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Estimating Topographic Heights with the StickGrip Haptic Device

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*Abstract—***This paper presents an experimental study aimed to investigate the impact of haptic feedback when trying to evaluate quantitatively the topographic heights depicted by height tints. In particular, the accuracy of detecting the heights has been evaluated visually and instrumentally by using the new StickGrip haptic device. The participants were able to discriminate the required heights specified in the scale bar palette and to detect these values within an assigned map region. It was demonstrated that the complementary haptic feedback increased the accuracy of visual estimation of the topographic heights by about 32%.**

I. Introduction

TO EXTEND imaging capabilities, visualization of multi-dimensional data using two-dimensional printing techniques intended for a regular paper and flat screens requires to use the conditional pictorial means such as gray tones and color palettes. Nevertheless, scale bar palettes have to be optimized for converting changes of various physical values into the color gradient of intensity with a predefined step [1]-[4]. Such a function of transformation should rely on non-linear perceptual sensitivity of the human vision. However, the color-dependent sensitivity of the human eye is often neglected in processing and presentation of geographical information.

Moreover, some of people have perceptual problems related to color discrimination. Therefore, it is often impractical with an acceptable error rate to assess visually measurable topographic parameters, such as depth and elevation, being originally coded by intensity of gray tones or color gradient. Consequently the significance of scale bar palettes as a measuring tool (based on colorimetric matching) degrades. Variations in lighting conditions and perceptual interpreting of the shades and color parameters of images can significantly modify the true physical values. 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 scale bar palette. Discreteness of labeling depends on the map scale and display constraints. But, labeling cannot solve the problem to accurately display the variation in landscape metrics.

On the other hand, there is an increasing interest in geographical maps for traveling and navigation. At that, the information depicted in digital maps should be presented in a way that is easily accessed and understood. Multisensory integration of geoscientific data has been examined in a number of studies: for geophysical exploration of deeper geological structures on the seafloor [5] and complex geographical areas [6], [7]; for haptic exploration of climate maps [8], [9], and improving visualization data from the oil and gas domain [10]–[12]; for cartographic software creation and navigation of blind sailors [13], [14] and for the purposes of personal safety travel around the city and neighborhoods [15], [16], planning and hiking in a national park [17], and so on.

Among other visualization techniques, such as 3D rendering with autostereoscopic and multi-projectors (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 exploration of satellite images. Simultaneous activity of vision and touch creates a coherent and robust percept of the virtual objects and a sense of immersion into geographical environment [18]-[20]. Let us consider several examples of relevant studies.

Faeth, Oren and Harding [19] implemented and evaluated the multimodal mesh manipulation system for 3D visualization of geospatial data. Pushing and pulling the tip of Phantom stylus provided haptic information about deformation of the inspected virtual surface.

Haptic Tabletop Puck-device [21], [22] 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 textures and properties of digital objects such as the height, malleability, and friction. They also displayed ocean temperature through different vibration frequencies.

Chang at MIT Media Lab [23] presented Formchaser device – a single point finger-held mechanism that raised and

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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 suffered from technical and usability problems such as bulkiness, residual friction and visual misalignments.

Simonnet with colleagues [13], [14] studied another aspect of alternative visualization of navigation parameters for blind sailors. They developed and evaluated the haptic-auditory navigational instrument "SeaTouch". Haptic exploration of different textures helped to the blind sailors to discriminate the sea, the land, the coastline and the silent objects in virtual maritime environment in the absence of visual feedback.

It is worthwhile to note that most researchers distinguish information related to cutaneous, kinesthetic, and haptic sensory systems [24]. To provide an awareness in peripersonal space, a cutaneous system implies physical contact between objects of interest and the outer surface of the observer's body. The kinesthetic sensory system integrates afferent information originating from the muscles, joints, and skin and efference copy, which enables the brain to evaluate sensory discrepancy resulting from the comparison between the predicted and actual feedback [25-26]. Thus, the kinesthetic sense contributes to the body self-awareness providing information related to the static and dynamic body postures (relative positioning of the head, torso, limbs, and digits) [25], [27]. The haptic system combines both cutaneous, kinesthetic and proprioceptive signals.

The research presented in this paper was addressing a practical question: is it possible to increase the accuracy of the subjective assessment of the local topographic elevation coded by shades of gray and/or color intensity when haptic feedback, presented as a function of the terrain height, could be associated with values of the light intensity? The accuracy of detecting the topographic heights had been evaluated visually and instrumentally with the new StickGrip haptic device. The topographic heights were randomly selected from the gray scale palette and detected within an assigned geographical region. At that, we hypothesized and sought to confirm that a kinesthetic sense of distance to tablet or/and perception of the finger joint-angle positions [28], can enhance visual accuracy in estimating topographic heights encoded by light intensity.

II. Experimental Setup and Procedure

According to Castleman [29], 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 color 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 given map, the selected topographic objects had different geographical scale, the palettes comprised of different sets of the shades of gray and each of images was presented only once in two experimental conditions (StickGrip vs. Visual).

Moreover, the map exploration is greatly affected by background information and visual attention distribution. Therefore, before actual exploration of the map elevations we aimed to evaluate the individual baseline sensitivity in more strict conditions using a matching-sorting task.

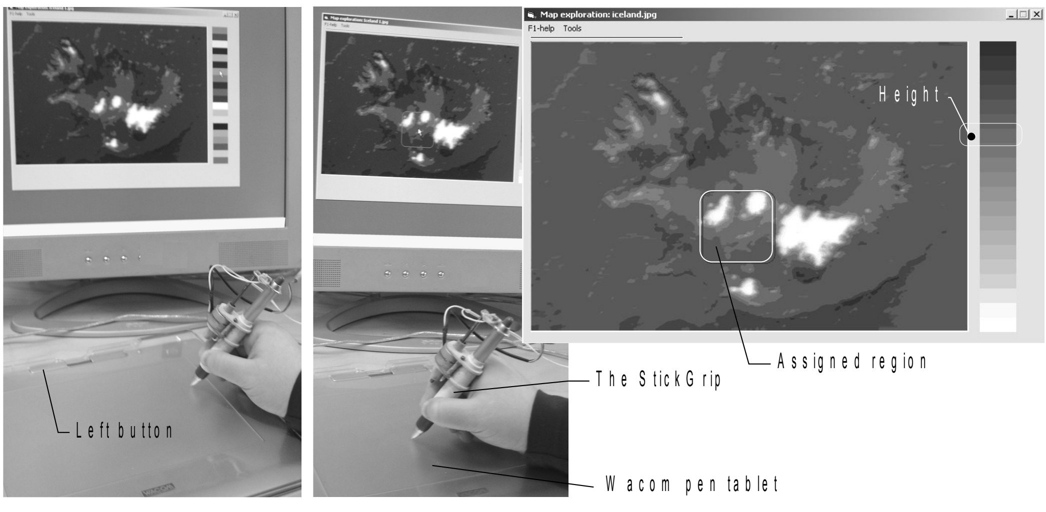

Fig 1. Experimental setup. Testing of the intensity discrimination ability (on the left) and detecting the topographic height within an assigned map region (on the right)

A. The StickGrip haptic device

The StickGrip haptic device was used to evaluate the topographic elevation haptically. It 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 participants explored the map, they felt as their hand was displaced towards and away from the physical surface of the pen tablet. Distance and direction of the grip displacements were coordinated with visual parameters encoding height of the map regions under inspection [30]. Functionality of the StickGrip was controlled using the pen tablet buttons to activate displacements continuously (the right button) or to complete the task (the left button).

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 topographical heterogeneity. In our experiments, we also aimed to examine how the new technique for exploration of the topographical maps is accurate and robust.

B. Pretesting the intensity discrimination ability

During this part of research, we examined the visual ability of the participants to differentiate only 20 levels of gray which have been used to encode the heights of the satellite images preprocessed with the reduced number of gray tones.

During the first session, the order of intensity levels of the grayscale palette grid was randomized as shown in Fig. 1 (on the left). 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 grid to have a smoother transition between gray tones, as they perceived it.

The task has required from the participants of visual sensitivity to light, self-perception of the finger joint-angle positions [28], 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. In order to reduce the cognitive load and to reveal the perceptual problems, 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 error rate. It was expected that the error rate could indicate the problematic areas of the scale bar palette where the person could not differentiate two or more neighbor intensities.

C. Detection of the local topographic heights

Immediately after testing the intensity discrimination ability, the participants were asked to perform an exploration of the topographic heights within the map. During this session, each participant had to discover 20 topographic heights randomly selected from the palette grid. Each of height was repeatedly ascertained within 10 randomly assigned regions of the map (the white quadrangle in Fig. 1, on the right). 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. In this way we aimed to reduce and align the difficulty of the height detection task in different geographical regions. The

TABLE I.
BASE-LINE PERCEPTUAL PERFORMANCE IN THE MATCHING-SORTING TASK. THE DATA WERE AVERAGED OVER TEN PARTICIPANTS.

Map of region	Permutations , (SD)		Time, s (SD)		Errors, (SD)	
	StickGrip	Visual	StickGrip	Visual	StickGrip	Visual
Africa	18.6 (1.6)	19.6 (3.2)	52.3 (3.9)	46.5 (9.6)	0.03 (0.1)	2.5 (2.7)
Baycal, RF	20.4 (3.4)	19.7 (2.9)	76.6 (17.4)	47.4 (9.0)	0.2 (0.1)	2.1 (1.7)
Iceland	18.2 (3.3)	18.8 (2.8)	51.3 (3.8)	43.3 (8.7)	0.01 (0.1)	1.7 (2.1)
Japan	21.4 (3.3)	20.7 (2.8)	71.5 (13.3)	46.6 (6.4)	0.02 (0.2)	2.7 (1.0)
Kamchatka, RF	18.2 (2.2)	20.7 (3.2)	50.6 (5.9)	45.8 (6.7)	0.2 (0.1)	2.1 (1.3)
Malaysia	21.7 (1.9)	21.4 (3.1)	78.9 (9.6)	45.9 (6.3)	0.4 (0.1)	2.8 (1.5)
New Zealand	20.0 (1.3)	19.5 (2.0)	60.7 (7.3)	45.2 (4.4)	0.2 (0.1)	2.1 (1.4)
Norway	19.8 (2.6)	21.5 (4.3)	53.7 (6.8)	46.7 (7.9)	0.01 (0.1)	1.9 (1.5)
Panama	19.8 (3.0)	22.0 (5.6)	62.0 (6.2)	45.4 (11.3)	0.01 (0.2)	1.9 (1.1)
Swiss Alps	18.4 (1.8)	20.3 (2.1)	49.5 (7.6)	43.4 (4.4)	0.01 (0.1)	2.5 (5.2)
Turkey	18.4 (1.8)	20 .0 (2.8)	53.4 (5.1)	40.3 (5.9)	0.02 (0.1)	0.4 (0.8)
Mean (SD)	19.5 (1.3)	20.4 (1.0)	60.1 (10.9)	45.1 (2.1)	0.1 (0.1)	2.1 (0.7)

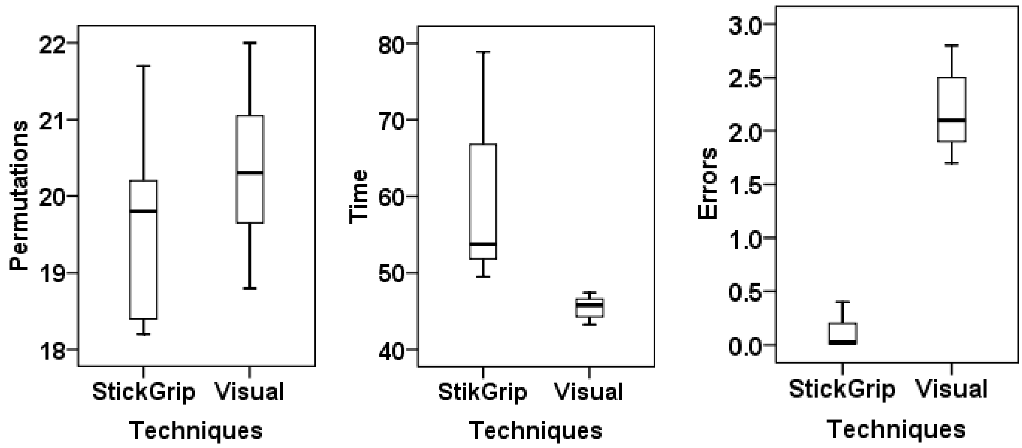

Fig 2. Comparative box plots of the base-line perceptual performance in the matching-sorting task with two techniques of exploration and rearranging of 11 scale bar palettes. The data were averaged over ten participants.

perceptual performance was evaluated in terms of the task completion time and deviation of the local elevation detected from the height assigned within the palette.

D. *Procedure*

In one block of trials (marked as "Visual"), both for testing of the intensity discrimination ability 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 height (intensity) specified in the scale bar palette and the local elevation of the map at selected locations.

During the matching-sorting task, they swapped the corresponding rows of the palette grid 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 shade intensity and could evaluate the difference between neighbor intensity levels of rows of the palette grid or neighbor map locations.

Both conditions (StickGrip vs. Visual) were randomly presented throughout the experiment. The entire test was repeated for 11 different regions of the Earth with no more than three sessions per day.

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.

E. *Participants*

Ten volunteers participated in the study (7 males and 3 females). 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. They had normal or corrected-to-normal visual accuracy, and none of them reported sensitive dysfunction in fingers. The participants were right-handed regular computer users and during the test, they used their right hand under both conditions: Visual vs. StickGrip. None of the participants were familiar with experimental setup or were involved earlier in the experiments with haptic feedback.

III. Results

The results were collected under two conditions: visual observation only, and a situation when the visual observation of the map and the height in the scale bar palette was accompanied with the complementary haptic sense of elevation of the point of grasp of the StickGrip device. The statistical analysis was performed using SPSS 18 for Windows (Chicago, IL).

A. *Pretesting the intensity discrimination ability*

The number of permutations needed to rearrange palettes was averaged over ten participants for each geographical region and presented in Table I. The comparative box plots of the overall data averaged over ten participants are presented in Fig. 2. As can be seen from Table I and Fig. 2, the number of permutations was close to the number of shades within the palette grid, indicating that the participants used a sub-optimal strategy. The comparative box plots demonstrated that the participants spent significantly more time when they used the StickGrip device but there were few accidental errors. In the absence of haptic feedback, a significant increase of errors was systematically recorded.

When the participants used the StickGrip 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

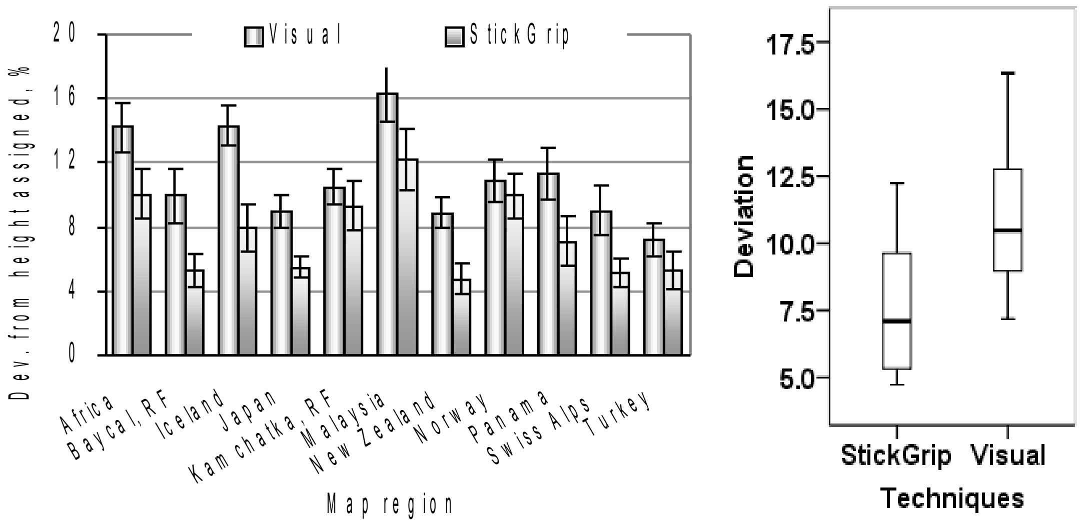

Fig 3. The deviation of the local elevation detected from the height assigned within the palette. The data were averaged over ten participants under two conditions of exploration of eleven map regions.

the palette of shades collected from the 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 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 about 0.437 and not significant ($p>0.01$).

When the participants used the StickGrip device, the average task completion time changed from 49.5 s (SD=7.6 s) in a case of palette associated with the Swiss Alps region to 78.9 s (SD=9.6 s) for the palette related to the Malaysia region, with a mean of about 60.1 s (SD=10.9 s). The visual condition of rearranging rows of the maps' palettes (Table I) demonstrated that an average task completion time ranged from 40.3 s (SD=5.9 s) for the map of Turkey region to 47.4s (SD=9.0 s) for the palette of the Baycal map, 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 and not significant 0.482 ($p>0.01$).

The analysis of error rates under two conditions (StickGrip vs. Visual) of rearranging the color palettes showed that with the use of the StickGrip the mean of the number of errors ranged from 0.01 to 0.4 with a mean of about 0.1 (SD=0.1).

TABLE II.
PAIRED DIFFERENCES BETWEEN ASSIGNED AND SELECTED TWENTY HEIGHTS AND THE TASK COMPLETION TIMES UNDER TWO CONDITIONS (STICKGRIP VS. VISUAL) THE DATA WERE AVERAGED OVER TEN PARTICIPANTS

Map of region	Heights (intensity levels)		Time, s	
	Corr., Sig.	t(df=19), Sig.	Corr., Sig.	t(df=19), Sig.
Africa	0.981 p<0.001	9.0 p<0.005	0.133 p>0.5	8.92 p<0.0001
Baycal, RF	0.893 p<0.001	4.27 p<0.001	0.121 p>0.5	11.84 p<0.0001
Iceland	0.928 p<0.001	4.13 p<0.001	0.019 p>0.5	11.71 p<0.0001
Japan	0.976 p<0.001	0.03 p>0.5	0.291 p>0.5	10.92 p<0.0001
Kamchatka, RF	0.880 p<0.001	2.75 p>0.01	0.391 p>0.5	11.98 p<0.0001
Malaysia	0.962 p<0.001	2.06 p<0.05	0.435 p>0.5	10.36 p<0.0001
New Zealand	0.956 p<0.001	3.68 p<0.05	0.025 p>0.5	15.70 p<0.0001
Norway	0.940 p<0.001	3.94 p<0.001	0.482 p>0.5	12.27 p<0.0001
Panama	0.935 p<0.001	3.99 p<0.001	0.127 p>0.5	20.50 p<0.0001
Swiss Alps	0.893 p<0.001	2.64 p>0.01	0.562 p>0.5	14.38 p<0.0001
Turkey	0.937 p<0.001	3.44 p<0.005	0.162 p>0.5	13.19 p<0.0001

The average number of error rate 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.

The results of the paired samples t-test revealed that the participants committed 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 error rates under two conditions over different regions was very low and not significant 0.351 ($p>0.01$).

B. *Detection of the local topographic heights*

Providing the visual matching task with relevant haptic information demonstrated that deviation of the detected local elevation from the height assigned varied in different geographical maps (Fig. 3) from a minimum of 4.7% with a standard deviation (SD) of 1.9% to a maximum of 12.2% (SD=3.8%) with an *average of about 7.5%* (SD=2.6%).

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 7.2 % (SD = 2.0%) for the map of Turkey region to a maximum of 16.3% (SD= 3.4%) for the map of Malaysia with a *mean of about 11.0%* (SD=2.7%).

The results of the paired-sample t-test of deviation of the local elevation from the height specified in the scale bar palette indicated that adding the complementary haptic sense significantly increased an accuracy of estimating the height 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 less extent, due to differences in the satellite images.

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 difference of intensity. After acquiring some experience in the use of the StickGrip device during pretesting, detection of the local topographic heights did not cause any problems. The experimental data indicated that relying on complementary haptic feedback the participants were able to assess a subtle difference between the assigned heights and elevations of the selected locations within a specified region of the map.

As can be seen from Table II, the elevations detected in all geographical maps under two conditions (StickGrip vs. Visual) were highly and significantly correlated with the heights 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 revealed a significant difference in accuracy of detection of the assigned values under two experimental conditions (StickGrip vs. Visual) in eight of eleven map regions. The differences in accuracy varied significantly 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 not significant.

The index of correlation of the time spent to complete the perceptual matching task under 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 under two conditions (StickGrip vs. Visual) varied from a minimum of $t(19) = 8.92$ ($p<0.0001$) to a maximum of $t(19)=20.50$ ($p<0.0001$).

IV. Conclusion

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

By performing the matching-sorting task, during the baseline experiments the participants were examined for their ability of the light intensity discrimination. In the second session, the participants explored the map heterogeneity to detect the height randomly selected from the scale bar palette. Both experiments have required from the participants of visual sensitivity to light, self-perception of the finger joint-angle positions, attention concentration and patience.

The results of the paired-sample t-test revealed that the participants committed significantly more errors in the baseline experiments when they performed the task in the absence of haptic feedback, the difference was high and significant $t(10) = 10.556$ ($p< 0.001$). The experimental data collected in the second session of the map exploration indicated that relying on the complementary haptic feedback the participants were able to assess a subtle difference between the assigned heights and elevations of the selected locations 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 sense increased an accuracy of estimating the height by about 32%. The difference between two conditions was high and significant $t(10) = 7.31$ ($p < 0.000$). The benefits of instrumental support for human performance are evident.

We hypothesized and confirmed that a kinesthetic sense of distance to tablet or/and perception of the finger joint-angle positions, can enhance visual accuracy in estimating topographic heights coded by shades of gray. It was also demonstrated that untrained participants can accurately detect geographic locations with necessary height when values of the grayscale intensity were complemented with haptic feedback presented as a function of elevation.

In further research, we plan to examine more complex scenario of interaction with cartographic information by exploring topographic surfaces with different types of discontinuity and textures. 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.

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