both strategies require more information processing steps than any of the two other tasks. Finally, we contend that the qualitative, open-ended "route description" task (4th bullet) is less complex than the "highest point" task (2nd bullet), because for "route description" participants are asked to analyze a short portion of the route, and not the entire route, and they do not have to provide exact elevation information.

We operationalized human–map interaction by measuring the type and frequency of tool use, commonly found with interactive map displays: zooming and panning, as well as rotating and tilting, especially useful for 3D tasks. These four tools are also the most commonly available interaction tools for navigation with 3D geo-browsers. We hypothesized that using any one of the interaction tools (i.e., zooming, panning, rotating and tilting) would lead to higher response accuracy, and thus higher response confidence. However, all chosen tasks can potentially also be solved without interacting with the map display at all, or, more precisely, without using any of the four interaction tools.

Participants

Twenty-one participants (11 males and 10 females) took part voluntarily in this study. The majority were students and staff of the Department of Geography at the University of Zurich. Two of the 21 participants mentioned they use maps "very frequently" (10%), five "frequently" (24%), eight "occasionally" (38%), and six "never" (29%) in their daily working lives. As for leisure time activities, three stated they use maps "very frequently" (14%), thirteen "occasionally" (62%), and five "never" (24%).

Participants were also asked how familiar they were with GoogleEarth or other types of 3D geo-browsers. Three participants professed to be "very familiar" (14%) with 3D geo-browsers, eleven "rather familiar" (52%), five "rather not familiar" (24%), and two "not familiar at all" (10%). The two participants who were "not at all" familiar with geo-browsers were in fact geographers by training. The distinction "non-geographer" and "geographer" can therefore not simply be made by measuring the variable "familiarity with 3D geo-browsers".

Nine of 21 participants (43%) mentioned playing video games at least occasionally, and fourteen participants (67%) mentioned that they rotate paper maps when navigating in the field. Seven of the nine "video gamers" (78%) were males, while eight of the twelve "non-video gamers" were females (67%). The average Mental Rotation Score of participants is 20.7 (SD = 8.0). On average, females scored 15.7 points, while males scored 25.2 points. The median was 21.0. The participant sample represents the expected gender differences in mental rotation abilities.

Materials

As this experiment focused on tasks where the third dimension is particularly relevant, the test stimuli shown in GoogleEarth depict GPS tracks of human movement in mountainous areas from all over the world. We chose GoogleEarth as the 3D geo-browser for our experiment, as it represents the most frequently used 3D geo-browser (Schöning et al., 2008). Eight GPS tracks had been downloaded from a GPS track sharing website and imported to GoogleEarth. Seven marker symbols were added to the GPS tracks in GoogleEarth. The marker symbols indicate a start location (using the standard red marker labeled "A" from the GoogleEarth icon collection), an end location (a red marker labeled "B" from the same icon collection), and five waypoints on the GPS track. Three waypoints were represented as red markers, and labeled 1, 2, and 3, and two waypoints symbolized pushpins, one of them in yellow, and a second in green color. All other default layers in GoogleEarth (place names, points of interest, etc.) were deselected, and thus not visible in the test displays. A screenshot of a sample stimulus including a complete GPS track with all types of markers is shown in Figure 1 below.

Procedure

The experiment took place in a windowless office, specifically designed for controlled experiments. Participants were welcomed and asked to sign a consent form. Next, participants were asked to complete the Vandenberg Mental Rotation Test (MRT), in order to assess their mental rotation abilities (see Vandenberg and Kuse 1978). In this paper-and-pencil test, participants are asked to decide if rotated block shapes match each other or not. The MRT consists of 20 trials. After reading the instructions, participants were given six minutes to solve the entire test. The MRT took approximately 15 minutes, including warm-up.

Following the MRT, participants were introduced to the computer-based part of the experiment. It was administered on a Dell Precision 390 Windows workstation, equipped with a 20-inch flat panel display, set to a screen resolution of 1024 × 768 pixels. At the beginning of the experiment, participants were introduced to the four map interaction tools; zooming, panning, rotating and tilting, and other task-relevant map elements visible on the screen (i.e., the scale bar, and the elevation information). Following that, participants were introduced to the concept of slope, and how to calculate it (e.g., rise over run). This was first done with a sketch on paper, and then by reading distance information from the scale bar, and elevation information off the screen in GoogleEarth. Participants were then asked to perform a warm-up trial identical to the task in the main part of the experiment, which consisted of answering four questions on the basis of a single GPS track:

(1) Elevation AB: What is the elevation (above mean sea level) of point A and point B?
(2) Highest point: Where is the highest point (above mean sea level) along the entire path/GPS track?
(3) Steepest slope: When travelling from A to B, at which of the three points (1, 2, or 3) does the path/GPS track have its steepest slope?
(4) Profile description: How would you verbally describe the elevation profile between the yellow and the green pushpin? For instance, "only downhill", "flat", or "first uphill, then downhill"?

Figure 1. Screenshot of a sample stimulus in GoogleEarth showing a GPS track including markers (© 2013 Mapcity; Image © 2013 DigitalGlobe; © 2013 Inav/Geosistemas SRL; Image © 2013 GeoEye).

After the warm-up trials, participants completed the first half of the experiment. In this first half, participants were asked to solve the four tasks four times, with four different GPS tracks. After participants had solved all tasks for one GPS track, the geographical extent of the map changed, so that the full extent of the new GPS track could be seen on the screen. The sequence of the two scenarios, time pressure (TP), and no time pressure (NTP) was systematically varied across participants: For one half of the experiment, participants were under a time limit of two minutes for solving all tasks for each track. In the TP condition, participants were instructed to answer all four questions within a given temporal limit, as accurately as possible. This time limit was identified after pilot testing. For the other half of the experiment, participants were not given any constraint (NTP), and they were told that they could take as much time as they needed for responding. The order of the eight GPS tracks was systematically varied as well. At the end of the first half, participants were asked how confident they were in their decisions for each of the four tasks. Confidence was assessed using a rating scale ranging from 1 (not confident at all) to 4 (very confident). Following that, participants continued solving the second set of four GPS tracks in the second condition (TP and NTP, respectively). Participants were again asked to indicate their confidence for the second set of trials. Finally, participants were asked to fill out a background questionnaire, in which they specified their map use experience, their familiarity with GoogleEarth and 3D displays, whether they rotated paper maps when navigating in the real-world, and how often they played video games. The duration of the entire experiment, including the MRT, was between 40 and 60 minutes. After completion of the experiment, participants were debriefed, and given a meal voucher for the university cafeteria in return for their participation. The entire workflow of the Experiment is shown in Figure 2.

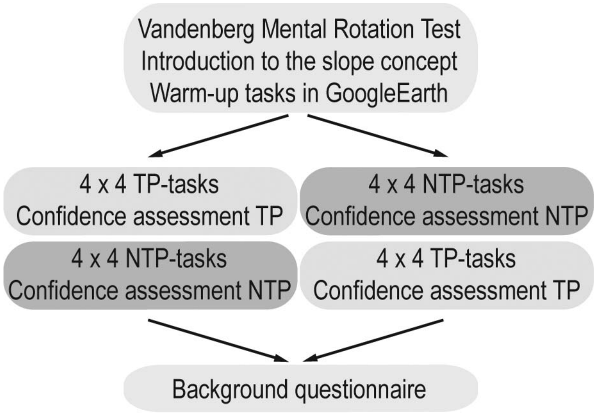

Figure 2. Illustration of the workflow of the experimental procedure.

Results

We first discuss how time pressure and task type influence the frequency and the type of human–map interactions. Then, we report how response accuracy and confidence are affected by time pressure, with respect to task types and interaction tools. Finally, we present how user-related factors (see respective four working hypotheses listed earlier) can influence human–map interactions, response accuracy and confidence.

Effect of time pressure and task on human–map interactions

As mentioned in the section "Procedure", participants were asked to perform four tasks with four different GPS tracks, under TP and NTP conditions. For every task and stimulus, we recorded which tool(s) participants used to solve the test questions. We did not record how often a tool was used per stimulus, or how much time participants spent using a certain tool, but rather whether a tool was used at all or not. Hence, the maximum interaction frequency for each map type is four per task type. This means 4 stimuli × 4 tasks per time pressure condition (TP/NTP), and thus, a maximum attainable frequency of sixteen possible interactions. The average frequencies of human–map interactions per task and tool type are shown in Tables 2 (TP) and 3 (NTP). Our first hypothesis was that people overall would interact more when they are not under time pressure. Moreover, we also hypothesized that people would interact more when solving complex tasks compared to more simple tasks.

In Tables 2 and 3, the cell values represent average interaction tool frequencies, with standard deviations in brackets. The maximum possible value for each cell is 4, and 16 for the overall row and column sums, as mentioned earlier. The tables reveal that, overall, participants interacted most for the steepest slope task, the most complex of the closed-ended questions, and least for the elevation detection task, which we considered the easiest of the performed tasks in this experiment (see respective "overall" column sums in Table 2).

We ran a three-way (within-subject) repeated-measures ANOVA (alpha level = .05) for pressure type (two levels: TP and NTP) by tool type (four levels: zoom, pan, rotate, and tilt), and by task type (four levels: elevation AB, highest point, steepest slope, and profile description), using a Bonferroni correction for multiple comparisons. The ANOVA results suggest significant main effects of time pressure ($p < .01$), tool type ($p < .01$), and task type ($p < .01$) on human–map interactions. We also find a significant two-way interaction effect of tool type by task

Table 2. Average frequencies of human–map interactions under time pressure (TP).

Tool/Task	Elevation AB	Highest point	Steepest slope	Profile description	Overall
Zooming	1.6 (1.7)	1.6 (1.3)	2.5 (1.5)	2.1 (1.5)	***7.8 (4.6)***
Panning	1.7 (1.7)	2.6 (1.4)	3.6 (1.0)	3.4 (0.9)	***11.4 (3.7)***
Rotating	0.3 (0.7)	1.0 (1.5)	2.2 (1.5)	1.7 (1.3)	***5.2 (3.7)***
Tilting	0.4 (0.9)	2.0 (1.8)	2.4 (1.6)	1.7 (1.4)	***6.4 (3.7)***
Overall	***4.0 (4.1)***	***7.2 (5.0)***	***10.7 (3.8)***	***9.0 (2.9)***	

Table 3. Average frequencies of human–map interactions without time pressure (NTP).

Tool/Task	Elevation AB	Highest point	Steepest slope	Profile description	Overall
Zooming	2.8 (1.8)	2.8 (1.4)	3.2 (1.2)	2.4 (1.4)	***11.2 (4.6)***
Panning	2.8 (1.7)	3.2 (1.2)	3.9 (0.3)	3.5 (0.8)	***13.4 (3.3)***
Rotating	0.2 (0.9)	2.1 (1.3)	2.5 (1.2)	2.1 (1.4)	***7.0 (3.4)***
Tilting	0.2 (0.9)	2.4 (1.5)	3.1 (0.9)	2.0 (1.2)	***7.7 (2.9)***
Overall	***6.0 (4.1)***	***10.6 (4.3)***	***12.7 (2.1)***	***10.0 (2.4)***	

type, and a three-way interaction effect of pressure type by tool type by task type.

Time pressure type: As hypothesized, we find that overall, the interaction tools are significantly more used when participants are not under time pressure ($p < .01$).

Tool type: As hypothesized, we find that overall the 2D pan tool is significantly more used than all the other tools, irrespective of the time pressure condition. For the second frequently used zoom tool this pattern is true only in the NTP condition, but where the statistical difference to the most frequently used pan tool is borderline ($p = .05$).

Task type: As hypothesized, tool use frequency also significantly depends on the type of task. As predicted, tool use frequencies significantly increase when the hypothesized task complexity increases (closed-ended tasks 1–3), in both, TP and NTP conditions, as shown in respective “Overall” task rows at the bottom of Tables 2 and 3.

As mentioned earlier, panning and zooming are indeed the most frequently used tools overall, followed by tilting, and least, rotation. This order is consistent for both the TP (Figure 3) and NTP (Figure 4) conditions, but the use differences across tools are not all statistically significant. On average, participants consistently panned significantly more than they used all other interaction tools, in both conditions, and all tasks. The highest point identification task was the only task for which people used one of the 3D interaction tools (i.e., tilting) more than a 2D tool (i.e., zooming), but this difference is not significant.

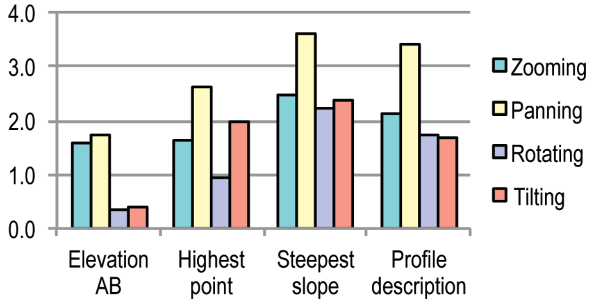

Figure 3. Average usage of interaction tools under time pressure (TP).

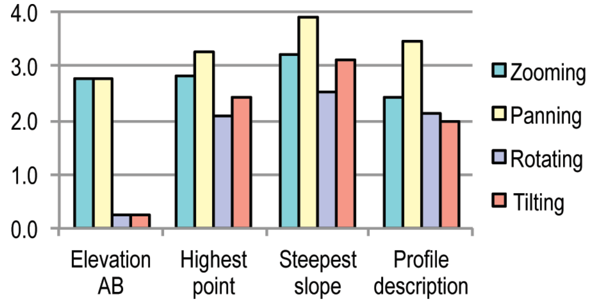

Figure 4. Average usage of interaction tools without time pressure (NTP).

On average, participants did not only rotate the display significantly less frequently ($p < .05$), but also zoomed and panned significantly less when under time pressure ($p < .01$, (compare “Overall” columns across Table 2 and 3). The differences between TP/NTP conditions are not significant for the tilting tool ($p = .057$).

We conducted an ANOVA to investigate whether the order of the time pressure conditions might have influenced human–map interactions. This analysis did not yield any significant results. In other words, we did not detect potential asymmetrical transfer effects of tool use.

Effect of time pressure and task on response accuracy and confidence

Next, we investigate how time pressure and the differences in task complexity influence response accuracy and confidence. The analysis of accuracy focuses on the two tasks highest point and steepest slope, as highest point represents a typically simple, and steepest slope a typical complex, task. For the other two tasks, response accuracy is either a question of how detailed participants zoom in (elevation AB), or it cannot be measured quantitatively (i.e., profile description). Therefore, quantitative analyses of accuracy seem not meaningful for these two tasks. We hypothesized that participants would be more accurate and more confident about their answers when not under time pressure. Based on our previous experiments, we also assumed that time pressure would have a stronger effect on response confidence than on accuracy.

For the highest point task, we computed the deviations (i.e., absolute values) of participants' answers from the true highest elevation for each of the eight tracks, and aggregated them for both TP and NTP conditions. For the steepest slope task, we recorded whether participants selected the correct steepest slopes or not, and then grouped responses for each of the conditions.

For the highest point task, the average deviation from the true highest elevation is 421.3 meters (SD = 293.1) in the TP, and 284.3 meters (SD = 320.7) in the NTP condition. As expected, average response accuracy is worse under time pressure for this task. However, the TP/NTP differences are statistically not significant. When having to select the steepest slope, participants on average responded 1.52 (out of 4 possible) answers correctly (SD = 0.75) for the NTP scenario, while under time pressure, the number of correct answers is slightly lower (M= 1.48, SD = 0.93). The TP/NTP differences are again not significant for this task.

Confidence was measured on a scale from 1 (lowest) to 4 (highest) for each task. As Table 4 shows, participants, on average, were most confident solving the easiest elevation AB task in both time limit conditions, and least confident for the steepest slope task, perhaps because these two tasks are perceived to be particularly easy (elevation AB) and difficult (steepest slope), respectively. Average confidence ratings are higher in the NTP condition for all tasks, as expected. The average of all confidence ratings in the NTP condition (M = 3.0, SD = 0.4) is significantly higher than in the TP condition (M = 2.8, SD = 0.5), assessed with a paired samples t-test ($p < .05$). Comparing each of the four tasks, however, the differences are only significant for the steepest slope task. For this particularly complex task, the confidence ratings are generally lowest amongst all tasks under time pressure.

In summary, time pressure seems to have a stronger effect on response confidence than on accuracy, when people make 3D map-based decisions with a 3D geobrowser. People's confidence is not only time-pressure dependent, but also task-dependent. Specifically, response confidence seems to be most negatively affected by time pressure for the most complex task, that is, when having to identify the steepest slope.

Effect of interactivity on response accuracy and confidence

The potential interaction effect between human–map interaction and response accuracy was investigated by means of a Pearson's correlation analysis. Use frequencies for each interaction tool were analyzed, as well as the response accuracy for the two "highest point" and "steepest slope" tasks. This analysis shows only one significant correlation (out of 16 possible): For the steepest slope task, the quantity of zooming is positively correlated with response accuracy (Pearson's Rho = 0.46, $p < .05$) in the no time pressure condition. This might suggest that zooming leads to a significantly higher accuracy for the slope detection task, particularly when participants are not under time pressure. However, it could also imply that people who are better at interpreting slopes tend to zoom more. Under time pressure, the frequency of zooming and response accuracy are also positively correlated (Pearson's Rho = 0.33), albeit not significantly ($p > .05$).

We also calculated the correlation between human–map interactions and response confidence. In three (out of 32 possible) correlations, human–map interactions are significantly associated with the confidence with which people make decisions. The three significant correlations concern the easiest of the four assessed tasks: elevation AB. Firstly, we find that people who rotate the display more have lower confidence scores under time pressure. This negative correlation between rotation frequency and response confidence is significant (Pearson's Rho = 0.52,

Table 4. Mean confidence ratings per task and TP/NTP conditions. Standard deviations in brackets.

	Elevation AB	Highest point	Steepest slope	Profile description	Overall
TP	3.7 (0.5)	2.4 (0.8)	1.8 (0.9)	3.2 (0.8)	***2.8 (0.5)***
NTP	3.8 (0.4)	2.6 (0.7)	2.7 (0.7)*	3.4 (0.6)	***3.0 (0.4)****
Overall	***3.7 (0.4)***	***2.6 (0.6)***	***2.1 (0.8)***	***3.3 (0.6)***	

* $p < .05$

$p < .05$). Perhaps cognitive resources are at a limit for the perceptually and cognitively more demanding rotation interaction when little time is available for decision-making. Secondly, we find a similar negative correlation between display rotation and response confidence, in the no-time-pressure condition. Moreover, when not under time pressure, participants who tilt the display more have also a significantly lower confidence in their responses (Pearson's Rho = –0.57, $p < .01$ for both rotating and tilting). This could mean that the reason why people use the 3D interaction tools for additional visual feedback is that they feel unsure about their answers in this easy task, regardless of time pressure. Another interpretation for this could be that tilting seems too costly for a seemingly easy task, thus people choose not to tilt, when not under time pressure, but take lower confidence as a consequence. On a cautionary statistical note, one might also mention that the more correlations are computed for a statistical analysis, the higher the potential risk of a Type 1 error occurring.

User-related factors

Of all potential user background and training factors we initially hypothesized (see beginning of section "Empirical Study"), only how often people play video games seems to be relevant for decision-making performance in our study. People who stated that they play video games on a regular basis were also more confident in their decisions when interacting with 3D geo-browsers. On average, the confidence ratings for people who play video games is 3.2 (out of 5), in both the TP and the NTP conditions (SD = 0.4 in both cases). In contrast, average confidence ratings for people who do not frequently play video games is 2.5 in the TP (SD = 0.4), and 2.9 in the NTP (SD = 0.3) condition. A one-way ANOVA confirms significant differences on response confidence based on familiarity with video games in both the TP ($p < .01$) and the NTP ($p < .05$) conditions. While participants who play video games more frequently seem to exhibit higher confidence ratings for all tasks than participants with less video game exposure these differences are only significant for the hardest task steepest slope ($p < .05$).

However, this "over-confidence" by people who play video games frequently resembles typical confidence difference patterns between males and females found in previous experiments. As seven out of our nine "video game players" (78%) are indeed male, and eight of the twelve "no video game players" are female (67%), this could simply suggest a relationship between sex and video game familiarity. Regarding gender differences, we do find that male confidence is higher than female confidence. Male confidence is higher under time pressure in each of the four tasks, but in only two out of four tasks without time pressure. In both tasks where response accuracy was measured, males are, on average, also more accurate than females under time pressure.

Our results do not suggest, as previously hypothesized, that people who rotate a paper map when navigating in the real-world would also rotate an interactive display more often than "non-rotators". On average, "non-rotators" (N = 7) even rotated the interactive display more often than the "rotators" (N = 14), in both the TP condition (non-rotators: M = 8.4, SD = 4.7, rotators: M = 5.4, SD = 2.9), and the NTP condition (non-rotators: M = 8.4, SD = 2.4, rotators: M = 7.4, SD = 3.1). Furthermore, we did not find any evidence in our study that spatial abilities might have an influence on how often people would rotate a map display, or that people more familiar with geo-browsers would tilt the display more often.

Discussion

We could replicate the response patterns found in our previous preference study with this study. That is, the 2D interaction tools, zooming and panning, are not only the most preferred, but also the most frequently used interaction tools, with and without time pressure, in a 3D decision-making context. Surprisingly, the two 2D modes of interaction are also used significantly more than rotating and tilting, even though we specifically assessed tasks where the third dimension is highly relevant. In other words, our participants did not see any benefits of using 3D interaction tools offered by globe viewers, i.e., tilting and rotating a map display, even though these tools are probably one of the key features defining the popularity of globe viewers. More importantly, in none of the four assessed 3D tasks are people more accurate, or more confident, when rotating or tilting the display more.

Our empirical findings confirm the contention by Harrower and Sheesley (2005) that 2D interaction tools, such as zooming and panning, are key components in any information display, and that these two modes of interaction are also more important than 3D interaction tools, such as rotating and tilting. However, these authors do not offer any reason why this could be.

One way to interpret these somewhat surprising results is by treating human–display interactions as cognitive costs (Bleisch 2011; Nielsen 2007; Shepherd 2008). A user has to decide for which task and context cognitive demands have to be invested in order to realize an inference-making or decision-making benefit (Smith et al. 1982). In the context of this experiment with a geo-browser, the benefits can be measured in solving a 3D task effectively (e.g., accurately and confidently) and efficiently (within a given time constraint). Under time pressure, people can only spend a limited budget of their cognitive capacities. The harder a task, the higher the cognitive demands, the less cognitive costs a user might want to invest for interaction. Arguably, different interaction modes require different cognitive costs. When having to solve a spatial task with an interactive globe viewer, users will probably want to find the view that will help them to solve the task efficiently. Performing 3D interactions (i.e., tilting and rotating) might require more cognitive effort because of the additional display dimension, and respective time resources, than the 2D interactions zooming, or panning. From this cost-benefit point of view, it seems that users are only willing to invest in cognitively high-cost interactions (i.e., tilting or rotating) for hard tasks, but only if they can anticipate high benefits resulting from it (i.e., nothing comparable is otherwise available to solve the task successfully). Alternatively, when there is no time pressure, participants might be willing to explore the potential benefits of rotation and tilting, but more in a playful way, when efficiency is not key. As users mentioned in the preference study, they regard tilting and rotating as a superfluous interaction mode, and would rather not use it under time pressure. Conversely, when cognitive demands for a particular 3D task seem low, thus the task appears to be easy, a user might not want to waste additional cognitive costs for cognitively demanding interactions, and thus will resort to easier 2D interactions for at least equal, or perceived to be higher, decision-making benefit. Another finding that might be explainable with the proposed cognitive cost-benefit hypothesis is that our participants generally interact less with a geo-browser when they are under time constraints for solving any of the tested tasks. This is statistically significant for all four interaction tools. Time pressure, in essence, limits the amount of cognitive costs that can be allocated to a task, and indeed this limit has an effect on human–map interactions in the context of geo-browsers. The strength of this effect is, however, again dependent on perceived task complexity. The TP/NTP differences were most striking with respect to zooming in and out of a display. People seem to weigh the cost of zooming as particularly low when they are not under time pressure. One possible reason for this could be that if participants have more decision time available, they might want to invest it in obtaining more detailed information with zooming into the display. While panning, rotating, and tilting change the viewing perspective or viewing location, only zooming allows changing the spatial resolution of the display when using a globe viewer, and thus is the only tool of the four tested to access more detailed spatial information.

In our previous preference study discussed in “own previous work”, participants offered that they would tilt the map less under time pressure for a road selection task. However, in the experiment reported in this paper, participants tilt the display significantly less in the time pressure condition only for the hardest of the four tested tasks (i.e., steepest slope). Participants’ confidence ratings overall are also lower for the hardest steepest slope task, compared to all other tasks. Overall confidence ratings also significantly decrease under time pressure. One could interpret this in the sense that participants perceive cognitive costs to be both high for hard tasks, and time pressure. This, in turn, could imply that the benefit–cost ratio for tilting is best for solving complex map-based tasks only without time pressure, because tilting is too demanding for solving complex tasks under additional time pressure. In contrast, when having to identify the elevation of two points, thus a task where response confidence is generally high, participants also hardly rotate, or do not tilt at all. In this case, one could argue that the task is easy enough, even under time pressure, that it does not warrant the investment of cognitively demanding 3D interaction (i.e., rotation) for a seemingly small benefit. Removing time pressure does not lead to higher rotation or tilting frequencies for this task either. As previous findings by Keehner and colleagues (2008) suggest, interacting with a 3D display seems to be less important than seeing the task-relevant information.

Again, for this seemingly simple task, less cognitively demanding 2D interactions like panning and zooming are sufficient, to get an accurate answer. In other words, small benefits when potentially using the 3D interaction tools (i.e., rotating and tilting) for a simple identification task do not seem to outweigh the high cognitive costs for these two 3D interactions. Perhaps, another explanation for this is the relationship between effort and accuracy, as has been investigated in prior behavioral decision research (Payne, Bettman and Johnson 1993).

We did find one task where the interaction with a geo-browser seems to increase the effectiveness of map-based decisions: participants who zoom in and out of the display are significantly more accurate in the steepest slope task, but only when participants are not under time pressure. In other words, the 2D zooming tool already provides sufficient interaction for this more complex 3D task, and suggests that indeed interacting with spatial displays can actually help people make more accurate decisions. This result does indicate that interaction can indeed increase the quality of human decision-making with map displays. In this respect, it supports the findings of studies showing significant advantages of interactivity in the field of visual object recognition (James et al. 2002), and the acquisition of spatial knowledge through visual exploration of simulated environments (Peruch et al. 1995).

Unlike in previous studies, we did not find any evidence for a speed–accuracy trade-off in this experiment. This is in contrast to other decision-making studies under time pressure without maps (Johnson et al. 1993; Pew 1969). For the complex steepest slope task, response accuracy is even higher under time pressure compared to no time pressure. This might be another example where time pressure can have a positive effect on decision making, as shown for example by Hwang

(1994) for non-map-related tasks. We found this somewhat counter-intuitive effect also for map-based decision making in our previous slope detection experiment with static maps (Wilkening and Fabrikant 2011a). Interestingly, not only are people less accurate with the steepest slope task when not under time pressure, but it is also the only task in this experiment where users feel significantly more confident in their responses when not under time pressure. This is another good example for the fact that response accuracy (e.g., performance) might not always be congruent with response confidence (e.g., perception of performance) in map use studies. We also found this discrepancy in our previous road selection experiment in 2D (Wilkening 2010), and this pattern is consistent with many studies outside of cartography (Klayman et al. 1999). As mentioned earlier, we believe that time pressure might have a particularly strong influence on participants' confidence in complex tasks, but this might not necessarily affect their response accuracy.

Overall, the discovered pattern of people's response confidence replicates the speed–confidence tradeoffs we found in our previous experiments with 2D maps (Wilkening 2011; Wilkening and Fabrikant 2011a). This, in turn, might indicate that spatial tasks with maps do not differ from non-spatial tasks (Maule 1998; Maule and Andrade 1997; Smith et al. 1982), as far as the speed–confidence trade-off is concerned. The speed–confidence trade-off might not only be a useful characterization of human map-based decision making with static 2D maps, but also hold true for interactive 3D globe viewers.

Finally, the only significant effect of the assessed user-related factors is that participants who claim to frequently play video games seem to be more confident in their map-based decisions than participants who play video games less frequently, albeit without being more accurate. This over-confidence in performance is similar to the well-known pattern of male over-confidence found for various tasks in previous empirical studies (Furnham 2001; Furnham et al. 1999; Wilkening and Fabrikant 2011b), and even our own previous study on map-based decision-making (Wilkening 2011a). As most of the frequent video players are indeed male, and the less frequent video players are mostly female, the found correlation between video gaming frequency and response confidence might be due to gender, rather than video game experience.

Conclusions and future work

We investigated how people solve 3D tasks of varying complexity with a geo-browser under different temporal constraints. In particular, we assessed how time pressure might influence human–map display interactions in geo-browsers, and people's spatial decision-making effectiveness (i.e., response accuracy and confidence).

As our study does not provide any empirical evidence for the added value of using 3D interactive map displays to solve 3D tasks (with or without time pressure), we are still left with the open question when and how interactive 3D map displays could indeed provide more efficient and effective spatio-temporal decision- and inference-making compared to static, 2D paper maps.

As task complexity seems to have had a greater influence of the effectiveness of map-based decision-making in our study than time pressure, future studies in this research domain could identify those spatio-temporal tasks where interactive 3D map displays might be key to provide efficient and effective support for map-based decision-making. Given that paper maps still seem to be the state-of-the-art in professional map-based decision making contexts (in 2D and 3D) for solving real-world emergency situations under time pressure (Wilkening and Fabrikant 2011a), it could be worthwhile to directly compare decision-making performance with geo-browsers compared to 2D paper maps, considering background and training differences of expert and novice decision-makers.

Additional studies could shed light on the important question of how 3D interaction tools should be optimally designed to increase effectiveness and efficiency of map-based decision-making in 3D. Follow-up studies could examine human–map interaction in a more detailed way. For instance, future studies could focus on how long participants spend on each tool, or study the sequence of tool use when interacting with a dynamic map (e.g., do people zoom first, and then tilt?).

Finally, as individual differences have been shown to be relevant for effective and efficient map and tool use, further work might focus on how people with varying spatial abilities should be efficiently trained to maximize benefit from interaction with highly interactive 3D map displays. Since we did find interesting effects already at this "coarse level" of analysis, we do propose to further investigate them with future studies, including a larger number of participants, and more detailed analyses of human–map interactions.

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