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The Information Value of Tactile Maps: Comparison of Maps Printed with the use of Different Techniques

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As public awareness is growing constantly, the needs of visually impaired people are considered, including those regarding access to spatial data. The best way to present spatial phenomena is to use maps. Visually impaired people use tactile maps that can be read by the sense of touch or, to a limited extent, with eyes. This article concerns the methods of assessing tactile maps in terms of their information value. In the research, methods used to assess traditional maps have been adopted to assess tactile maps. Tactile elements of two maps - one developed with use of traditional methods and the second developed with use of 3D printing - have been compared. Structural measure of information as well as the information efficiency coefficient of each map have been determined to assess whether new cartographic signs proposed on a multi-level 3D printed map can increase its information value.

Keywords: information value; structural measure of information; tactile maps; map analysis; 3D printing; blind and visually impaired

Introduction

Nowadays we are surrounded by various types of data. A growing number of maps being produced is connected with the increasing demand for information provided in a very concise and convenient way, available for quick assimilation. These conditions, undoubtedly, are fulfilled by using cartographic form. This results in a huge number of maps being produced. However, not many of them are of truly high quality. The process of map assessment is considered a part of cartography theory (Arnberger, 1966). When evaluating maps, one should take into account both the utilitarian purpose and the aesthetic values. The assessment process can be divided into three main stages: determining the subject and purpose of the assessment, selection of assessment criteria and techniques, and, finally, the presentation and verification of evaluation results (Kałamucki, 1998). The aforementioned assessment techniques can be quantitative or qualitative. However, it is the map's intended use that determines how it should be designed: the selection of content, the classification of this content, the choice of presentation methods, generalization standards and the general information resource (Salistchev, 2002).

People tend to think that if a map contains many cartographic signs, covering almost the whole map sheet, then it means that it also contains much information and that it is what makes a good map. However, this is not always true. Over the years, cartographers have developed a number of criteria for assessing the cartographic form of communication. Boczarow (Boczarow, 1966) distinguishes: legibility of the map, statistical regularity of the visual perception of cartographic signs, and the graphic and numerical load of the map. The author describes some of these parameters in detail. One of the examples is the graphic load of a map, which is defined as the area that is covered by all graphic elements on the map. The same approach was also proposed by Fiłatow (Fiłatow, 1988). However, Salistchev in one of his books (Salistchev, 2002) showed the weakness of this approach. He pointed out that changing the size of cartographic signs would be visible in the change of the graphic load of a map but at the same time this action would not provide any additional cartographic information. This is why he suggests using methods of mathematical information theory, if we wish to make an objective evaluation of spatial unification (or differentiation) of phenomena and their mutual compatibility (Shannon, 1948). One of the basic functions of this theory is entropy that can be used to define the heterogeneity of the cartographic image – as an indicator of spatial diversity of phenomena. The pioneering work on using this approach in the quantitative assessment of map information was done in 1967 (Sukhov, 1967) but it has been commonly used until the present day (Li and Huang, 2002; Harrie and Stigmar, 2010). Salistchev (Salistchev, 2002) also proposes using a structural measure of information to assess a map. This approach is based on calculating the amount of information as the sum of quantities characterizing the informational significance of signs that depict discrete objects, with respect to the number of information elements contained in each sign. Every difference in the position or characteristics of objects is measured in this approach.

However, all the methods described above apply to classic maps that are based on classic cartographic sign features used on maps, such as: shape, size, grain, orientation, value and hue (Bertin, 1967). To the best of our knowledge, there was no research in this field regarding tactile maps – maps that are used by blind and visually impaired people. This kind of maps show graphic information using relief and tactile symbols and are normally used with their corresponding legends (Gual *et al.*, 2015), they are read by the sense of touch or, to a limited extent, with eyes (Ojala *et al.*, 2016). Tactile maps base on haptic variables, such as: height, size, grain, profile, shape, texture, orientation, temperature, and resistance. The juxtaposition of these two kinds of variables is presented on Figure 1.

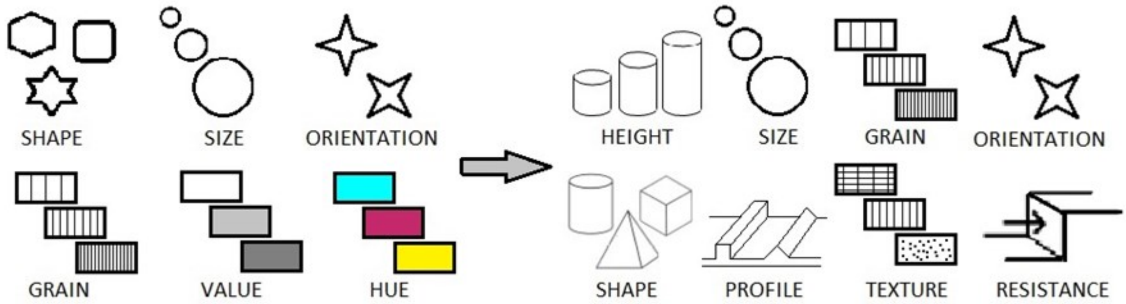


Figure 1. Graphic variables and the most important haptic variables, source: own work

In case of tactile maps all the factors that determine how maps should be designed ought to make it possible to meet the basic condition: they have to be legible. Sometimes it is even worth considering abandoning the existing cartographic standards in favour of better legibility of the map. It results from the fact that the way of "reading" such maps is completely different. An average man, without any visual impairment can distinguish two points or lines as separate under normal viewing conditions if they are 0.15 mm apart from each other (Yanoff and Duker, 2009). To distinguish two points as separate with the use of touch, they have to be at least 2.4 mm apart from each other (Klatzky and Lederman, 2003). Persons without vision impairment usually cover the whole map sheet at once with their eyes. Blind and visually impaired people read the map in fragments and memorize them (Olczyk, 2014). The signs commonly used in traditional cartography are usually too small or too complicated to be read correctly using sense of touch or a damaged sense of sight, even after raising them to a spatial form. This makes tactile maps less detailed and requires them to be printed in larger formats (Edman, 1992).

Moreover, tactile map production is very expensive. Methods commonly used for their production: plastic thermoforming or relief screen printing are only cost-effective for large-volume production. This leads to a situation where blind and visually impaired people do not have access to as much spatial information as others. In the face of these restrictions research is underway to improve the process of tactile map production. New production methods are also being tested. These include additive methods (also called 3D printing) (Voženílek *et al.*, 2009; Götzelmann and Pavkovic, 2014; Gual *et al.*, 2014; Taylor *et al.*, 2016; Wabiński and Mościcka, 2017). This technology is characterized by a fixed, low unit cost and it allows rapid prototyping. The cost of performing tests with different materials, sign shapes and arrangement of map content is relatively low. This method also allows tactile map designers to fully experiment with the appearance of a tactile map.

Taking the above into consideration, the aim of the paper is to compare the information value - understood as ‘the level of satisfying the information needs of the user’ (Potelarska-Walczyńska, 1979) - of the tactile map produced with use of traditional methods with the one developed with use of 3D printing that enables the use of new cartographic signs that can be designed freely - as 3D printing allows to print almost everything that is designed. Therefore it is important to analyze their impact on the information value of a tactile map. Thus, this leads us to the research question: how does the production method used affect the cartographic information value of the tactile map? This question is related to the next one: do the new cartographic signs, used on 3D printed maps, increase the information value of a map? And most importantly: can the methods for computing map information value on classic maps be applied to tactile maps?

Due to the fact that the existing literature does not provide any information about studies related to the research on the information value of tactile maps, their first stage that is presented in this article will be related to the determination of the statistical measures necessary to calculate the cartographic information value of tactile maps. Subsequent studies will expand the results obtained by additional research on the topological relationship between map elements and different production methods.

Materials and Methods

The study described in this paper aims at measuring the information values on sample elements of tactile maps and, at the same time, comparing the amount of this value on 2 maps presenting the same geographical phenomenon but prepared with use of different production methods. This approach is innovative not only because so far there have been no attempts to measure the cartographic information value on tactile maps described in literature, but also because one of the compared maps represents a novel approach to tactile map generation (Wabiński, 2017). Therefore, **we examine whether methods for measuring cartographic information value on classic maps can be applied to tactile maps and how the method of production of a tactile map influences these measures.**

Maps Used in the Research

The first map, for the purpose of this article referred to as the ‘original map from atlas’, comes from the ‘Atlas of the Nature for the Blind – Volume 1’ issued in 2010(*Atlas do przyrody dla osób niewidomych i słabowidzących - TOM 1 Polska*, 2010) that is commonly used in schools for blind and visually impaired in Poland. It is the ‘p3 – Poland – Geographical Regions’ map prepared in a foldable A2 format in a scale of 1:2 000 000. It presents the main geographical regions of Poland along with the main rivers and lakes. The atlas is built of cartographic and textual content. The cartographic part consists of 34 map sheets in A2 or A3 format. Volume 1 contains 15 sheets and a legend in A4 format that focus on Poland, designed in scales 1:200 000, 1:400 000, 1:750 000 and 1:2 000 000. The textual part consists of: ‘Explanation of abbreviations used on map’ written in Braille and classic black font text. The publication also includes an audio disc containing the ‘Student’s guide’ and ‘Methodological guidelines for the teacher’. Each text on the CD explains the content of a particular map and allows student to work independently or with the help of their parents or teacher. The map, as well as the entire atlas, was created with use of transparent relief print imposed on a coloured base, suitable for both blind and visually impaired students. This solution allows obtaining a relief print but with a certain limitation – all the elements are raised to the same, fixed height (*Atlas do przyrody dla osób niewidomych i słabowidzących - TOM 1 Polska*, 2010).

Figure 1. The maps used in the research: overview. On the left side - original map from atlas, source: (Atlas do przyrody dla osób niewidomych i słabowidzących - TOM 1 Polska, 2010). On the right side - 3D printed map, source: own work

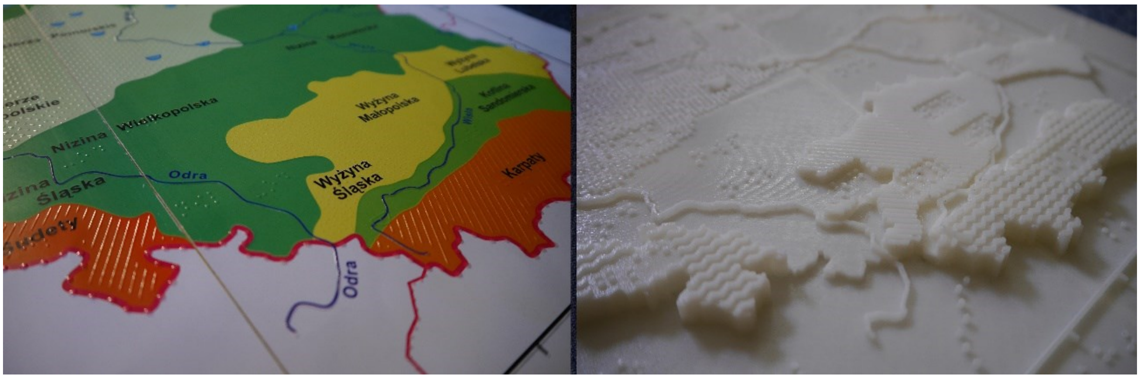


Figure 2. The maps used in the research: zoom-in. On the left side - original map from atlas source: (Atlas do przyrody dla osób niewidomych i słabowidzących - TOM 1 Polska, 2010). On the right side - 3D printed map, source: own work

The second map used in this research was developed as a part of the MSc thesis of Jakub Wabiński (Wabiński, 2017) with use of 3D printing technology, and more specifically Fused Deposition Modelling that uses thermoplastic material to form a physical model layer by layer on the 3D printer's surface. A tactile map presenting the geographical regions of Poland (Wabiński, 2017), similar to the one described previously, was developed with the help of tactile pedagogues working at the Society for the Care of the Blind in Laski (Towarzystwo Opieki nad Ociemniałymi w Laskach, 2019). The designed map is based on 'good practices' in the field of tactile map design (Edman, 1992; Braille Authority of North America and Canadian Braille Authority, 2011) and complies with the current curriculum. However, some modifications were introduced, resulting from the possibilities of 3D printing technology. The map sheet was created in A3 format, which is considered as an optimal format that takes into account the maximum reach of the reader's arms (Gual, Puyuelo and Lloveras, 2012). This fact defined, basing on the map extent, the scale of the map: 1:3 000 000. Thanks to the use of 3D printing technology it was possible to eliminate the disadvantages of the original map from atlas and to develop a multi-level map. It means that an additional variable - height - was used, as an element differentiating objects on the map. On the 3D printed map individual geographic regions are extruded to different heights depending on the average altitude above the sea level in a given area. This is a novel solution, unheard of in the existing literature. Because of the modification described above, line signs depicting rivers run through different geographical regions (at different heights), so another proprietary solution had to be applied. In order to follow the course of the river from its source to the estuary, special ramps were designed that transfer river signs between individual geographical regions, without disturbing their course. These ramps rise and fall at 45 degrees (Wabiński and

Mościcka, 2017). The 3D printed map was tested by 4 pupils from the school run by Society for the Care of the Blind in Laski (Towarzystwo Opieki nad Ociemniałymi w Laskach, 2019). At the time of testing, 2 of the pupils were at the primary school level, while another 2 were at the level of secondary school. 2 of the students were blind and 2 with severe visual impairment. . The pupils were asked to solve 6 tasks that simulated an exemplary geography class. The map was assessed by them as clear and understandable but they suggested some possible amendments (Wabiński, 2017).

The comparison of characteristics of the 2 maps is presented in Table 1.

Table 1. Characteristics of maps compared in the research. Source: own work

Parameter	**Original map from atlas**	**3D printed map**
Map sheet dimensions	595 x 420 mm	420 x 297 mm
Data frame dimensions	374 x 340 mm	246 x 232 mm
Scale	1:2 000 000	1:3 000 000
Joints	Folded sheet (2 equal parts), Distortion: approximately 1 mm	Rectangular segments with dovetail joints (6 parts), Distortion: negligible
Meridians and parallels	Insets on the edge of data frame every 1˚ of lat/lon (even values described)	Insets on the edge of data frame every 1˚ of lat/lon (odd values described)
Numerical/linear scale	Top left/top right corner	Top edge of the sheet/top right corner
North indication	Top right corner – convex triangle	Top right corner – convex triangle
Additional features	- coloured base - part of an atlas - multimedia guide for the student - wind rose	- height differentiation - ramps used to transfer linear signs - can be washed - durable

Both maps were developed in accordance with good practices described in literature (Edman, 1992; Braille Authority of North America and Canadian Braille Authority, 2011; Lawrence and Lobben, 2011; Wang et al., 2012) as well as tested and used by blind people. Both maps are readable for them so neither the degree of readability nor cartographic editing were the subject of our research. Although the scales of the maps are different, the degree of generalization of their content as well as the scope of tactile content are almost the same. So, these maps can be compared in terms of the amount of tactile information they provide, because only tactile elements designed for the blind people have been used in the research. The coloured elements used on the original map from atlas and designed for visually impaired people have not been taken into consideration. Because the map contents are almost the same, it was assumed that the ability of their readers (blind students) to read them is the same. The method of using these maps, which may be different in the case of a single map and an atlas map, does not influence the research results, because only the information value of particular tactile signs has been determined.

Map Comparison Principles

In order to measure the information values of tactile elements on both maps, we have calculated structural measure of information, in a way proposed by Salistchev Salistchev, 2002). It consists in calculating the amount of information as the sum of quantities characterizing the informational significance of cartographic signs according to the number of information each sign provides. Each difference of objects in terms of position and properties is considered as a unit of measurement. The Salistchev approach previously used for evaluation of traditional maps was adapted for tactile maps. The way of calculating structural measure of information was generally the same as in the original Salistchev method. The only difference in the proposed methodology is that instead of graphical variables distinguishing signs, three-dimensional haptic variables were used. The challenge here was to identify the variables used for cartographic signs differentiation correctly. For classic maps, the most commonly used graphic variables are those proposed by Bertin (Bertin, 1967). Unfortunately, they cannot be used in case of tactile maps as these require the use of a different set of variables - haptic variables. Haptic sciences are divided into two main components: one refers to skin sensations caused by touch and the other related to muscle mechanics. Years of work and experience led to the construction of a set of haptic variables that include those associated with the impression of touch and can be used to describe cartographic signs on tactile maps (Griffin, 2001; McCallum *et al.*, 2005). During this research we focused on blind readers and have taken into account only the haptic variables useful for blind readers. The reason behind it is that one of the maps used for comparison is suitable only for blind users (i.e. the 3D printed map).

Salistchev proposes to first assign to every cartographic sign used on the map, the number of information it presents. These values are then used to weigh the individual signs in order to compute the structural measure of information. This approach can be visualized by a simple example. A cartographic point sign representing residential area provides information on the location of this area in real world, which is a default property of objects on maps, but it can also provide additional information, such as population or administrative significance. In order to differentiate this kind of point symbols, a number of graphic variables has to be used. The appearance of a cartographic sign representing a city on a regular topographic map can be differentiated by changing its size, hue or value. So in the given example more populated cities can be indicated by bigger signs, while capital cities can be depicted by using different hue than any other cities on a map (Salistchev, 2002).

In order to measure the structured information value correctly, it is necessary to compute the number of cartographic signs of each type on the map. While the job is fairly easy in case of point symbols – they have to be counted one by one, for line and area symbols a different approach has to be used. It is necessary to apply geometric measures, i.e. the measurement of the length of individual signs and then to multiply these measures by the number of information represented by the sign of the corresponding object. As far as area symbols are concerned, their territorial differentiation and fragmentation is reflected in the lengths of their boundary lines (Salistchev, 2002).

For these measurements we used real-scale flat vector drawings of both maps (Figure 2). In order to facilitate the process of information value determination and to provide additional material for analysis, these drawings were divided into segments. As both maps are characterized by different scales (1:2 000 00 for the original map from atlas, 1:3 000 000 for the 3D printed map), it was necessary to divide them into the same number of segments but different in size. We determined the optimal number of segments empirically and it amounted to 36 (if a point symbols fell on the border of the segments, we then determined the centre of the sign's bounding box to indicate the segment that it should belong to). All the measurements were carried out in Rhinoceros 3D software. In order to analyze the spatial distribution of information values on both maps, these values were measured independently for each segment.

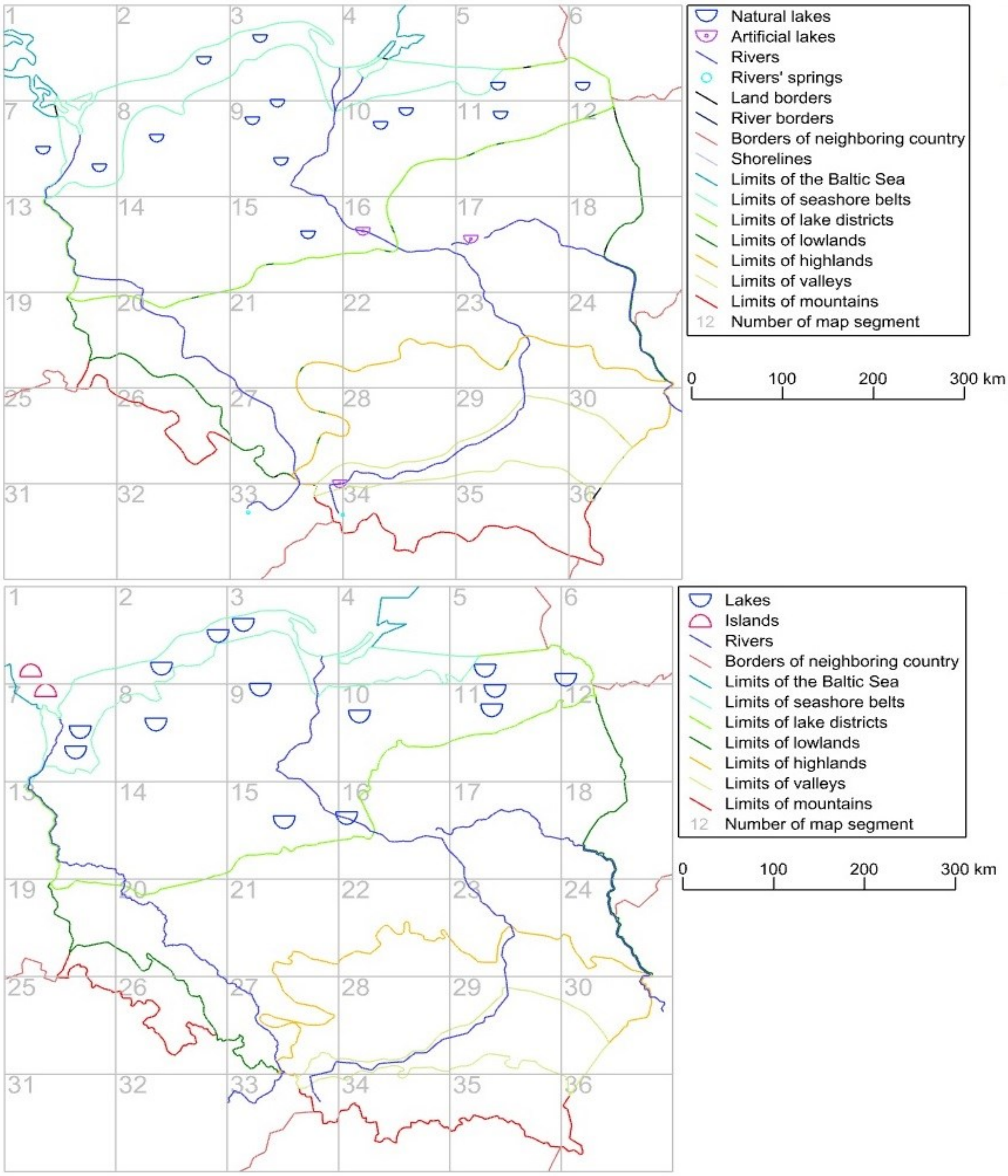


Figure 4. Flat vector drawings used for calculations. On the top – original map from atlas, at the bottom – 3D printed map, source: own work

We calculated structural measure of information with use of the proposed methodology, for particular segments of each map as well as for the whole maps. On the basis of the above assumptions, structural measure of information (*SMI*) has been calculated basing on the formula:

$$SMI = \sum_{i=1}^{n} SMI_i \qquad (1)$$

where:

n – the number of segments,

SMI_i – structural measure of information of particular map segment.

Structural measure of information of particular map segment (SMI_i) has been calculated basing on the formula:

$$SMI_i = \sum_{i=1}^{k} a_i * p_i + \sum_{i=1}^{l} b_i * p_i + \sum_{i=1}^{m} c_i * p_i \qquad (2)$$

where:

k, l, m - the number of particular types of point, line and area cartographic signs in map segment,

a_i - the number of point signs of particular type in map segment,

b_i - the length of linear signs of particular type in map segment,

c_i - the length of boundary lines of particular type of area sign in map segment,

p_i- the number of information assigned to a particular sign type (sign's weight).

While calculating the lengths of line signs and area borders it was important to reduce measurements to the same scale. In this case the values measured on flat vector drawings were expressed in the map scale. Thus, it was necessary to apply a scale factor. We multiplied values measured on the 3D printed map by a scale factor of 1.5, which shows the ratio of the scales of both maps used in the research.

It is not possible to compare the measurements of points, lines and area symbols directly, as they are measured in a different way. Therefore in order to compare the results obtained from measurements carried out on both maps, it was necessary to normalize the raw results. The normalization process also enables free choice of the way of measuring particular values on maps. It does not matter whether values measured will be expressed in the map scale or in real (terrain) values as long as they will be normalized later.

Final data should not have negative values and ought to range from 0 to 1. This is why the authors decided to use the simple min-max normalization method (Larose, 2005) based on the following formula:

$$V' = \frac{V - V_{min}}{V_{max} - V_{min}} \qquad (3)$$

where:

V' – normalized value,

V – original measured value (number of a specific type of point symbol or length of a particular line or area symbol in a particular map segment),

V_{min} V_{max} – minimum or maximum value measured on both maps.

Additionally, we decided to distinguish two categories of information presented on the maps: thematic (geographical regions) and background. A structural measure of information was calculated both for the entire map and separately for the background and thematic data.

Moreover, dividing maps into segments enables to perform an analysis of the distribution of the values of the structural measure of information of both maps to show the information density and its spatial arrangement. Therefore, we have created maps of distribution of the values of the structural measure of information of each map, as well as a map of value differences on both maps.

Knowing the number of individual pieces of information that the cartographic sign provides, it was possible to compute the information performance of a cartographic sign, proposed by a Polish cartographer Wiktor Grygorenko (Grygorenko, 1973) and called the information efficiency coefficient of a map (W). Instead of graphic variables, Grygorenko uses cartographic means of expression, that is all graphic elements used to create signs, which not only differentiate signs from each other, but also affect the readability of the map. For the purpose of tactile map assessment, the Grygorenko formula of information efficiency coefficient calculation was adopted in the following form:

$$W = \frac{i}{z} \tag{4}$$

where:

W - information efficiency coefficient of a map,

i - number of pieces of information given by all cartographic signs present on a map,

z - number of all cartographic means of expression used to create cartographic signs present on a map.

This coefficient can be also computed for each cartographic sign used on a map. According to Grygorenko, its optimal value should be equal to one - then one graphic symbol is used to transmit one information.

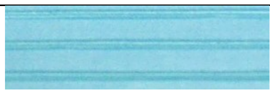
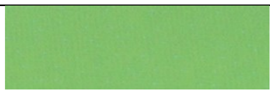
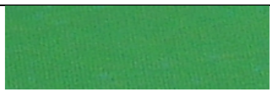
In the face of the fact that the Braille writing takes up much more space than the traditional one (because of larger characters), one should not only limit the descriptions of the objects constituting the basic content of the map but also apply the appropriate code system. When describing a geographical object, e.g. a river, the first letter of the code means the category and the rest stands for the particular name of the object. A common solution in Polish tactile cartography is that three-character abbreviations are used, where the first character is the category code and two consecutive ones identify the presented object uniquely (Więckowska *et al.*, 2015).

It was not possible to define how to efficiently measure these inscriptions. This is why at this stage of research we did not take map inscriptions into account. We have computed only the total number of each type of inscriptions that appears on both maps.

Results

The analyzed maps were created with use of different production techniques. This is why the appearance of particular cartographic signs as well as the number of information assigned to them is different. A list of all signs along with the number of information and haptic variables used is presented in Table 2 and 3.

Table 2. Map symbols and number of information assigned to them - original map. Source: own work

No.	Sign	Appearence	Number of information assigned	Cartographic means of expression	Haptic variables
1a	Natural lakes		1: type	1: shape	1: shape
1b	Artificial lakes		1: type	1: shape	1: shape
2	Islands	n/a	0	0	0
3	Rivers		1: type	1: line	1: shape
4	River springs		1: type	1: shape	1: shape
5a	Land borders		1: type	2: line, grain	2: shape, grain
5b	River borders		1: type	2: line, grain	2: shape, grain
6	Borders of the neighbouring country		1: type	2: line, grain	1: shape
7	Shorelines		1: type	2: line, grain	1: shape
8	The Baltic Sea		1: type	1: texture	1: texture
9a	Seashore belts		1: type	1: texture	1: texture
9b	Lake districts		1: type	1: texture	1: texture
9c	Lowlands		1: type	1: texture	1: texture

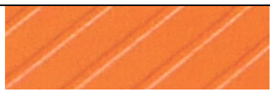
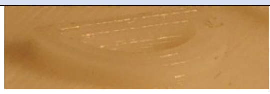
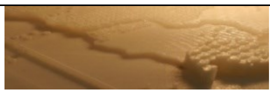
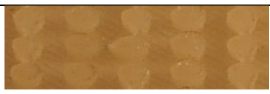
9d	Highlands		1: type	1: texture	1: texture
9e	Valleys		1: type	1: texture	1: texture
9f	Mountains		1: type	1: texture	1: texture
		Total	18	19	18

Table 3. Map symbols and number of information assigned to them - 3D printed map. Source: own work

No.	**Sign**	**Appearence**	**Number of information assigned**	**Cartographic means of expression**	**Haptic variables**
1	Lakes		1: type	1: shape	1: shape
2	Islands		1: type	1: shape	1: shape
3	Rivers		1: type	1: linie	1: shape
4	River springs	n/a	0	0	0
5	Polish border		1: type	1: line	1: height
6	Borders of the neighbouring country		1: type	2: line, grain	1: shape
7	Shorelines	n/a	0	0	0
8	The Baltic Sea		1: type	1: texture	1: texture
9a	Seashore belts		2: type, height	2: texture, height	2: texture, height
9b	Lake districts		2: type, height	2: texture, height	2: texture, height
9c	Lowlands		2: type, height	2: texture, height	2: texture, height
9d	Highlands		2: type, height	2: texture, height	2: texture, height
9e	Valleys		2: type, height	2: texture, height	2: texture, height

9f	Mountains		2: type, height	2: texture, height	2: texture, height
		Total	18	19	18

It is worth mentioning that the haptic variable of shape, in case of tactile maps, represents a three-dimensional shape and therefore there is no need to identify height as a separate variable. The only exception here is when signs within one category are differentiated by height variable. The same applies to textures. For example, in case of a sign representing the Baltic Sea the only variable used here is texture, which determines its three-dimensional shape. At the same time this symbol provides only one piece of information – position. The haptic variable of texture is also used to represent geographical regions, but in case of 3D printed map, individual geographical regions are also differentiated by height. This results in two haptic variables used (texture and height) and provides the user with three types of information: the position of a geographical region, its type and mean height.

In order to enable the comparison of the two examined maps, the same sign categories had to be used. This is why, even though in some categories there were zero signs on a particular map, these categories are still present in the table. As during the research we used the final products (maps), rather than developed them from the scratch, it was not possible to have exactly the same cartographic signs categories. This results for example in the presence of point signs representing river springs on the original map from atlas that do not exist on the 3D printed map.

In order to use the obtained results for comparison, we normalized all the signs' categories, using the previously described min-max method (formula (3)).

We then summed these individual results to provide information on the structural measure of information in each segment (SMI_i - formula (2)) and on each map (*SMI* - formula (1)). Tactile maps, as well as their classic counterparts, contain thematic and background content. In case of the map of geographical regions of Poland particular geographical regions (Lowlands, Mountains, etc.) form the thematic content. We checked the portion of total information value that was included in the thematic content of each examined map with use of the described methods. The results are presented in Table 4.

Table 4.Comparison of total values of structural measure of information (SMI) of both maps. Source: own work

	Original map	3D printed map
Whole map	54.15	61.68
Thematic content	18.69 (35%)	32.70 (53%)
Background content	35.46 (65%)	28.98 (47%)

It is clearly visible that the 3D printed map is characterized by a higher total cartographic information value, which provides the answer to the first and second research questions. It confirms that 3D printing and multi-level signs improve the value of information of tactile map. Besides, using the methods described, we demonstrated that over 53% of the information value of the 3D printed map is represented by area signs of geographical regions (thematic content). The original map from atlas, on the other hand, contains approximately 13% less information than its 3D printed counterpart, while at the same time less than 35% of the information value is represented by thematic content.

Division of maps into segments allows to perform an analysis of the distribution of the structural measure of information values (namely information density) of both maps (Figure 3). This might help in the future design of tactile maps, as it can be easily seen where the density of information is the highest and where is the lowest. Such information may prove invaluable as tactile maps require a decent level of generalization to keep the maps legible and optimizing the process of distribution of data on maps is of high importance.

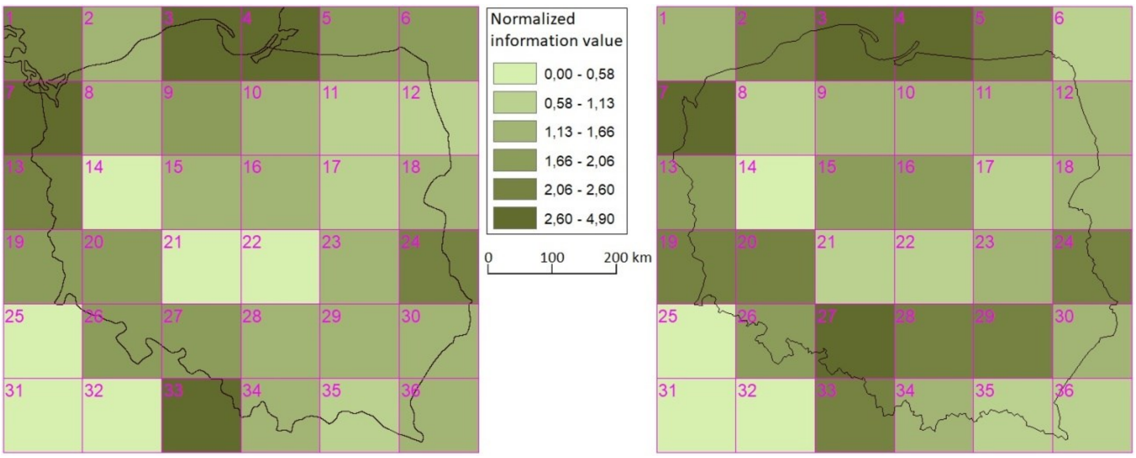


Figure 5. Distribution of the values of structural measure of information. Left – original map from atlas, right – 3D printed map. Source: own work

Both figures were normalized to the same scale. At first glance one can see that the 3D printed map is characterized by higher information value. The pattern of information distribution on both maps is similar. The corners of the maps, which contain little information, have lower information value. The same applies to central regions of Poland, where not much content is presented (this refers to the map of geographical regions).

As comparing the two maps is one of the aims of this paper, it seems to be reasonable to analyze the differences in information distribution that occur between these two maps. Figure 4 presents the differences between values of the 3D map and the original map from atlas. The biggest differences in this case occur, in segments with a higher number of point symbols. This is due to the fact that these cartographic signs are often highly generalized (displaced) and thus might count for different segments, although they represent the same phenomenon. Besides, as the course of the Polish border coincides on both maps, in these "bordering segments" the differences are relatively low.

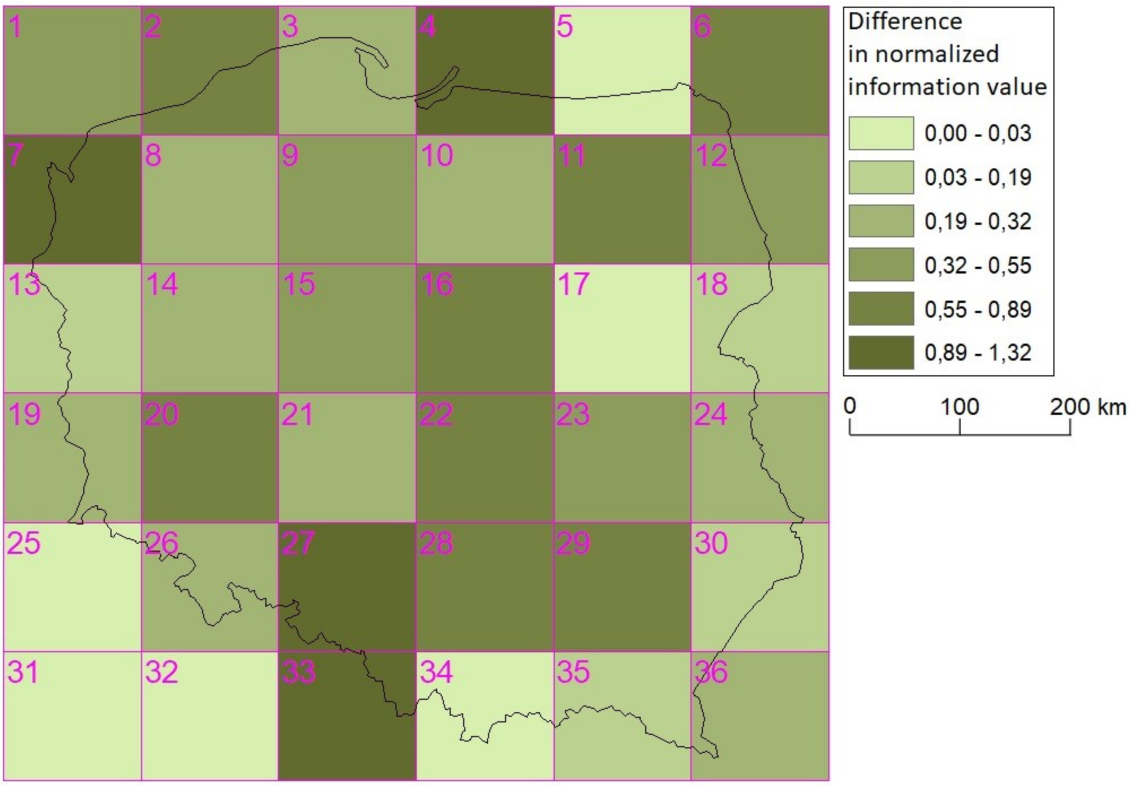


Figure 6. Comparison of information value distribution on both maps, source: own work

According to the method proposed by Grygorenko (Grygorenko, 1973), the amount of information assigned to each cartographic sign on both maps along with the number of cartographic means of expression used to present it were determined. This allowed us to compute the information efficiency coefficient of both maps (W):

- original map from atlas: 0.79
- 3D printed map: 0.95.

At this stage of research we did not take map inscriptions into account. Only the total number of each type of inscriptions that appears on both maps has been calculated. Table 5 presents the number of each type of inscriptions that appears on both maps.

Table 5.Number of each type of inscriptions used on both maps. Source: own work

Map inscriptions		
	Original map	3D printed map
Geographical regions	14	14
Rivers	9	8
Neighbouring countries	0	7
TOTAL	23	29

Discussion

The results presented in the paper allow for a better understanding of importance of the height differentiation of cartographic signs on tactile maps. It was already stated in the past research (James, 1982) that height differentiation is the best method for hierarchizing map content. Besides, maps on which symbols are put on different heights above the background level are easier to read due to the characteristics of the sense of touch. As a result the minimum distances between particular symbols at different heights can be reduced (Edman, 1992).

We had access to flat vector drawings of both maps. The calculations carried out as a part of this research did not require much time. The graphics software used is characterized by very high measurement accuracy. There was no need to produce any materials specially for this research as the 3D printed map was produced as a part of master thesis (Wabiński, 2017) and the other map was borrowed from the library of the Society for the Care of the Blind in Laski (Towarzystwo Opieki nad Ociemniałymi w Laskach, 2019). We acquired vector files of the original map from atlas from the authors of the map.

At the same time it is important to note that we could use only two map sheets. Although these maps were presenting the same geographical phenomenon, they were prepared in different scales and are characterized by slightly different content and level of generalization. Moreover, it is difficult to perform an objective evaluation and comparison of the readability of the two maps examined. The original one from atlas is commonly used in schools by blind and visually impaired students, while the 3D printed one was only tested by several students (Wabiński, 2017).. Students at the Society for the Care of the Blind in Laski (Towarzystwo Opieki nad Ociemniałymi w Laskach, 2019), with which the authors cooperate, are used to work with one of the maps examined (original from atlas) and find working with it easy, while, at the same time, the 3D printed map is something new and still unknown to them. In the future it is important to perform tests with volunteers from different societies and schools as well as with different backgrounds to provide an objective evaluation of both maps in terms of the cartographic information value they contain. The obtained results can mean, however, that it is still possible to enrich the tactile maps produced in terms of information value, while at the same time, keep them legible.

The obtained results demonstrate that the method of determination of structural measure of information used for traditional maps can also be applied to tactile maps. The only difference is that haptic variables have to be used instead of graphic ones. This constitutes the answer for the third research question and confirms that the methods of map assessment used for classic maps can be adopted to evaluation of tactile maps. This requires some experience in both designing and using these variables to obtain comprehensive information on their basis.

Information efficiency coefficient of a map is an excellent criterion for assessing the value of a cartographic image. High value of the coefficient indicates a more rational and economical system of signs. On the other hand, low coefficient indicates that the signs collection is not homogenous and that there is a superfluous congestion on the map. It also means that the map contains certain graphic elements that do not carry information. In our research, the information efficiency coefficient of the 3D map was higher (0.95) than on the original map (0.79). Moreover, the coefficient of the 3D map was very close to 1. It means that this map uses a more rational sign system, close to the optimal solution. It is an advantage of creating a multi-level map, which uses new signs at varying heights, so that it can provide more information. Besides, as it was stated in this paper, there is a positive correlation between the information efficiency coefficient and the structural measure of information of a single map.

3D printing technology is still not perfect and research on using it for tactile map printing requires further development. This production method is relatively slow and requires from the author a decent level of expertise to design the 3D model properly. Limitations in terms of the maximum size of printed elements do exist due to the constraints related with construction of modern 3D printers. On the other hand this production method has almost no limitations in terms of the shapes to be created. When combined with low-cost microcontrollers, it can be used for production of interactive maps and small-scale models that are adaptable to various teaching situations, such as education of blind and visually impaired (Giraud *et al.*, 2017). 3D printing was designed for rapid prototyping and is a perfect choice for creation of personalized tactile maps. It can be also used for production of complete tactile atlases.

The selection of material pleasant to the touch, legible braille inscriptions, patterns readability, 3D symbols design and their coexistence on tactile maps are only few research directions that should be undertaken to work out complete solutions in 3D printed tactile mapping. But the results confirmed our assumptions that use of 3D printing creates new possibilities in the design of signs on tactile maps, as well as new challenges. This is possible thanks to differentiation of signs by means of additional variable, i.e. height. It seems to be justified to undertake further work in this area and to develop proposals for new cartographic signs and thematic tactile maps. It is also important because of the fact that the cost of 3D printing of one unique map sheet is a lot cheaper than using traditional printing techniques. This might result in a wider access to tactile maps by blind and visually impaired users.

Conclusion

The aim of the authors was to analyze whether the methodology developed in the past (Grygorenko, 1982; Garmiz, 1989; Salistchev, 2002) for evaluating map information value is still up to date and can be applied to tactile maps. Results of the research presented in this article allow us to conclude that, after some minor modifications, it is possible to use the methods developed for classic maps to compute the structural measure of information also on tactile maps. Besides, it can be seen that the use of 3D printing, or any other manufacturing technology that allows full freedom in height differentiation of cartographic signs, makes it possible to increase the information value of a particular tactile map. This kind of analysis may be conducted at the design stage of every tactile map to be produced. This will allow tactile cartographers to design cartographic materials of higher value and to distribute the map content in a more efficient way.

The next step in the research in this area is to examine how this methodology might apply to colourful hybrid maps, which are useful for both blind and visually impaired people. It might be a good idea to also check the methodology with maps produced with different methods. However, at this point it has to be mentioned that the results presented are only numerical. According to Salistchev (Salistchev, 2002), these methods do not take into account the information that is obtained when analyzing the interrelations between certain phenomena presented on the map, and above all, they do not take into account the quality of this information: its accuracy, importance and utility. In case of tactile maps and aids for blind and visually impaired people in general, their utility is the most important factor. This is why further research should be carried out, to analyze how the results obtained translate into practical use of maps by blind and visually impaired people.

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