International Journal of Computer Science and Applications

Vol. 9, No. 3, pp. 61 – 76, 2012

EVALUATION OF EFFECTIVENESS OF THE STICKGRIP DEVICE FOR DETECTING THE TOPOGRAPHIC HEIGHTS ON DIGITAL MAPS

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Multimodal visualization of landscapes and cityscapes requires new concepts and metaphors for intuitive operations with multidimensional data in fully immersive virtual environments. Variations in lighting conditions and perceptual interpretation of the reduced topographic colors can significantly modify an assessment of the true elevation profiles on a digital map. This paper describes the results of the empirical evaluation of the new interaction technique that has potential to enhance the imaging functionality of the two-dimensional maps. It was demonstrated that untrained subjects become much more accurate at detecting the altitudes in a range of 0-4000 m assigned within the palette when values of the light intensity had been associated with the haptic information. The results confirmed that the accuracy of the height estimation with the StickGrip haptic device appeared to be higher by about 32% in comparison to visual assessment.

Keywords: Geoscientific data; topographic elevation profile; the StickGrip haptic device.

1. Introduction

The term GeoMultimedia is referred to a variety of new interaction tools (software and hardware), which have been developed for data visualization in cartography and geosciences. Virtual Reality and interactive techniques in modern cartography can provide experts and researchers in different fields with the opportunity to create and evaluate dynamic spatial models of local and global geographical and geological processes, for understanding and interpreting global connections and relationships. Multimodal visualization of landscapes and cityscapes requires new concepts and metaphors for intuitive operations with multidimensional data in fully immersive virtual environments [Cartwright et al. (2007), (2001)].

The imaging capabilities of regular printing techniques and visualization of terrain surface on a flat (two-dimensional) screen are largely limited and require the usage of conditional pictorial and graphic means such as tonal gradation (shading), hachuring and slope lines [Cartwright et al. (2007); Hodges (2003)]. To numerically assess visually encoded parameters at a glance, appropriate shading, labeling (annotation) and segmentation (contour intervals) have to be chosen. Moreover, the color palette[a] have to

[a] Color palettes for the topography and bathymetry at: (checked on January 2012) http://en.wikipedia.org/wiki/User:Captain_Blood/GMT_Example#Color_palettes

be optimized to properly convert physical measurements into relevant perceptual metrics. That is, incrementing and decrementing the color intensities of the palette should be adjusted according to the non-linear perceptual sensitivity of the human vision [Evreinova et al. (2012); Moreland (2009); Bjorke and Saeheim (2007); Chesneau (2007); Rogowitz et al. (1996)].

However, the contrast sensitivity of the human eye is often interpreted based on a simple rule, for instance: “dark and light colors should be used in the same manner as dark versus light grey tones” [Hodges (2003), p. 547] or even neglected (e.g., the rainbow color map) in processing and presentation of scientific information [Moreland (2009); Borland and Taylor (2007)]. Some of people (7-10% of the population) have perceptual problems related to color deficiency. Therefore, it is often impractical with an acceptable error to assess visually measurable topographic parameters, such as depth and elevation, being originally coded by intensity of gray tones or color gradient.

Although a simple grayscale color map is effective to create and use, the human eye is most sensitive to the luminance (visually perceived brightness), contrast between the object and its surroundings [Mullen (1985)]. Therefore, when asked to compare the brightness of the two regions of the map separated in space and having different surroundings, the error rate can exceed 20% [Ware (1988)]. Consequently, the significance of the palette as a measuring tool (based on colorimetric matching) and functionality of the two-dimensional digital map degrades. Variations in lighting conditions and perceptual interpretation of the shades and color parameters of images can significantly modify the true elevation profile on a digital map. To compensate for a perceptual error, the landmarks on a map are usually accompanied with the labels of the true values being roughly transformed into brightness, contrast and saturation regarding the color palette. Discreteness of static labels (“all at once”) depends on the map scale and display constraints, resulting in imaging that is largely indecipherable. A dynamic pop-up labels triggered by a mouse-rollover, tooltips and quick properties palette provide a smoother path for users to access the data in more detail but the variation in landscape metrics compromise the integrity of the entire terrain profile when interpreting global and local terrain’s attributes and their relationships [Faeth *et al.* (2008); Kibria (2008)].

On the other hand, there is growing interest in the use of geographic information systems and services. At that, the information depicted in digital maps should be presented in an intuitive way making it easy to understood and manipulate. Multisensory integration of geoscientific data has been examined in a number of studies: for geophysical exploration of deeper geological structures on the seafloor [Harding *et al.* (2002)] and complex geographical areas [De Felice (2007); Papadopoulos (2005); Parente and Bishop (2003)]; for seismic modeling [Salisbury (1999)]; haptic exploration of climate maps [Lee *et al.* (2008); Yannier *et al.* (2008)], and improving visualization data from the oil and gas domain [Harding *et al.* (2000); Fröhlich *et al.* (1999); Salisbury (1999)]; cartographic software creation and navigation of blind sailors [Simonnet *et al.* (2009)], to get a sense of topography of remote planets [Walker and Salisbury (2003)], and for the purposes of personal safety travel around the city and neighborhoods [Landau *et al.* (2008); Murai *et al.* (2006)], planning and hiking in a national park [Magnusson *et al.* (2009)], and so on.

Is it possible to increase the accuracy of imaging and the subjective assessment of the global and local terrain's attributes of the topographic variables and their relationships (altitude, slope angle, aspect, and so on [see e.g., Barrio *et al.* (1997)]) being encoded by multiple sensory modalities (e.g., visual and auditory, visual and haptic)? Is it possible to optimize haptic interaction devices for visualizing geospatial data, for map exploration? Is it possible to provide an intuitive interface for direct interaction with geographical information by enhancing the imaging functionality of two-dimensional digital maps?

2. Related Work

As has been demonstrated in numerous studies, the use of auditory cues and messages enriches tactile information during interaction with virtual geographic environment [Miele *et al.* (2006); Zhao *et al*, 2005); Landua and Wells (2003)]. A recent study on sonification of the geo-referenced information [Delogu *et al.* (2010)] indicated that for certain recognition tasks typical for exploration of topographic maps a quick overview of the data can be obtained with the auditory display in an intuitive way. For instance, the location-specific parameters such as shape, size and boundaries, area, statistical data related to population demography, unemployment and crime situation in different regions as well as historical events can be easily presented by combining tactile-kinesthetic and auditory information by helping the students to get a fast and comprehensive overview about the map locations.

An overall tactile exploration of topographic maps through sonification and tactile vibrations helps to clarify and improve visualization of the basic notions, such as coordinate systems, relative distance, area and boundaries, and to complement a symbolic description of the region with a physical sense and audible comments [Barbieri *et al.* (2007); Jansson *et al.* (2006, 2005); Trbovich *et al.* (2005); Parente and Bishop (2003)]. In order to render haptically the geophysical irregularities (hills, valleys, mountains, the surfaces of rivers, lakes and forest) on the map Treviranus used the PenCAT haptic device [Treviranus (2000)]. Each geographic structure was given an associated environmental sound, spoken label and haptic effects such as stiffness, damping, friction and dynamic friction, pulsing waves of resistance and so on.

However, simulated vibration cues had not always been unequivocally associated with the human real-world scene perception inferred from previous experience. Moreover, the use of vibration signals is quite limited to the surface-related physical properties such as roughness, smoothness and their combination in a kind of textures, which can be discovered through tangential skin displacement. Since reaction forces contribute to the sense of physical characteristics such as stiffness, gravity, friction and elasticity, only the use of vibration does not allow simulating the properties containing the components perpendicular to the surface at the point of contact (the torque, force or/and displacements).

Among other geo-visualization techniques, such as 3D rendering on an autostereoscopic display and edge-blended digital dome displays or multi-touch spherical displays, the haptic component can complement visual information for deeper understanding of traditional geographical maps and active exploration of satellite images. Due to seismic imaging technology that allows creating detailed three-dimensional maps of geological structures, the cost of prospecting for minerals and petroleum is becoming cheaper. However, already in 1999 Kenneth Salisbury [Salisbury (1999)] had proposed to add physically tangible sensation to 3D imagery, enabling geologists to feel soil density, stratification, and other properties. This work has inspired significant commitment to haptics by a number of major commercial companies, including Shell Oil. Thus, it was proved that simultaneous activity of vision and touch creates a coherent and robust percept of the virtual objects and a sense of immersion into geographical environment [see also Faeth *et al.* (2008); Kibria (2008); Ernst and Bulthoff (2004)].

The benefits of haptic scientific visualization for exploration of climate information such as wind, cloud water, humidity, temperature, pressure level and their dynamics in different geographical regions have been demonstrated in a number of studies [Lee *et al*. (2008); Yannier *et al*. (2008); Omata *et al.* (2005)]. The climate model [Yannier *et al.* (2008)] was based on observed behavior and the cause-and-effect relations between climate variables and the terrain features such as local (latitude, longitude, height) and global (hemisphere) coordinates and geophysical irregularities (hills, valleys, mountains, lakes, seas and ocean). The experimental results have demonstrated that haptic feedback significantly improves the understanding of climate data and the cause-and-effect relations such as cloud and rain formation and the effect of climate variables on these events.

Harding with co-authors [Harding *et al.* (2002)] described the geoscientific data investigation system (GDIS) in which three-dimensional computer graphics (stereovision), haptics (Sensable PHANToM) and a real-time sonification had been integrated. Relying on high-resolution bathymetric map of the Mid-Atlantic Ridge, the GDIS has been used for an exploration of deeper geological structures on the seafloor. Through varying friction (haptic feedback), the geoscientists had an opportunity to feel the raised tectonic features of the oceanic crust. A multisensory visualization helped to further improve the traditional models of the Mid-Atlantic Ridge.

However, the earlier non-mobile force-feedback devices were designed for indoor use only. The reported Phantom-based systems appeared to be bulky with a limited workspace and great power consumption. The compact lightweight mechanisms providing complementary haptic feedback could enhance the imaging functionality of two-dimensional digital maps. They could be directly used in practical applications.

Haptic Tabletop Puck-device [Marquardt *et al.* (2009); Ledo *et al.* (2012)] for haptic exploration of geographical maps was implemented and tested in the Interactions Lab at the University of Calgary. The authors presented various types of the terrain by simulating various tangible properties of digital objects such as the height, shape, texture, consistency and friction. They also displayed ocean temperature through different vibration frequencies. Chang at MIT Media Lab [Chang *et al.* (2008)] presented

Formchaser device – a single point finger-held mechanism that raised and lowered index fingertip when the color intensity of the image pixels was changed. The prototype and implemented a series of interfaces which allowed the map observers to get a feel of ascent over mountains and immersion into valleys, to sense the waves and ripples on the water surface in a video. However, both Tabletop Puck and Formchaser had a very limited range of elevation (less than 10 mm) of the prominent part (rod, tip or lever) that should raise and lower the finger, on which it was mounted. The earlier prototypes also suffered from technical and usability problems such as residual friction and visual misalignments.

With the new availability of digital planetary data, there is a need to browse and explore the topography, geology and geophysical properties of extraterrestrial surfaces. Walker and Salisbury [Walker and Salisbury (2003)] have developed an interactive 3D browser "MarsView" allowing the user to interact visually and haptically (the PHANTOM desktop of Sensable Tech. Inc.) with the surface of remote planets, navigate and fully immerse into virtual geographic environment. The software transformed a very high density of geometric information displaying the surface into high-resolution data, which users felt as slippery, sticky and textured.

In addition, it is worthy to note that the haptic system combines cutaneous, kinesthetic and proprioceptive signals. But namely the kinesthetic intelligence is responsible for the integration of afferent information originating from the muscles, joints, and skin and efference copy, which enables the brain to evaluate sensory discrepancy between pictorial cues and the sense of distance (actual feedback) to the map location [Graziano and Botvinick (2002)]. Thus, the kinesthetic sense of the finger joint-angle positions can significantly contribute to the subjective assessment of the global and local terrain's attributes of the topographic variables and their relationships [Tan *et al.* (2007)]. The goal of the research presented below was the assessment of human performance and the accuracy of detecting the topographic heights visually and instrumentally with the new StickGrip haptic device. We also aimed to examine how the new technique is accurate and robust.

3. Experimental Setup and Procedure

A map exploration is greatly affected by variations in lighting conditions and the density of background information, which have an impact on the visual attention distribution. Therefore, the subjective interpretation of the depth encoded by light intensity can significantly modify the true elevation profile on a digital map displayed in touch-based handheld devices for educational and military purposes. According to Castleman [Castleman (1996)], the human eye can distinguish hundreds of different colors and about 40 shades of gray in a monochrome image. The present experimental research was conducted to evaluate the impact of the haptic component on visual discrimination of the topographic heights associated with an intensity of the grayscale palette.

Eleven different regions of the Earth have been collected from the Google Maps satellite images. After sliding averaging on 5 by 5 pixels, the original color screenshots were processed to convert them into grayscale images having the colors reduced to only 20 tones of grayscale, as shown in Fig.1. Herewith, in order to avoid side effects, such as learning and participants' familiarity with a map, the selected topographic objects had

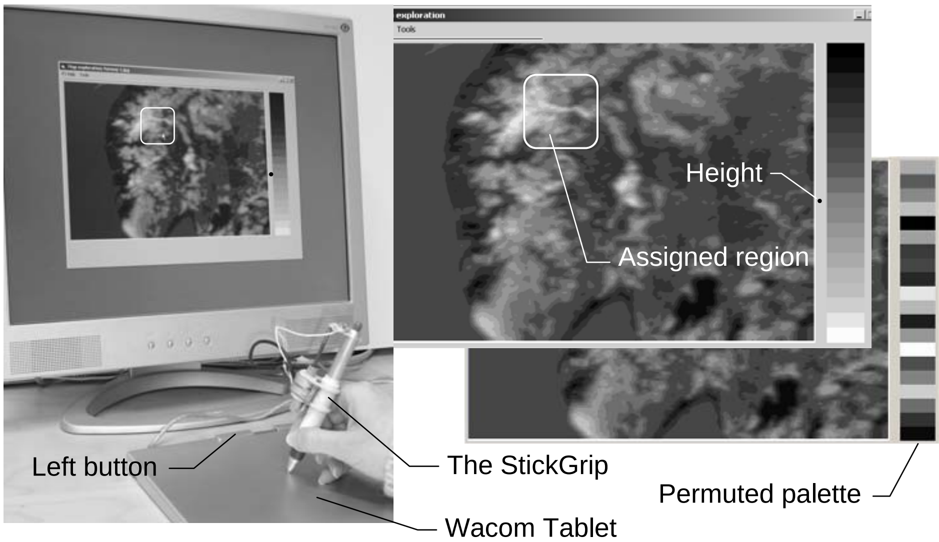

Fig. 1. Experimental setup. Testing the contrast sensitivity (see permuted palette on the right) and detecting the topographic height within an assigned map region of Norway (on the left).

different geographical scale and each of images was presented only once in each of two experimental conditions (StickGrip vs. Visual). The palettes of the maps comprised of different sets of the shades of gray, which were collected from images after their preprocessing. Moreover, before actual exploration of the map elevations, the participants were tested for their individual contrast sensitivity in more strict conditions using a matching-sorting task of the palette.

3.1. *The StickGrip haptic device*

The StickGrip haptic device was developed to provide an intuitive interface for direct interaction with geospatial data by making the elevation profile on a digital map touchable. The StickGrip comprises of the Wacom pen input device added with a motorized penholder as shown in Fig. 1. A point of grasp of the penholder is sliding up and down the shaft of the Wacom pen. When the users explore the map, they feel as their hand is displaced in a range of 25-65 mm towards and away from the physical surface of the pen tablet. Distance and direction of the grip displacements are coordinated with visual parameters encoding altitude (height) of the map regions in a range of 0-4000m [Evreinov *et al.* (2009)]. Functionality of the StickGrip device is controlled using the pen tablet buttons to activate displacements continuously (the right button) or to complete the task (the left button). Thus, the StickGrip has a range of 40 mm of the total displacement with an accuracy of (±0.8 mm) for the Wacom pen having a length of 140mm coordinated with the intensity of gray levels ranging from 0 to 255.

The use of the Portescap 20DAM20D18-L linear stepper motor did not require any additional gears, led to a low noise and equal torque with no differences in directionality that could confound the user. The displacements of the point of grasp in this range (±20 mm) with an average speed of about 15 mm/s give a true feedback about the distance and direction (closer and further) regarding the surface of the pen tablet (or pen tip) and, consequently, such a feedback is a part of the afferent information regarding the local heterogeneity.

3.2. *Examination of the human contrast sensitivity*

Before actual map exploration, the participants were tested for their individual contrast sensitivity regarding 20 levels of gray, which were presented in the satellite images with the reduced number of gray tones. During this session, the order of intensity levels of the grayscale palette was permuted as shown in Fig. 1 (see the same palette on the right). By placing the darkest row of the palette in the upper position and the lightest one in the bottom position, the participants were asked to rearrange the palette to have a smoother transition between gray tones, as they perceived it.

The task has required from the participants a normal sensitivity to contrast differences, self-perception of the finger joint-angle positions [Tan *et al*. (2007)], attention concentration and patience. Of course, perceptual abilities in such a task cannot be separated from cognitive and behavioral components such as the sorting optimization strategy. However, in order to reduce the cognitive load and to reveal the perceptual problems in visual sensitivity, the participants were neither required to minimize the number of permutations nor the time to complete the task.

Nevertheless, the perceptual performance was evaluated in terms of the total numbers of permutations, the task completion time and the number of errors committed. It was expected that the erroneous order of the gray tones could indicate the problematic areas of the palette where the person could not differentiate two or more neighbor color intensities. The time and the number of permutations could demonstrate how well the subjects were able to use the StickGrip as an indicator of the altitude (topographic elevation) shown in the palette.

3.3. *Detection of the local topographic elevation*

At once after testing the visual contrast sensitivity, the participants were asked to perform an exploration of the topographic elevations within the map. During this session, each participant had to discover 20 altitudes randomly selected from the palette. Each of heights was repeatedly ascertained within 11 randomly assigned regions of the map (the white quadrangle in Fig. 1, on the left). At that, the center of the assigned region was displaced in a random direction from the original height location. An exploration of images was carried out inside the restrained region. It is important that such a way helped to reduce and align the difficulty of the elevation detection task in different geographical regions. The perceptual performance was evaluated in terms of the task completion time and deviation of the local elevation detected from the altitude assigned within the palette.

3.4. *Procedure*

Detailed verbal instructions were given to the participants regarding the procedure of the experiment. Each of the participants was given an opportunity to refuse the continuation of the experiment at any point without any explanation of the reason. Then an informed consent from each participant about the procedure of the experiment was obtained.

In one block of trials (marked as “Visual”), both for testing the visual contrast sensitivity and during an exploration of the topographic heights, the participants relied only on the visual observation of the images on the computer screen and used a regular optical mouse to point at the exact location and to complete the task.

In another block of trials, the participants were asked to use the StickGrip haptic device to have an ability to assess haptically (on demand) the altitude specified in the palette (grayscale intensity) and the local elevation at the selected locations.

During examination of the contrast sensitivity, the subjects had to sort the palette by swapping the corresponding rows of the palette by clicking with the left mouse button. During haptic exploration of maps, it was required to examine different locations on the tablet without input of any command. Therefore, the participants pressed the left button of the tablet to indicate their decision. With the StickGrip device, the participants perceived haptically the level of gray intensity and could evaluate the difference between neighbor intensity levels (altitudes) of the palette rows or altitudes of the neighbor map locations. Both conditions (StickGrip vs. Visual) were randomly presented throughout the experiment. The study took about one hour. The entire test was repeated for 11 different regions of the Earth with no more than three sessions per day.

3.5. *Participants*

Ten participants from the local university (7 males and 3 females), who had no previous experience with haptic feedback equipment (like the force-feedback joysticks or the PHANToM), voluntarily took part in the experiments. They were unpaid, only beverages were provided. The age of the participants ranged from 21 to 36 years, with a mean age of 26.5. All participants had normal or corrected-to-normal visual accuracy, and none of them reported sensitive dysfunction in fingers that could prevent their participation in the experiment. The participants were right-handed regular computer users and during the test, they used their right hand for each task under both conditions: Visual vs. StickGrip. It was expected to have successful performance using their regular computer skills. None of the participants were familiar with the experimental setup or were involved earlier in the similar experiments with the StickGrip haptic device.

4. Results

The results of the present study were obtained under two conditions: visual observation of the digital maps and altitudes in their palettes, and a situation when the visual observation was accompanied with the complementary haptic sense of elevation of the point of grasp of the StickGrip haptic device. The statistical analysis was performed using SPSS 18 for Windows (Chicago, IL).

4.1. *Examination of the human contrast sensitivity*

The number of permutations needed to rearrange palettes (see subsection 3.2 for more details) were averaged over ten participants for each geographical region and presented in the bar chart in Fig. 2, on the top-left. The comparative box plots of the overall data averaged over all map regions are presented in Fig. 2 on the top-right. As can be seen from Fig. 2, the number of permutations was close to the number of shades (20) within the palette, indicating that the participants used a sub-optimal strategy.

When the participants used the StickGrip haptic device, the average number of permutations was of about 19.5 with a standard deviation (SD) of 1.3, varying from 18.2 (SD=2.2) for the palette of shades collected from the map of Kamchatka region to 21.7 (SD=1.9) related to the palette of Malaysia. The number of permutations required to rearrange palettes relying only on the visual information and using a regular mouse to swap the rows of the palette varied from 18.8 (SD=2.8) associated with the palette of Iceland region to 22.0 (SD=5.6) representative for the palette of Panama region with a mean of about 20.4 (SD=1.0). The paired samples t-test[b] revealed a small but statistically significant difference between the number of permutations performed under two conditions (StickGrip vs. Visual): $t(10)=2.292$ ($p<0.05$), at that, the correlation of this parameter was low as 0.437 ($p<0.05$).

The bar chart in Fig. 2 (on the middle-left) and comparative box plot (on the middle-right) demonstrated that the participants spent significantly more time when they used the StickGrip device. During the use of the StickGrip device, the average task completion time varied from 49.5 s (SD=7.6 s) (the map of the Swiss Alps region) to 78.9 s (SD=9.6 s) for the palette of the map of Malaysia region, with a mean of about 60.1 s (SD=10.9 s). The visual condition of rearranging rows of the maps' palettes demonstrated that an average task completion time ranged from 40.3 s (SD=5.9 s) (the Turkey region) to 47.4s (SD=9.0 s) (the palette of the Baycal area), with a mean of about 45.1 s (SD=2.1 s). The results of the paired-sample t-test indicated that the difference in perceptual performance assessed by the parameter of the task completion time with two different techniques (StickGrip vs. Visual) was significant: $t(10) = 4.917$ ($p<0.05$), while the correlation index was low as 0.482 ($p<0.05$).

The analysis of the errors committed (Fig. 2, on the bottom) under two conditions (StickGrip vs. Visual) of rearranging the color palettes showed that with the use of the StickGrip the average number of errors ranged from 0.01 to 0.4, with a mean of about 0.1

[b] The paired samples t-test computes the difference between the two variables for each case and indicates whether the average difference is significantly different from zero.

(SD=0.1). The average number of errors for the visual condition varied from 0.4 (SD=0.8) (the map of Turkey region) to 2.8 (SD=1.5) instances (the Malaysia region), with a mean of about 2.1 (SD=0.7). In most cases, the errors committed were recorded when the participants had to compare the darkest rows of the palette (placed in the upper position, see Fig. 1). The results of the paired samples t-test revealed that the participants performed significantly more errors when the matching-sorting task was performed in the absence of haptic feedback, $t(10) = 10.556$ ($p<0.001$). Correlation of errors committed under two conditions over different regions was very low as 0.351 ($p<0.05$).

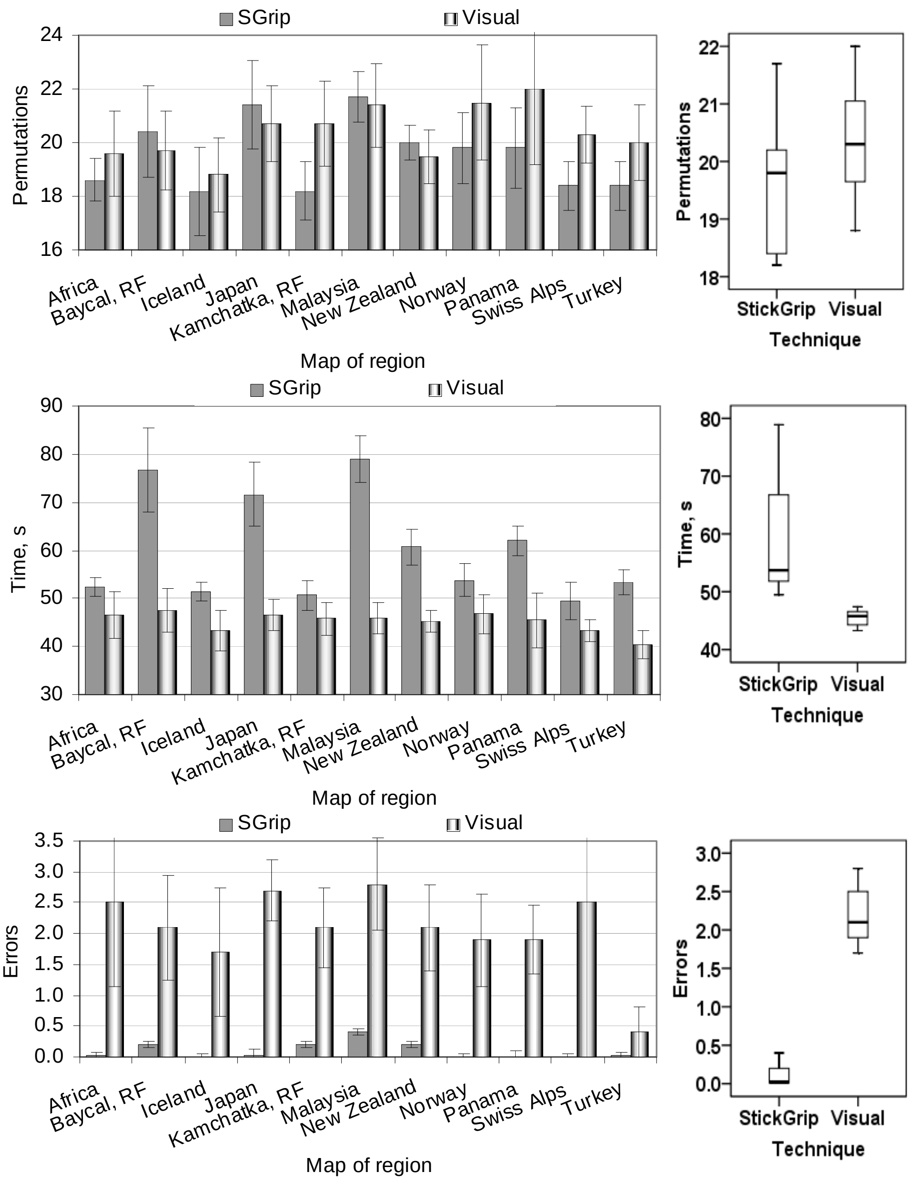

Fig. 2. Base-line perceptual performance of the subjects in the palette-sorting task. The data were averaged over 10 participants (on the left) and over all maps regions (on the right).

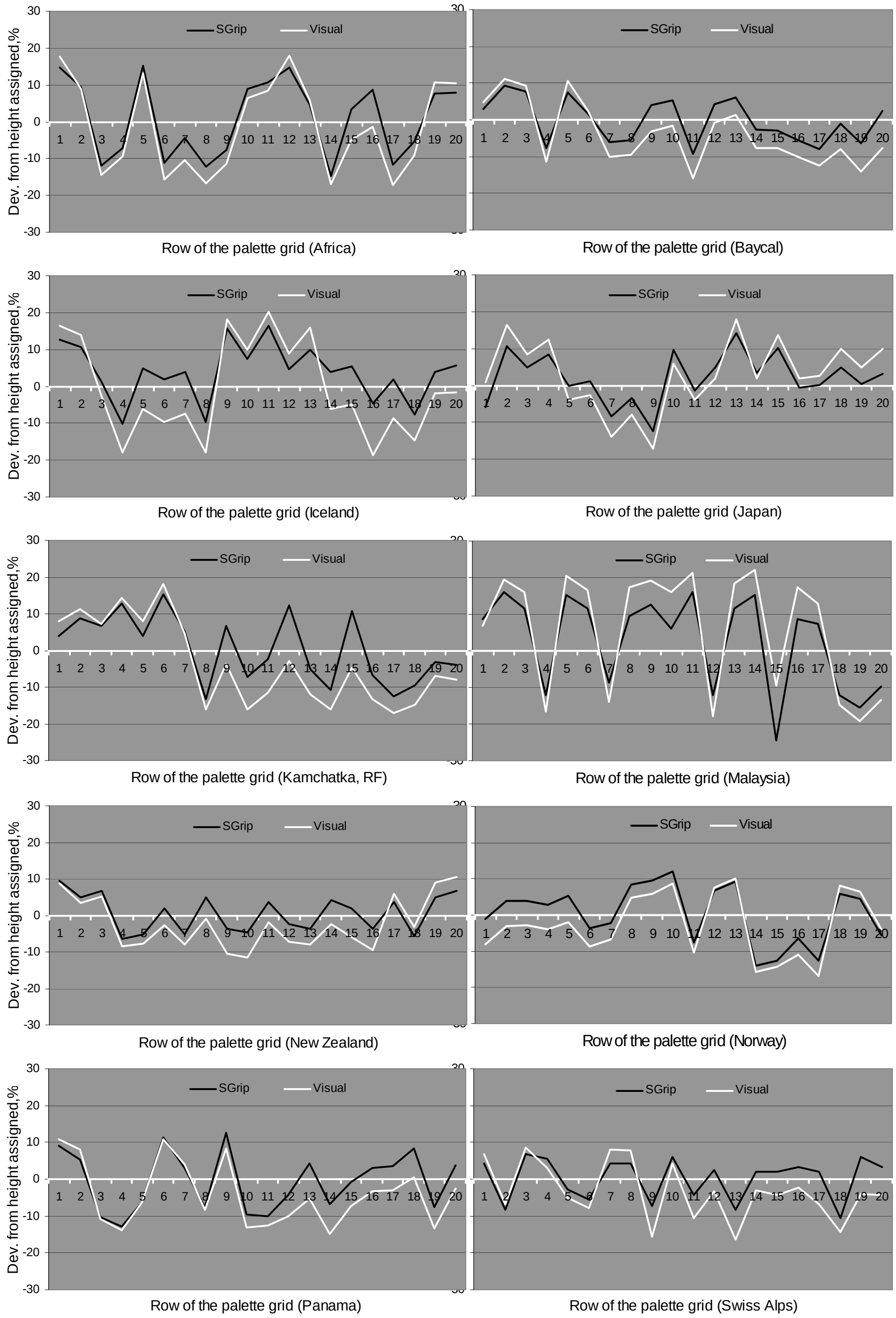

Fig. 3. The deviation of the local elevation detected from the height assigned within the palette. The data were averaged over ten subjects in two conditions of exploration, of eleven map regions ten of them are presented.

4.2. *Detection of the local topographic elevation*

Combining the visual matching with relevant haptic information increased an accuracy of detection of the required altitude (see subsection 3.3 for more details). When the participants had a chance to verify instrumentally (with the StickGrip haptic device) the divergence between the map elevation detected and the altitudes assigned within the palette, the deviation was systematically less than during the visual inspection (Fig. 3, see also Table 1). At that, deviation of the detected local elevation from the height assigned varied in different geographical maps (Fig. 3) from a minimum of 4.73% (SD=1.87%) for map of New Zealand to a maximum of 12.24% (SD=3.81%) for Malaysia region, with a mean of about 7.51% (SD=2.56%).

The visual condition of observing the map region and the height assigned demonstrated that the deviation of elevation values detected ranged from a minimum of 7.18 % (SD=1.97%) for the map of Turkey region to a maximum of 16.33% (SD=3.43%) for the map of Malaysia, with a mean of about 11.04% (SD=2.73%).

The results of the paired-sample t-test of deviation of the local elevation detected from the height specified in the palette indicated that adding the complementary haptic information significantly increased an accuracy of estimating the altitudes coded by shades of gray, by about 32% [in particular, (11.04-7.51)/11.04*100%=31.97%], $t(10) = 7.31$ ($p<0.000$). The index of correlation between the data collected under two conditions (StickGrip vs. Visual) was positive 0.824 and significant $p<0.005$. The correlation indicated that the differences in human performance were mostly observed due to the different exploration conditions and, in a lesser degree, due to differences in the test images.

Table 1. The deviation (%) of elevation detected from the heights assigned within the palette. The data were averaged over ten subjects in two conditions of exploration.

Map of region	**Deviation of elevation, %**	
	SGrip, mean (SD)	**Visual, mean (SD)**
Africa	10.05 (3.17)	14.20 (3.12)
Baycal, RF	5.35 (2.08)	9.96 (3.44)
Iceland	7.96 (2.93)	14.28 (2.5)
Japan	5.49 (1.29)	8.93 (2.11)
Kamchatka, RF	9.33 (3.07)	10.48 (2.28)
Malaysia	12.24 (3.81)	16.33 (3.43)
New Zealand	4.73 (1.87)	8.88 (2.01)
Norway	9.93 (2.84)	10.88 (2.78)
Panama	7.10 (3.05)	11.33 (3.27)
Swiss Alps	5.09 (1.76)	9.01 (3.14)
Turkey	5.30 (2.26)	7.18 (1.97)
Mean (STD)	7.51(2.56)	11.04 (2.73)

The elevations detected in all geographical maps under two conditions (StickGrip vs. Visual) were highly and significantly correlated with the altitudes assigned within palettes. The correlation varied from a minimum of 0.880 ($p<0.001$) to a maximum of 0.981 ($p<0.001$). The paired-sample t-test for the data averaged over ten participants under two experimental conditions (StickGrip vs. Visual) revealed a significant difference in accuracy of detection of the assigned values in eight of eleven map regions. The differences in accuracy were significant, varying from a minimum of $t(19) = 2.06$ ($p<0.05$) to a maximum of $t(19)=9.0$ ($p<0.005$). Only in three regions (Japan, Kamchatka and Swiss Alps), the differences in accuracy of height detection were low and were not significant ($p>0.5$, $p>0.01$ and $p>0.01$ accordingly).

The index of correlation of the time spent to complete the perceptual matching task between the altitude on the map and within palette in two conditions (StickGrip vs. Visual) was low and not significant varying from a minimum of 0.019 ($p>0.5$) to a maximum of 0.562 ($p>0.5$). The paired-sample t-test for the data averaged over ten participants (for 20 heights) revealed that the differences in completion time in two conditions (StickGrip vs. Visual) varied from a minimum of $t(19) = 8.92$ ($p<0.0001$) to a maximum of $t(19)=20.50$ ($p<0.0001$). The results of the paired samples t-test revealed that the difference between these results in two experimental conditions was statistically significant: $t(10)=3.63$ ($p<0.01$), the correlation was about 0.806 ($p<0.005$).

It was also reported by the participants that matching task was clear and helped them to estimate the benefits of the StickGrip device in distinguishing two gray tones with vanishing differences in the intensities. After acquiring some experience in the use of the StickGrip device during pretesting of the contrast sensitivity, detection of the local topographic elevation did not cause any problems. The experimental data indicated that relying on complementary haptic signals the participants were able to assess a subtle difference between the assigned altitudes and the elevations selected within a specified region of the digital map.

5. Conclusion

The goal of the empirical research presented in this paper was to evaluate accuracy and efficiency of detecting the topographic heights on satellite images visually and instrumentally with the StickGrip haptic device. Eleven different regions of the Earth have been collected from the Google Maps. The original color screenshots were processed to convert them into grayscale images having the limited number of intensity levels of twenty tones.

During the base-line experiments, the participants were examined for their visual contrast sensitivity. Then, the participants explored the elevation profile of the terrain within a small area of the map by looking for the altitudes randomly assigned from the palette. The experiments have required from the participants of attention concentration, the normal contrast sensitivity, self-perception of the finger joint-angle positions and hand displacement. The experimental data collected during the map exploration indicated that the kinesthetic sense of the distance to the surface of interaction (tablet) can significantly improve the visual assessment of the global and local terrain's attributes of the topographic variables and their relationships.

Relying on the complementary haptic information, the participants were able to assess a subtle difference between the assigned altitudes within the palette and elevations selected in different map regions. The results of the paired samples t-test of deviation of the local elevation from the height specified indicated that adding the complementary haptic information increased an accuracy of estimating the local map elevation by about 32%. The difference between two conditions (StickGrip vs. Visual) was high and significant $t(10) = 7.31$ ($p<0.000$). An efficiency of instrumental support is evident.

As a matter for further research, we plan to examine more complex scenario of interaction with cartographic information by exploring the surfaces with different types of discontinuity and other measurable physical properties of landscape. The StickGrip device can be considered as a robust tool having the potential for everyday work with graphic editors to engineers, architects, interior designers and ordinary users.

Acknowledgments

The authors gratefully acknowledge the support of Finnish Academy Grant 127774.

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