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Cartographic symbolization for high-resolution displays

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Abstract

The design guidelines for maps on screens constrain the symbol sizes due to the screen resolution limitations. However, high-resolution screens become increasingly popular and rethinking the map design for screens may be necessary. To investigate, if indeed currently available high-resolution screens create new rendering opportunities, first the related scientific work was reviewed on related topics such as visual acuity, visual display resolution, visual variables, and design guidelines for screens. Furthermore, the study with 27 participants was conducted, focusing on shape difference legibility for point and line symbols. The experiment was designed establish the smallest legible point symbols on tested high-resolution screens, and to inquire whether the screen resolution indeed limits the smallest symbols legibility. The results suggest, that only few people with perfect vision are likely to benefit from high-resolution displays. The minimal sizes of circles, squares and triangles were established for tested screen resolutions and compared to legibility results for proposed line symbols. Lastly, study limitations and research outlook was discussed.

Keywords: high-resolution, resolution, screen, visual display, cartography, web mapping, web map, Internet cartography, cartographic rendering

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Abbreviations

CSS - Cascading Style Sheets

HTML - Hypertext Markup Language

PNG - Portable Network Graphics

ppi - pixels per inch

1. Introduction

1.1. Background

Maps on screens can definitely be called the maps of our times. We come across maps in the online version our favorite magazine, or using a smartphone app to see the way to a Viennese cafe, where we hope to find an amazing Apfelstrudel.

The internet presents a great opportunity for accessing maps across the world, but also poses a challenge for the modern cartographer. One such challenge in modern mapmaking is that cartographers do not know what hardware or software will be used to display the designed content (Jenny, Jenny and Räber, 2008).

Screen resolution and pixel density are factors that seem to have a major influence on map design for screens. These factors constrain symbol size and complexity, as well as the amount of content presented. Several researchers call for simplified web map design because of lower screen resolution in comparison to the resolution of print (Lobben and Patton, 2003; Jenny, Jenny and Räber, 2008). This reasoning is generally true taking into consideration that most common computer screens have pixel density of about 90 pixels per inch in comparison to 600 dots per inch in case of standard laser printers.

A digital display can be called a high-resolution display, or high-resolution screen when "the quality of the perceived image is constrained only by the limits of the human eye and not the characteristics of the device"(Bardsley, 2012). Computer screens with pixel densities greater than 200 ppi are typically referred to as high-resolution, as their resolution is believed to exceed the eye limits at the standard viewing distance.

Such high-resolution displays became first commercially available in 2001 when IBM started producing the "Big Bertha" computer screen with a resolution of 3,840 x 2,400 pixels and pixel density of 204 ppi. Since then, there was further technological progress in the display technology. In 2010 Apple introduced iPhone 4 with a Retina display having a pixel density of 326 ppi. Currently as for September 2019, the highest resolution available for a computer screen is 7,680 x 4,320 pixels, with a resulting resolution of 280 ppi.[1] Even higher resolution was achieved by phone screen producers – Sony launched two smartphone models[2] with 4K display and as many as 806 pixels per inch. For mobile phones, high resolution screens are now common, and also for laptop and desktop computers, such screens can be found more and more often. The conventional guidelines for designing maps for screens may now be outdated, but new guidelines for designing maps for the wide range of display sizes and resolutions in use today are not yet available.

Cartographic rendering has been addressed by several authors. Malić (1998) conducted an interesting study, in which she derived minimum dimension for cartographic symbols on specific screens. Neudeck (2000) also investigated digital screen technology, focusing on applications for

[1] 8K Desktop computer screen, model Dell UP3218K

[2] Smartphone models: Sony Xperia Z5 Premium released in 2015 and its succesor Sony Xperia XZ Premium released in 2017, both with a 4K display

topographic maps. In the time of the above-mentioned studies, high-resolution screens as previously defined were not yet available.

The issue of high-resolution screens is more complex than it first appears for various reasons. Firstly, it is difficult to clearly define what value of pixel density exceeds the limitations of the human eye. The eye resolution cannot be estimated by a single value, and it differs from an individual to the individual. Second, the eye resolution can be expressed in a visual angle such as 1 arcmin, and the pixel spacing is linear value. Hence, whether a display exceeds eye capability also depends on the viewing distance.

Despite being almost 20 years since high-resolution displays were first produced, they are still not common, at least for typical desktop settings. Therefore, it is understandable that mapmakers need to consider design with most common, and available, display devices characteristics in mind.

Within the next decades, high-resolution displays are likely to become widely present and map design for such devices needs to be addressed.

1.2. Research Questions and Objectives

The design guidelines for maps on screens recommend using simplified geometries, larger symbol sizes and reduced amount of content in comparison to the printed maps. This thesis attempts to determine if map design for high-resolution displays should be different from the one for common lower resolution devices. It focuses on the aspect of minimum dimensions for point symbols and possible application of those findings in line symbolization.

This study aimed to address the following questions:

- Is the point symbol legibility dependent on the screen pixel density?
- What are the smallest point symbols sizes that can be visually perceived on screens?
- Are these sizes different for different screen resolutions?
- How can the insights from three previous questions be relevant for creating a new line symbolization?

In order to answer those questions, the following objectives were chosen:

- Establishing minimum dimensions of point symbols for different screen resolutions
- Conducting a study with around 30 participants to confirm the minimum dimensions
- Designing a line symbol and testing its legibility

Finding answers for the above-mentioned research questions may help to create more effective cartographic visualizations for high-resolution screens.

2. Background and related work

In this chapter it will be attempted to provide information essential for understanding the opportunities and problems related to the cartographic symbolization on screens, and more specifically, related to screen resolution and limitations of human vision.

2.1. Human Vision and Eye Acuity

In order to understand the abilities and limitations of a human eye, we need to investigate issues from two disciplines - biology (anatomy of a human eye) and physics (optics).

First, I will shortly discuss the anatomy of the eye and explain how human vision works. Some researchers compare the eye to the camera, as the eye's parts and camera's parts have analogous function Ware (2013). In the eye, as well as in the camera, there is a lens, the aperture (the pupil), and the sensor array (the retina).

When a ray of light enters an eye, it passes through a thin transparent layer of cornea, through an eye aperture which is called a pupil, and later goes through a lens (Figure 1). Both the cornea and the lens have the ability to focus rays of light, and are responsible for seeing sharply. The lens can change its curvature in a process called accommodation, which enables seeing objects clearly at different distances from our eyes. We are only able to see sharply when light rays get focused at the right distance, exactly on the surface of retina. This is where the portion of light is captured by light receptors - rods and cones, in the layer of fovea (Ramamurthy and Lakshminarayanan, 2015). Rods are responsible for seeing at night and cones during the day, therefore for the purpose of this research we will focus on cones.

It is the spacing of the cones that limits the resolution of human vision of daylight. The cones' density is the highest in the central part of a fovea (Figure 2) – spacing between centers of neighboring receptors is around 0.6 arcmin of visual angle (Westheimer, 2009).

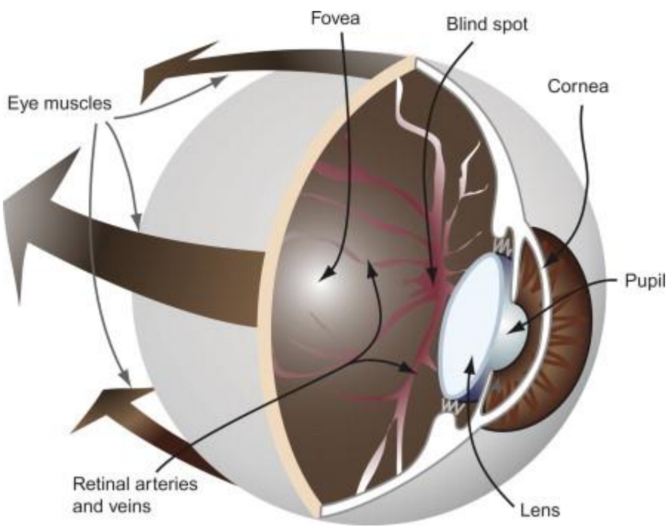


Figure 1 The anatomy of human eye (Ware, 2013)

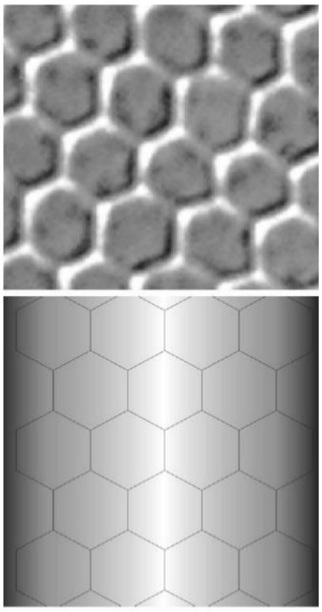


Figure 2 Microscopic image (upper) and schematic model (lower) of the central retina (Westheimer, 2009).

Eye resolution can also be described by Rayleigh criterion (Equation 1). It is a measure of optic system resolution and expressed by a function of wavelength of the light and the aperture diameter (Lakshminarayanan, 2015).

$$\theta_{min} = \frac{1.22\lambda}{D}$$

Equation 1 Eye resolution as a function of wavelength λ and pupil diameter D (Lakshminarayanan, 2015)

The visible light's wavelength varies with color from 380 nm to 740 nm as well as the diameter of a pupil changes in level of illumination. Under photopic (well-lit) conditions, the pupil size is 2-4 mm and for mid-visible wavelength θ_{min} is about 1 min of arc.

Visual angle, which can be a measure of visual acuity, is measured from the optical center of the eye. This measure can also be expressed by equation 2 (Ware, 2013). According to this formula, the visual angle of an object is dependent on the viewing distance. An object of 1 cm size viewed at the distance of 57 cm corresponds to approximately one degree of visual angle, while 1 mm at the same distance of 57 cm corresponds to 6 arc minutes of the viewing angle.

$$\theta = 2\arctan\left(\frac{h}{d}\right)$$

Equation 2 Visual angle of an object is dependent on viewing distance (Ware, 2013)

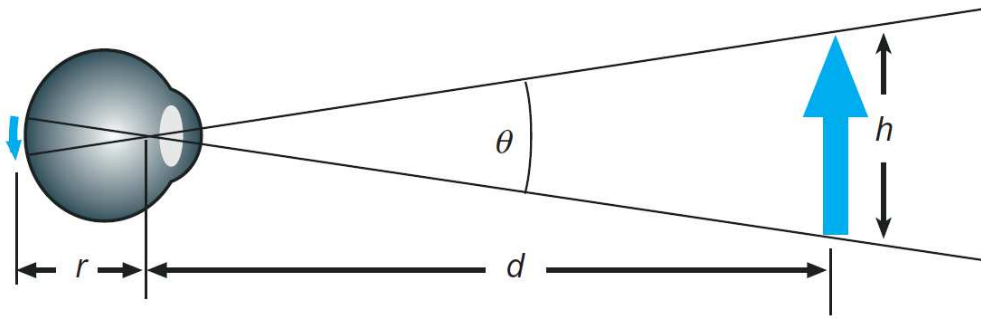


Figure 3 Visual angle of an object (Ware, 2013)

Visual acuity according to Lakshminarayanan (2015) is "a measure of the visual system's ability to see distinctly the details of an object". It is possible to measure the visual acuity using high-contrast stimuli. Visual acuity is also often expressed by the smallest distance between two objects (for instance lines or points) such that they are still seen as separate. It can be also expressed by width of thinnest visible line. Visual acuity value is usually represented by the angular value (e.g. 1 minute of arc) or in cycles per degree (e.g. 60 cy/deg).

The anatomy of the eye, especially the retina, has a major influence on vision acuity. Only photoreceptors in the central fovea have one-to-one connections with higher neural levels (Westheimer, 2009) and their density in this part of retina is the highest. With cones' spacing of 0.6 arcmin we can visualize how light levels are sampled at the photoreceptors. Figure 3 shows retinal light distributions for line pairs with different separation distances.

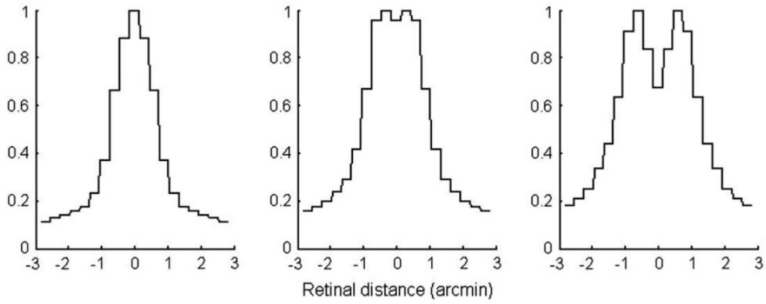


Figure 4 Lines with different separation distances sampled by retinal receptors in the fovea (lower part) (Westheimer, 2009).

The most common method of acuity measurement is the Snellen eye chart (Figure 4). The observer is asked to read letters in the chart from the distance of 20 feet (or 6 meters). A 20/20 Snellen test result means that the observer was able to read a letter which subtends 5 minutes of arc, when standing 20 feet away from the chart. Vision result 20/80 would mean, that the tested person has a vision defect which makes it only possible to read the line of the chart that would subtend 5 mins of visual angle when standing in the distance of 80 feet. This method of measuring eye acuity was developed in 1862 and it is the most popular method used in the optometrist office. It is worth mentioning that many young healthy individuals have vision better than 20/20, and closer to 20/15 (Lloyd *et al.*, 2015).

The results of acuity tests are dependent on several factors. Lakshminarayanan (2015) in the Handbook of Visual display technology mentions 8 of them: the choice of letters, letter spacing, target contrast, retinal illumination, retinal eccentricity, duration of target presentation and target motion, neural defocus, and age.

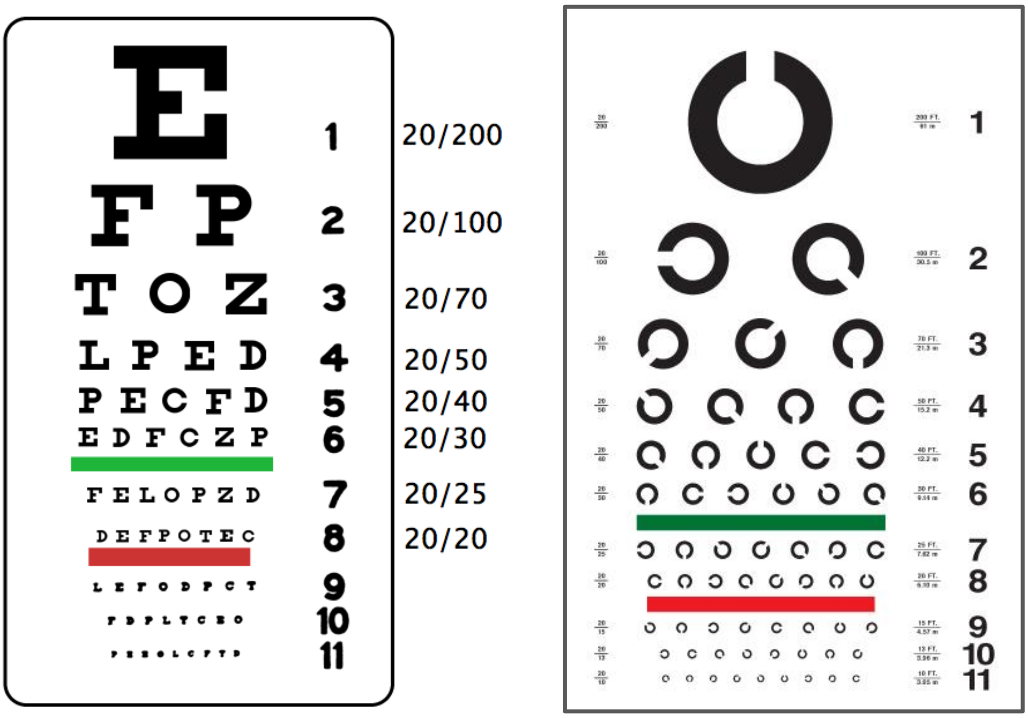


Figure 3 Two types of acuity tests Snellen letters (left part) – tested person is asked to read the letters, and Landolt C, also called Landolt rings (right part) – tested person is asked to say in which position is the gap in the ring.

Even though vision resolution is dependent on cones' spacing in the retina, it is possible to perform certain tasks with higher precision than expected from photoreceptor density or the Rayleigh criterion. Such high performance of vision is called hyperacuity. According to De Valois and De Valois (1980) this is possible, when information from several photoreceptors, sometimes spread over degrees of visual angle, is analyzed. One common example of hyperacuity test is Vernier's acuity test. The observer sees two lines and has to decide if one of them appears dislocated to the left or to the right comparing to the other line. Vernier acuity has a value of a few seconds of arc (Westheimer, 2010).

Desjardins (2014) provided a short summary of acuity and hyperacuity values found in scientific literature (Table 1). It is worth noting, that this is a wide range of values – from 1 arc minute to as little as 0.44 arc seconds.

Resolution	Source	Comment
1.72 cy/mr	Rash, 1998/Task, 1997	20-20 vision, 100 fL adapted
2.29 cy/mr	Desjardins	20-15 vision, extrapolated
56 cy/deg	Williams, 1992	theoretic Nyquist frequency
21-23 cy/deg	Williams & Coletta, 1987	Nyquist frequency, measured
60 cy/deg	Williams, 1992	gratings, "normal conditions"
221 cy/deg	Williams, 1992	interference fringes, 8mm eye
50 arc seconds	Hopper, 2000	20-20 vision
25 arc seconds	Hopper, 1999	high contrast conditions
30-35 arc seconds	Westheimer, 1979	interference fringes
10-12 arc seconds	Westheimer, 1979	smallest discernable posit Δ
1 arc second	Westheimer, 1979	"Minimum visible," line
10-35 arc seconds	Duke-Elder, 1938	"Minimum visible," points
0.5-10 arc seconds	Senders, 1949	"Min. distinguishable," line
4 arc seconds	Duke-Elder, 1938	"Min. distinguishable," line
0.5 arc seconds	Riggs, 1965	"Min. distinguishable," line
0.44 – 6 arc seconds	Low, 1951	"Min. distinguishable," line
2 arc seconds	Wright, 1944	"Min. separable," lines
1 arc minute	Helmholtz	"Min. separable," letters
1 arc minute	Riggs	"Min. separable," dots
60 cy/deg	Larimer, 2004 120	photoreceptors/deg
6 arc seconds	Larimer, 2004	"hyperacuity" experiments
0.5 arc seconds	Borish, 1975	"Min. separable angle," letters

Table 1 Spatial resolution of human eye (in cycles per degree or angular value), according to different sources (adapted from Desjardins, 2014)

2.2. Resolution of Digital Displays

Digital display resolution is the measure of screen size expressed by number of pixels available in horizontal and vertical direction. One example of common computer screen resolution is 1,920 x 1,080 pixels, which is also known as Full HD. Another way of describing the screen resolution is giving an approximate number of pixels in vertical direction. A 4K screen is such display that has around 4 thousand of pixels in vertical direction. One of 4K standard screen sizes is 4K UHD with 3,840 × 2,160 pixels. Similarly, 8K UHD will have 7,680 × 4,320 pixels. Figure 4 shows four examples of screen resolutions.

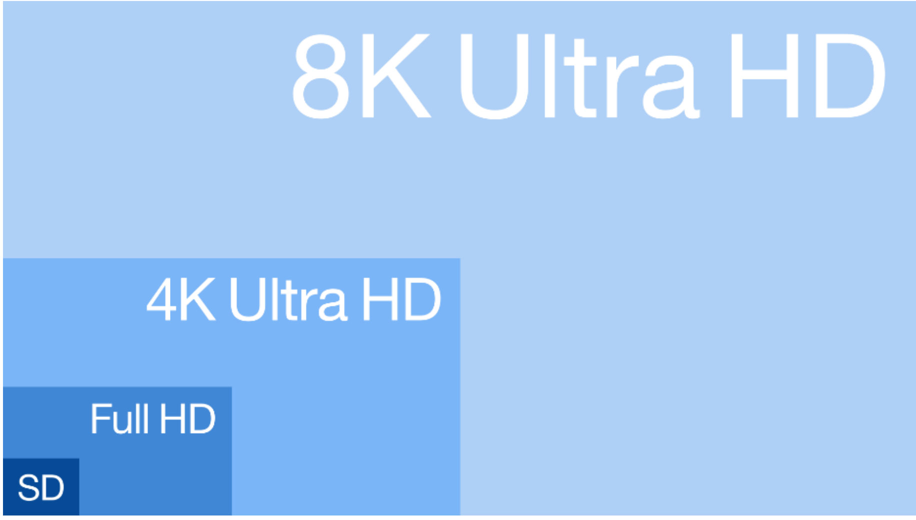


Figure 4 Four resolutions - SD 720 x 480 pixels, Full HD 1,920 x 1,080, 4K UHD 3,840 × 2,160 pixels and 8K UHD with 7,680 × 4,320 pixels

The display image quality is dependent not only on the number of pixels in the digital display, but also pixel density. It can be calculated dividing the number of pixels along the diagonal and it is expressed in ppi (pixels per inch). For instance, a 4K computer screen can be the same size (diagonal) as Full HD screen, but will have twice as many pixels per inch. High pixel density makes the images look sharper and makes it possible to render more details that are visible in the same viewing distance.

The ability to see the smallest details on a digital display depends also on viewing distance. For computer screens standard viewing distance differs somewhat in the literature. Ware (2013) gives value of 57 cm, Hopper (2000) 61 cm, Fihn (2016) mentions 91 cm (3 feet) as a typical viewing distance for a PC monitor. Even though getting closer to the screen may allow you to see more details, it is not recommended to decrease viewing distance because of the increased eye strain. This is why optometrists recommend between 40 and 76 cm viewing distance for computer screens.[3] For phone screens standard viewing distance is 30 cm (Spencer *et al.*, 2013). According to Bardsley (2012) for laptops and desktop monitors, but also for handheld devices, comfortable viewing distance is around 40-50 cm. Additionally he mentions that it is possible to bring handheld

[3] https://lookafteryoureyes.org/eye-care/screen-use/

devices closer to the eye, and this is why designers may want to include information that can be resolved at 25-30 cm.

Digital display designers have been trying to create a display that would meet the eye resolution. It would be such screen, that the quality of perceived images would be constrained by eye limitations, not the display characteristics (Bardsley, 2012). It is not clear what should be the pixel density of such display, as both definitions of visual acuity, as well as the viewing distance are not defined as single values. Visual acuity differs from individual to individual, with experiment conditions and depending on performed task. Even if we take a certain angle (e.g. 0.5') as an acuity estimate, the linear resolution that corresponds to that value will depend on the viewing distance, which can be estimated by certain standard values, but is not a fixed value

Several authors were doing research in order to find out what is the eye-limited visual display resolution.

Hopper (2000) mentions the need for resolution of 17,189 ppi for acuity of 0.5 seconds and viewing distance of 61 centimeters and resolution of 172 ppi for 20/20 vision (Table 2) at the same viewing distance of 61 centimeters. Hopper, who did this research for the U.S. Air Force also describes some limitations of 20/20 vision definition, such as limiting the complexity to letters, static image, and only black/white color. He also calls the 20/20 standard "the most conservative view". Nevertheless, nearly 20 years ago even the U.S. Air Force wasn't equipped with such high-resolution screens (even according to 20/20 acuity definition) in airplane cockpits or simulators.

Table 2 needed pixel density according to different acuity values at 24 inches (61 cm) viewing distance (Hopper, 2000)

Acuity	Comment	Pixels/inch @ 24 in.
100 arc seconds	Image perceivable	86
84 arc seconds	E-letter, orientation	102
50 arc seconds	20/20 vision	170
25 arc seconds	2 discs/bars	344
14 arc seconds	Detect square	614
5 arc seconds	Glint, stars	1,720
2 arc seconds	Vernier	4,297
0.5 arc second	Line > 1°	17,189

Lloyd *et al.* (2015) reviewed 5 common eye-limited resolution definitions:

- 20/20 acuity (1 arcmin resolution)
- inability to distinguish the image from the real world
- inability to detect image artifacts
- the smallest hyperacuity value (few seconds of arc)
- resolution of asymptotic visual performance

The last definition of asymptotic visual performance according to the authors was the most practical. It seems that for lower resolution screens, the task performance is almost linearly correlated with resolution, and close to 1 arcmin pixel pitch, the differences in performance are marginal so the function of visual task performance is asymptotic. An example of such visual task performance is shown in Figure 5. Upper curve in the chart shows performance in triangle orientation detection and the lower curve shows performance in Landolt C orientation detection.

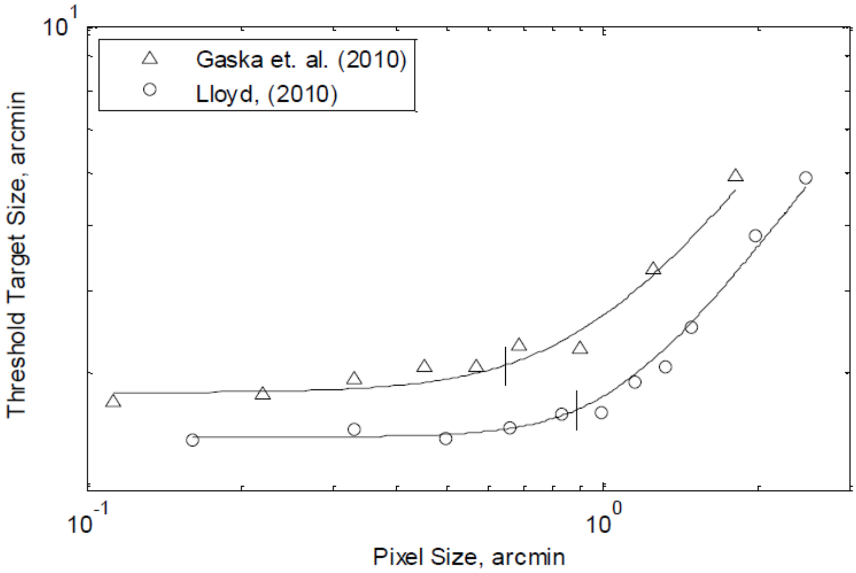


Figure 5 Target size threshold in arcmin as a function of pixel size for two visual tasks (Lloyd *et al.*, 2015)

Spencer et al. (2013) were investigating the ability to recognize lower and higher resolution images in order to find the minimum angular resolution for smartphones. The screen resolution was imitated by printing on a photographic film and placing a light behind the film. Images were resampled to 4 standard resolutions and printed with a 4.35” diagonal resulting in 254, 339,508 and 1016 ppi pixel density. Participants were seeing test images at 30 cm, typical viewing distance for mobile phones. Tested images were in two versions, with and without anti-aliasing, and it appeared that anti-aliasing has bigger influence on lower resolution images than on higher resolution images. Also, effectiveness of anti-aliasing differed according to the used stimuli. Study participants could still differentiate between antialiased pictures with high frequency components in resolutions 339 ppi and 508 ppi, which was not possible in case of an image with low frequency patterns.

While the study of Shishikui and Sawahata (2018) was focused on psychological connection between higher and lower order impressions, they also found evidence on differences in perception of images in different resolutions. Tested images were created with four standards 1K, 2K, 3K, 4K, and they were presented to the experiment participants in different viewing distances – 53 cm, 106 cm and 212 cm. The authors found evidence that image resolution influences perception of objects in the image even beyond the standard viewing distance.

The first commercially available screen that was said to exceed the eye limits was “Big Bertha”. It was a computer screen released by IBM in 2001 and it had a resolution of 3,840 x 2,400 pixels and 22 inches diagonal resulting in 204 ppi pixel density. With the viewing distance of 60 cm, such pixel density can be calculated to pixel spacing 1.4 arc min of visual angle, very close to the 20/20 acuity definition.

The next milestone in the digital display development was in 2010, when IPhone 4 with Retina display was released. This is how the Apple Retina display was introduced:

The resulting 326 pixels per inch is so dense that the human eye is unable to distinguish individual pixels when the phone is held at a normal distance, making text, images and video look sharper, smoother and more realistic than ever before on an electronic display[4].

While inability to distinguish individual pixels is one of definitions of eye-limited resolution, it is not the most demanding definition.

Currently, as of August 2019, the highest resolution computer screen available commercially is the model DELL UP3218K with 7,680 x 4,320 pixels and 31.5-inch diagonal. The resulting pixel density is 280 ppi.

Mobile phones with highest pixel density are Sony Xperia Z5 Premium that appeared on the market in 2015, Sony Xperia XZ Premium, released in 2017 and Sony Xperia 1 which was released in 2019[5]. All three phone models have 4K display and 806 ppi pixel density. Figure 6 shows flagship smartphones ranking according to the pixel density in 2017. Besides Sony Xperia XZ Premium, 12 models from different producers reached pixel density of 500 ppi and higher.

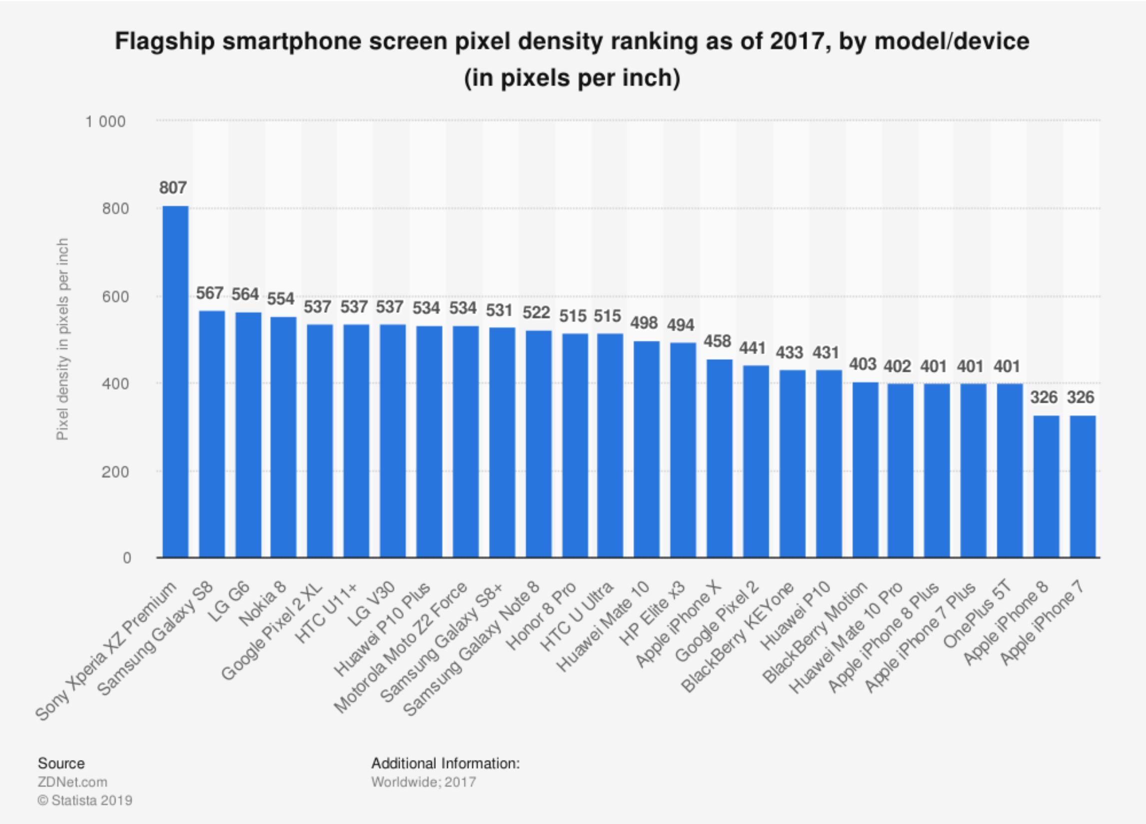


Figure 6 Flagship smartphones screen pixel density (in pixels per inch) ranking in 2017. Source: https://www.statista.com

[4] https://www.apple.com/newsroom/2010/06/07Apple-Presents-iPhone-4/

[5] https://www.sonymobile.com/global-en/products/phones/xperia-1/specifications/

There is a big discrepancy in resolution between flagship smartphone resolutions (up to 4K), and the most popular resolutions (Figure 7).

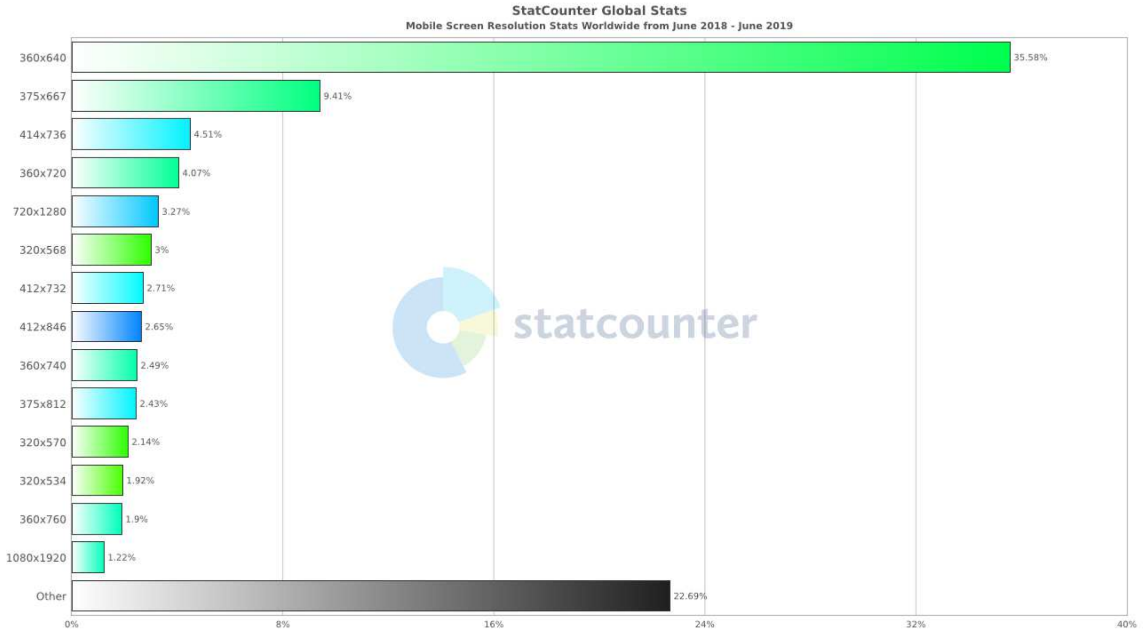


Figure 7 Mobile phone screen resolutions, June 2018-June 2019. Source: statcounter

Even though it has been almost 20 years since the high-resolution screens (like IBM big Bertha) were first produced, they are still rare. For computer screens the most common resolution is 1,366 x 768 pixels, which is less than Full HD, second most popular standard with 1,920 x 1,080 pixels (Figure 8). Higher resolution computer screens are still much more expensive than lower resolution devices, and this is why most of current population still cannot afford them. The distribution of computer screens resolutions worldwide is shown in Figure 8.

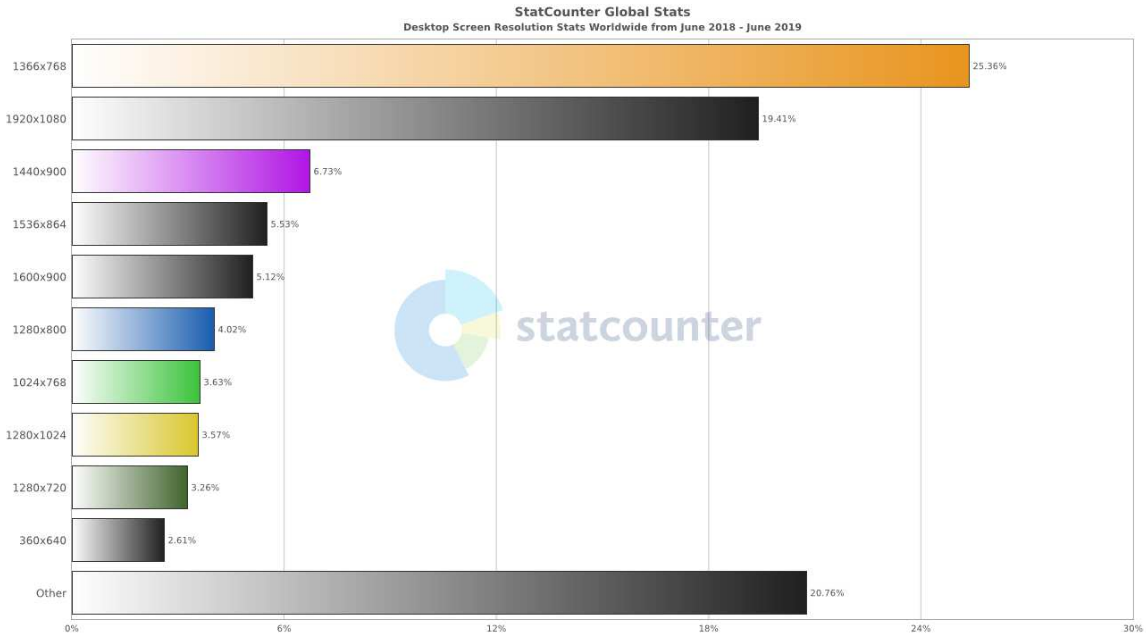


Figure 8 Desktop screen resolution, June 2018 - June 2019. Source: statcounter

2.3. Cartographic symbols and visual variables

In a map, real objects and phenomena are presented in a simplified way with means of symbols. In this chapter, it will be shortly explained what are cartographic symbols, what are the basic types of symbol geometries. Also, visual variables and their main characteristics will be discussed.

The understanding of symbols in cartography is based on Peirce's concept of signs. According to this concept, there is a connection between the referent (object), sign vehicle (a symbol), and the interpretant (understanding of a symbol).

The point, the line, and the area are the three types of geometries that can be recognized on the two-dimensional plane (Bertin, 1983). These geometries can be assigned to visualize topographic or thematic data. It depends on the scale of representation which of them should be used. For instance, a river can be visualized as a line but it could be also visualized as area if the scale of the map decreased enough (Kraak and Ormeling, 2009).

'A POINT represents a location on the plane that has no theoretical length or area. This signification is independent of the size and character of the mark which renders it visible.'

'A LINE signifies a phenomenon on the plane which has measurable length but no area. This signification is independent of the width and characteristics of the mark which renders it visible.'

'AN AREA signifies something on the plane that has a measurable size. This signification applies to the entire area covered by the visible mark.' (Bertin, 1983)

Previously defined geometries can be visualized in different modes. They can vary in size, texture, color, orientation, or shape (Figure 9). Those modes are called visual variables or retinal variables and they were systemized by a French cartographer Bertin (1983).

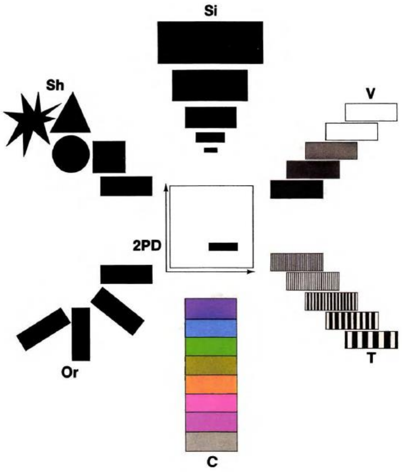


Figure 9 Six visual variables according to Bertin (1983). Variation in shape, size, value, texture, color, and orientation

According to Bertin (1983), visual variables can have the following properties: they can be selective, associative, ordered or quantitative.

Visual variables can be used with three types of geometries – points, lines, and areas (Figure 10).

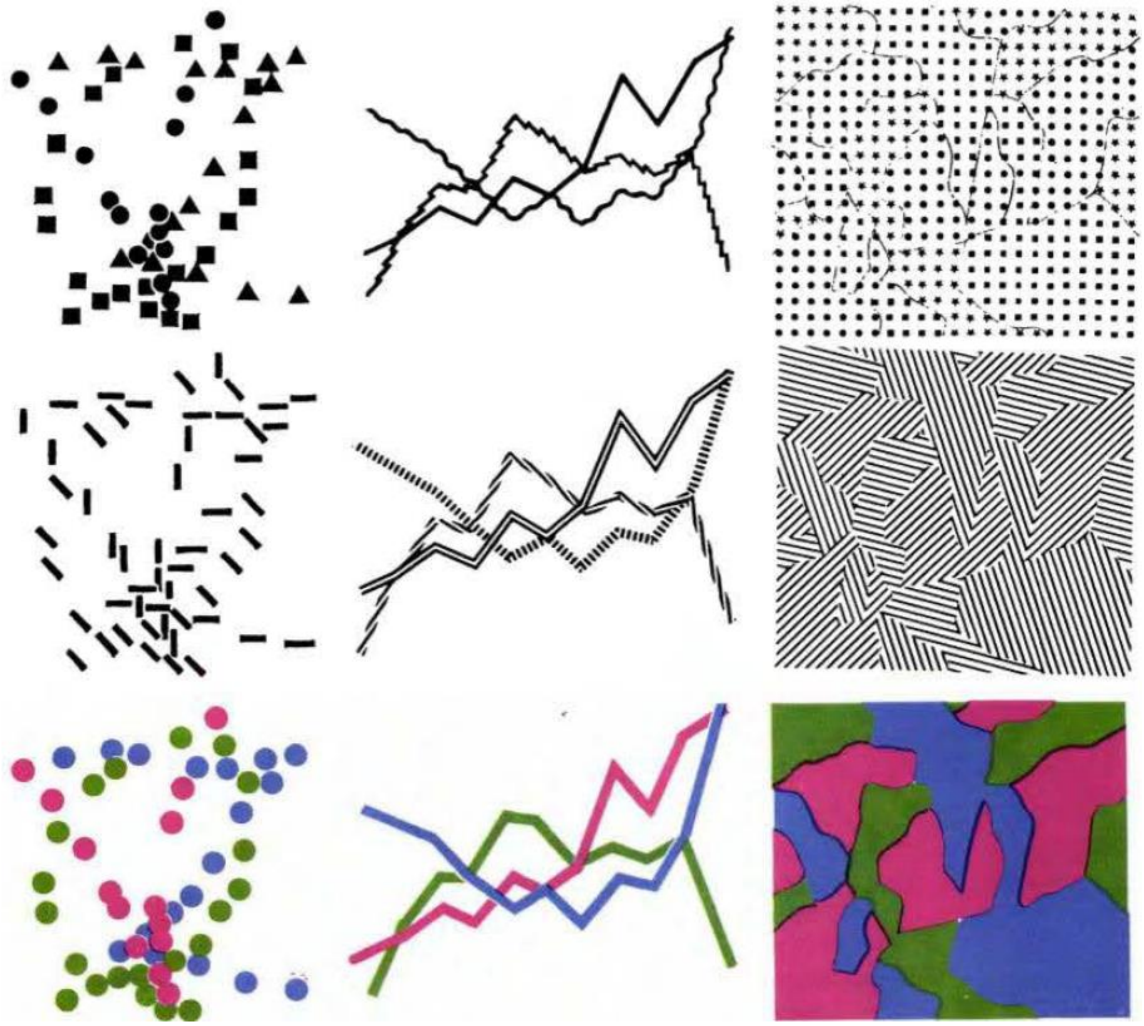


Figure 10 How graphic variables shape, orientation, and color can be used with geometries of points, lines, and areas (Bertin, 1983)

It is possible to combine visual variables within one cartographic symbol (Bertin,1983) Figure 11 shows how such combinations may look like.

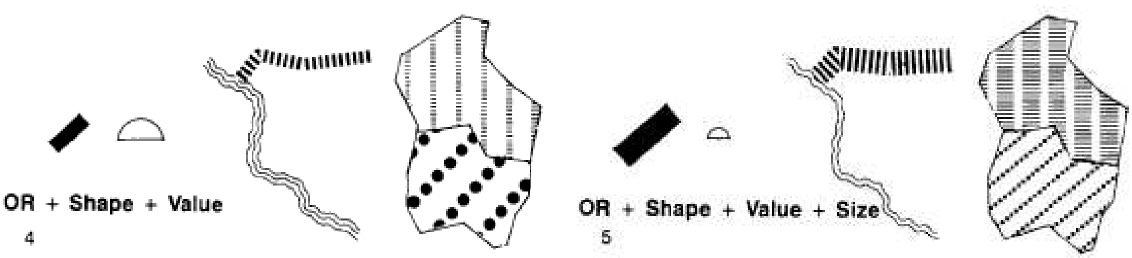


Figure 11 Example combination of visual variables (Berting,1983)

Bertin underlined that his study focuses on two-dimensional plane, and visualizations designed to be printed on white paper. He explicitly excluded i. a. relief representations and image movement (animation).

Kraak and Ormeling (2013) in their book 'Cartography: Visualization of Geospatial Data' recognized in addition to previously described variables, also shadow, blur, transparency, and blinking/focus (Figure 12). These visual variables seem to be more relevant for online maps.

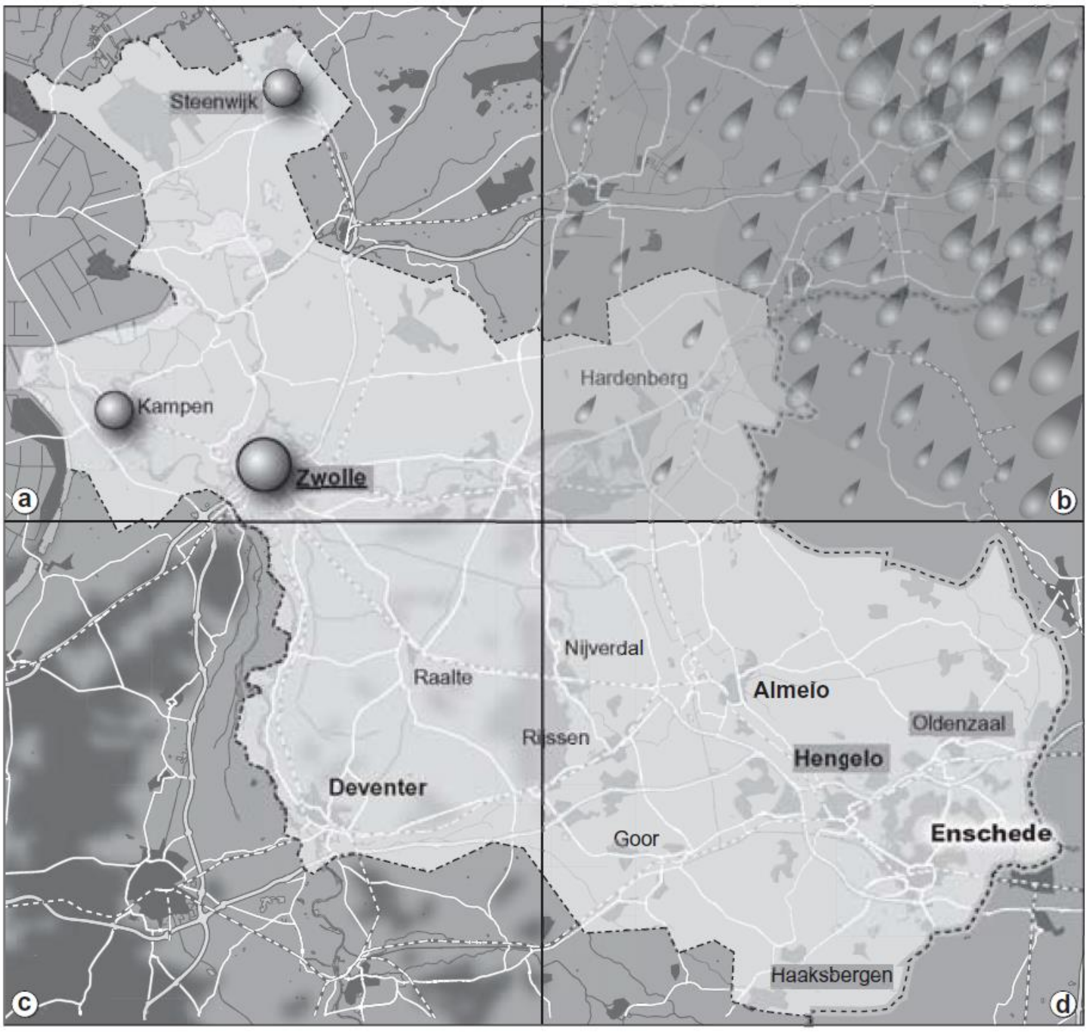


Figure 12 Additional graphic variables a) shadow; b) blur; c) transparency, d) blinking/focus. Source: Kraak and Ormeling, 2013)

In the context of minimum dimensions, Bertin only mentions that the smallest black mark on paper should have a diameter of at least 0.2 mm, but the constellation of smaller marks is also visible.

Concerning the topic of legibility of different symbols varying in shape, several authors (Malić, 1998; Neudeck, 2001) point to the specification of Swiss Society of Cartography (Rytz *et al.*, 1980), where smallest legible sizes for chosen symbols were established in the context of printed maps. According to this specification, the smallest legible square should have at least 0.35 mm side length, circle (hollow) should have 0.5 mm diameter, for a triangle side length must be as much as 1.0 mm. Those minimal symbol sizes, established by the Swiss Society of cartography, are a useful guideline for high-frequency and high-contrast patterns. For lighter colors, it is recommended to use significantly larger symbols.

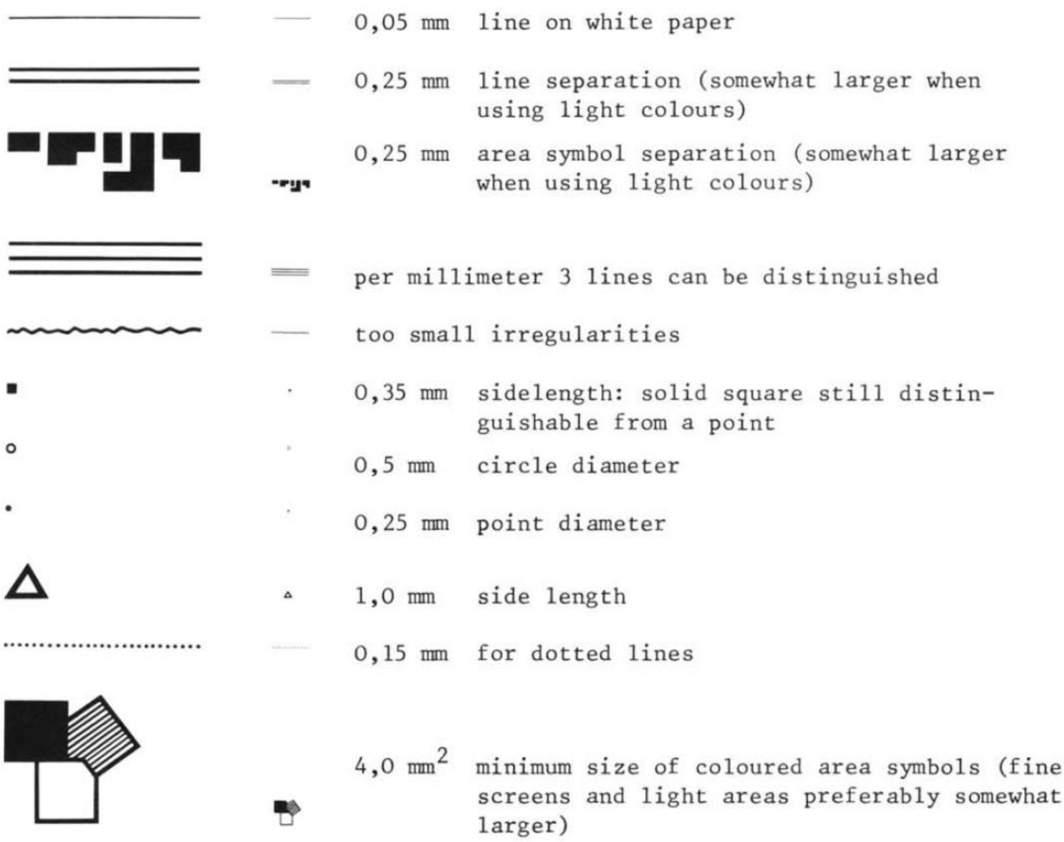


Figure 13 Recommendation for minimal dimensions according to the Swiss Society of Cartography (Rytz et al., 1980)

2.4. Map design for screens

Many authors addressed the issue of map design for screens. There are many applications of maps for screens, so it has to be taken into consideration that design for a specific purpose may differ. Web maps are also often evaluated taking into consideration usability as a measure of interface success (Nivala, Brewster and Sarjakoski, 2008; Roth, Ross and MacEachren, 2015). In this thesis though, the focus will stay on aspects of visualizing of content with special attention for topics related to the screen resolution, rather than interactivity and functionality of web maps.

'The new hypermedia technology can free the cartographer from conventional design constraints. Of course, all these technological design opportunities do not guarantee a better map - the general principles of good design do not change, even when the technology does.'
(Harrower, Keller and Hocking, 1997)

Most of the traditional cartographic rules, such as choice of visual variables should be also applied in web cartography (Muehlenhaus, 2014). Some standards on the other hand, as mentioned by the author minimal line thickness or type size, are at least useless or even harmful in context when the map is designed for screens.

Lobben and Patton (2003) mention that it may be difficult to create an aesthetically pleasing digital map, as it is not possible to control the viewing quality. They suggest simplifying this task by designing a map for a minimum display standard. They also presented a few guidelines improving the design of maps for the internet. They recommended using reduced information density and simplified geometries, in order to improve legibility (Figure 14).

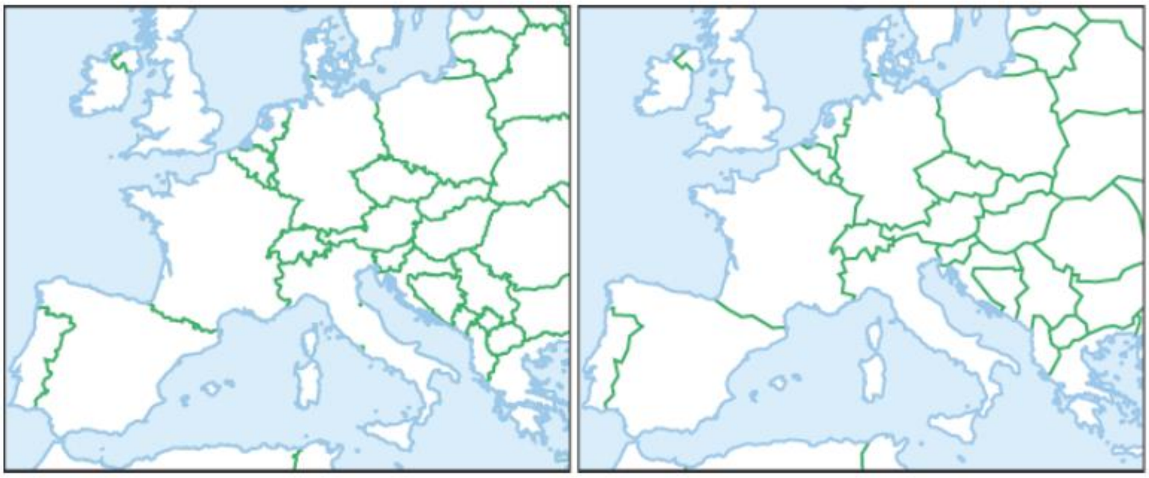


Figure 14 Simplified geometry improves readability on screen (Jenny, Jenny and Räber, 2008)

Anti-aliasing is a procedure that makes smooths the edges of map element (Jenny, Jenny and Räber, 2008). The authors adviced using this procedure for increased legibility. This technique creates blur along the objects when looked at from a close distance, but increases readability. The authors suggest that the rendering process with anti-aliasing might be time consuming, and result in increased hardware requirements. Without anti-aliasing, map elements appear jagged (Figure 15).

Figure 15 web map without anti-aliasing (left) and with anti-aliasing (right). Source: Jenny, Jenny and Räber, 2008

Jenny, Jenny and Räber (2008) recommend using types at least 12 points, and sans-serif rather than serif fonts. Lobben and Patton (2003) mention Times, Arial, and Helvetica as very legible, and installed on most computers, which can be another reason to choose them.

Graphic simplicity for web maps should also include fewer colors (Jenny, Jenny and Räber, 2008). Authors also notice that the different monitor settings (brightness, contrast, color temperature) can influence the final effect. Modern web maps use sometimes dark colors which would be not practical in case of printing on white paper (Figure 16).

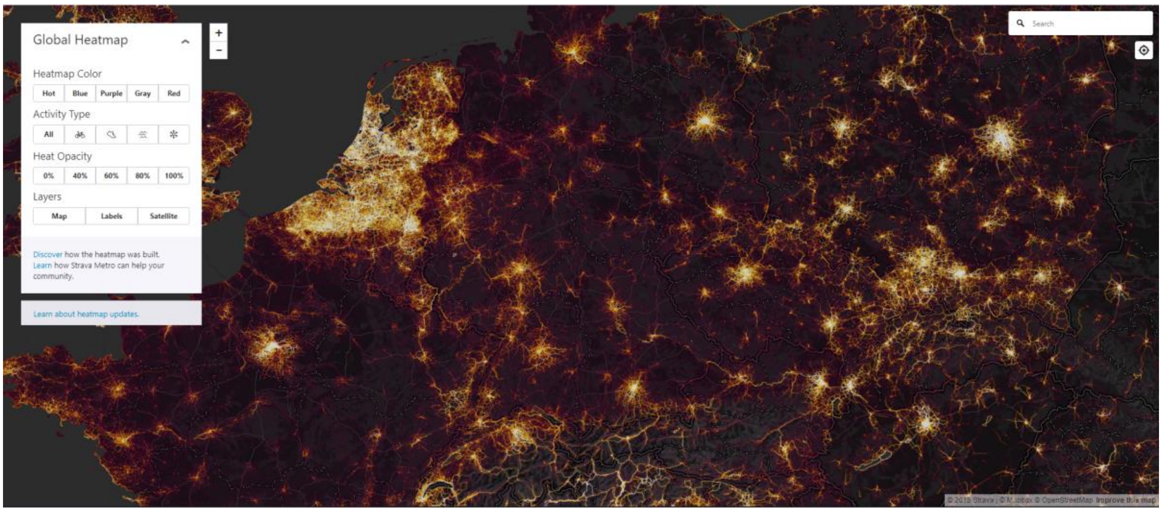


Figure 16 Some modern web maps use dark color schema, Source: strava.com

Minimum dimensions for screens have been investigated by several authors. Malić in 1998 focused on rendering of different sizes cartographic symbols on devices with 5 different resolutions. Every resolution was tested in 3 variants – 25” and 20” screens with aperture grille and 17” shadow mask screen. She tested point symbols – circle, square, triangle and diamond both hollow and full. She was also checking what is the minimum line width and line separation distance. The tests were done by analyzing the rendering of symbols on tested screens.

Several authors mention that minimum sizes of symbols should be “considerably larger” for screen maps (Jenny, Jenny and Räber, 2008) in comparison to analogical values for traditional printed maps. The authors of the paper recommend that point symbols have a diameter of at least 6 pixels. In the same paper, 30 cm is mentioned as viewing distance for paper maps and 60 cm as viewing distance for computer screens. It is another reason, besides screen resolution, to choose larger symbol sizes. Neudeck (2001) similarly to Jenny, Jenny and Räber (2008) recommends minimum dimensions expressed in pixels – at least 6 pixels width for a square, 10 pixels for a (hollow) triangle, and 10 pixels diameter for a circle.

3. Methodology

In this chapter, the methods and workflow of this thesis' research are explained.

Having in mind previous research on resolution discussed already in chapter 2, two approaches for preparing the experiment were considered. Either rendering vector graphics on different screens or imitating the effects of device resolution with lower resolution images was possible. When using different screens, not only pixel density changes, but also screen brightness, colors, contrast, etc. change. Hence, to investigate the effects of resolution on different screens, many devices would be necessary. Chosen devices should also have possibly similar other characteristics. An alternative way of investigating the influence of resolution would be using lower resolution images on a high-resolution screen. Lower resolution

Coming from the definition of high-resolution displays as such ones that their resolution exceeds the eye resolution, it became clear that an experiment with several participants is necessary. The individual differences in vision quality were expected have considerable effect on the results.

One of the commonly used methods of collecting data while investigating many study participants is through the online survey. Typically it is used to get answers from participants using various devices with internet access. I this study the online survey was chosen for the convenience of results collection.

The following parts of the thesis will explain the role of the used hardware and software in the experiment design, as well as demonstrate the way the survey images were created, and how the experiment was designed.

3.1. Used hardware and software

In this research two types of screens were used to investigate rendering of raster images with cartographic symbols. Images were rendered on a mobile phone screen with pixel density of 806 ppi and a computer screen, with 217 ppi. These pixel densities result in 0.03 mm and 0.12 mm pixel spacing respectively. The two chosen visual displays were chosen for a study as these devices are representing some highest commercially available pixel densities. Sony Xperia Z5 Premium (Table 3) is a phone with highest commercially available pixel density. Iiyama 5K computer screen (Table 4) is one of the highest resolutions available on the market. Those displays were chosen to be used in the experiment because of their high resolution.

Table 3 Phone screen characteristics

Model	Sony Xperia Z5 Premium
Diagonal	5.5", 14 cm
Panel	IPS LCD capacitive touchscreen
Native resolution	2160 x 3840 pixels, 4K UHD
Pixel density	806 ppi
Brightness	566 cd/m² typical[6]

[6] https://www.gsmarena.com/sony_xperia_xz_premium-review-1610p3.php

Table 4 Computer screen characteristics[7]

Model	Iiyama PROLITE XB2779QQS-S1
Diagonal	27", 68.3 cm
Panel	IPS LED
Native resolution	5120 x 2880 @60 Hz, 5K UHD
Pixel density	217 ppi
Brightness	440 cd/m² typical
Static contrast	1.200:1 typical

The computer screen was used with following settings: Brightness 50%, Contrast 50%, Color normal (warm/normal/cool). These were typical settings for work with this screen. Phone screen was used with the maximum brightness available for this model. Figure 17 shows microscopic images of digital displays used in the survey – 806 ppi IPS LCD screen and a 217 ppi IPS computer screen. Under the microscope it is possible to see a difference in the sub-pixel arrangement.

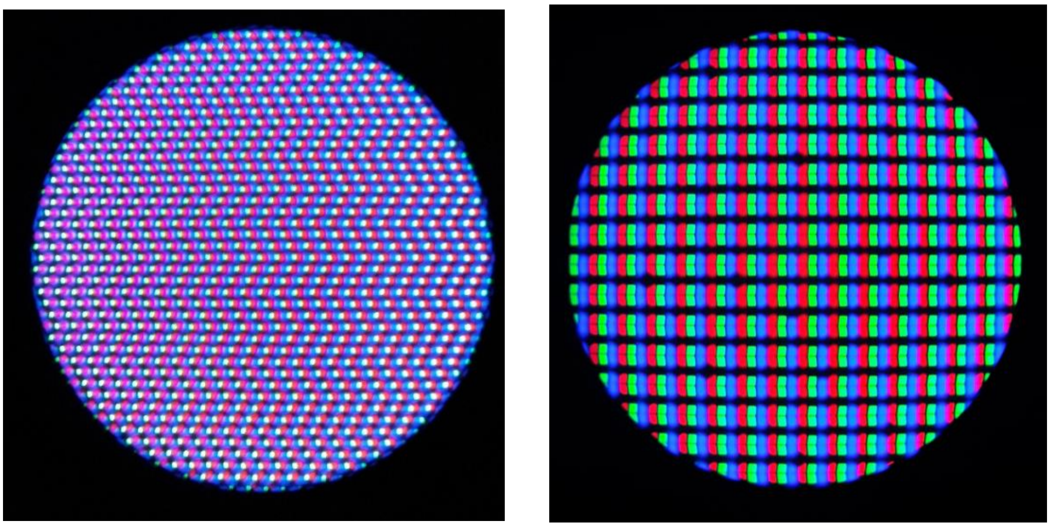


Figure 17 Microscopic images of used screens. Left - 806 ppi phone screen, right - 217 ppi computer screen

3.2. The process of creating and displaying images

There were 3 basic shapes taken into consideration – circle, square, and triangle. These are the shapes that were investigated by Malić (1998). In comparison to Malić, the rhombus was excluded, as it is essentially the shape of two triangles.

The results of vision tests are often dependent on participant’s knowledge of possible solutions (Westheimer, 2009). This is why some authors adjusted the results with the chance of guessing. For this reason, wider range of shapes was provided, so that the participants are not certain of the possible images that they can see. Even though the focus of the study was the legibility of the three basic shapes, for point symbol recognition additional images included a star, a pentagon, and a dinosaur (Figure 14).

[7] https://iiyama.com/gb_en/products/prolite-xb2779qqs-s1/

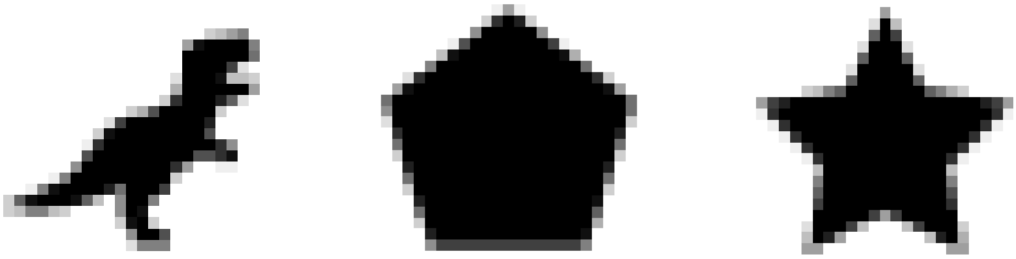


Figure 18 Enlarged images of additional shapes provided in the survey - a dinosaur, a pentagon and a star 0.7 mm wide, exported for an 806 ppi screen

Simple shape recognition is very similar to the optometrist test, and has very little to do with cartography. The question of ecological validity was raised, and both point symbols and line symbols used in the experiment were also tested in the map context. This cartographic visualization was not expected to influence the result of the test, as cartographic symbols were still appearing on the white background. The used cartographic visualization was meant to not distract the viewer from the investigated symbol.

Two cartographic visualizations were produced for the experiment. One map was an atlas-like representation of Austria with country borders and water bodies (Figure 19). The used data was downloaded from Natural Earth (Patterson and Vaughn Kelso, 2014).

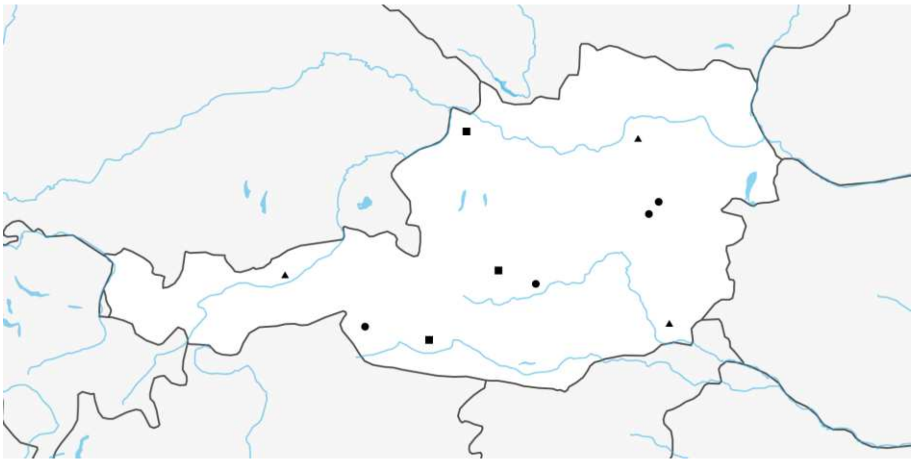


Figure 19 Atlas-like cartographic visualization for task 1b (200% enlarged)

The three basic shapes were also applied in the line symbolization (Figure 20). It was inspired by the idea of visualizing attributes of spatial data with varying shape and pattern density.

Line symbolization was created using "Pattern brush" tool in Adobe Illustrator. Initially, the pattern segments were based on a rectangle, 1:2 sidelength proportion. From such a rectangle, a half-circle was cut out, and merged on the other side. The same procedure was repeateed for a equilateral triangle.

Figure 20 A rectangle with 1:2 proportion, and two shapes constructed on its base

The pattern was designed to have a gap break equal to the width of the pattern. However, the break between the rectangles seemed to be much wider than the break in other pattern types. The rectangle length was extended, and the gap in rectangle pattern reduced, in order to be perceived similar to other patterns.

The designed line symbol was used along the streets of Vienna (Figure 21). The map data was acquired from data.gv.at, filtered and visualized for the purpose of this experiment.

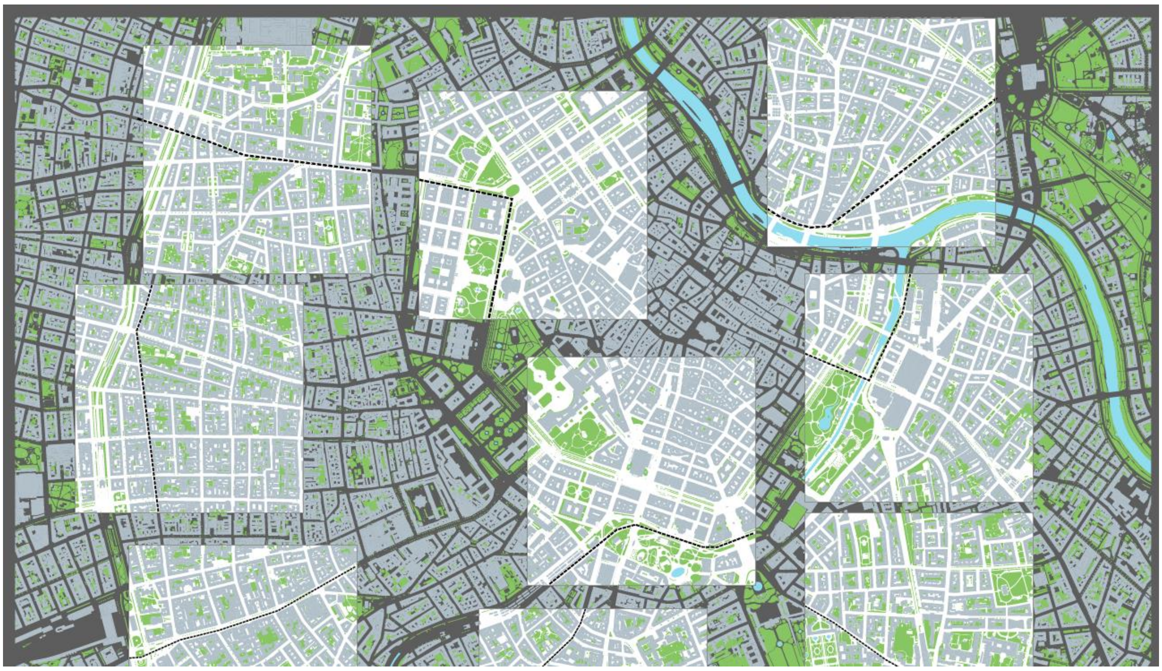


Figure 21 Vienna City Map, map context for linear symbol in survey tasks 2b, 3

According to the Swiss Society of Cartography, the smallest legible square should have at least 0.35 mm side length, circle (hollow) should have 0.5 mm diameter, the triangle a side length as much as 1.0 mm (Rytz *et al.*, 1980). These values were established for black print on white paper, and may differ for a digital display. For a computer screen, larger sizes may be needed because of bigger viewing distance. On the other hand, handheld devices such as a mobile phone, are commonly used closer to eyes, so the test results were expected to be similar to Rytz et al. (1980).

In this study, "the size" of symbols was understood as "the width of a symbol", as in other studies considering the problem of minimal legible symbols. It is not unambiguous, as symbols varying in shape can be perceived as different size, as they could have different surface area.

The decision about sizes of symbols investigated during the experiment was made after exporting test images in different resolutions – 806 ppi, 403 ppi, 202 ppi, 217 ppi, and 109 ppi. It seemed that for lower resolutions, it is quite clear which symbol sizes are legible, and which are not. For higher resolution, the eye acuity could have bigger influence than the image pixel size. It seemed to be a better idea to include also symbols smaller than they were expected to be recognized, rather than be surprised by the results of study participants with exceptionally good vision.

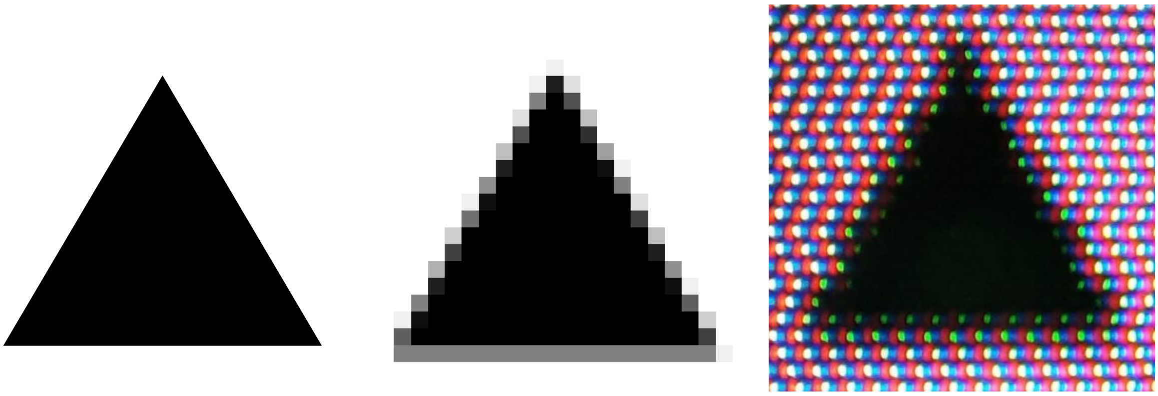


Figure 22 Vector image, raster image and raster image rendered on the screen – a 0.6 mm wide triangle on an 806 ppi phone display

Even though the 3 stages of image rendering (Figure 22) appear to be straightforward, there are many ways of creating raster images and also several factors that influence final rendering. All the steps made on the way from vector image creation to final results are carefully described in this chapter, with some indications of alternative procedures.

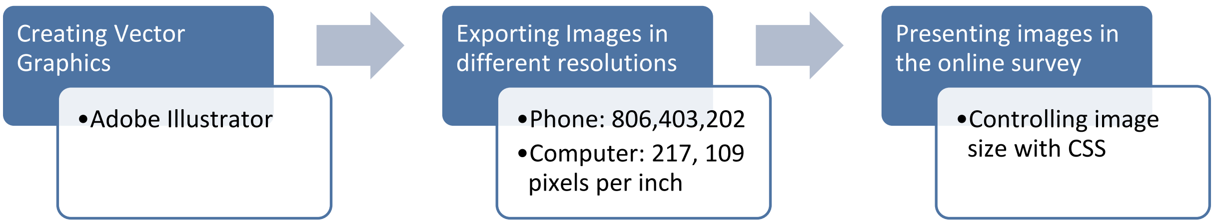


Figure 23 Three main stages - creating a vector graphic, export of a raster image, and image rendering in the device

Figure 23 illustrates 3 main steps of rendering images for the experiment.

The main steps are:

- creating vector images in Adobe Illustrator,
- exporting them with anti-aliasing in varying resolutions and
- displaying them with CSS styling.

Images were created in the vector graphics software Adobe Illustrator. Vector graphics have mathematical precision and used software/technology is not expected to have influence on final result. Meaning an equilateral triangle 0.6 mm wide, will have exactly this size and proportions.

The next step was exporting the vector images in different resolutions. Adobe Illustrator allows three export options – without anti-aliasing, with anti-aliasing (art optimized) or hinted (for text). The option with anti-aliasing was chosen, as anti-aliasing was proven to have a positive influence on image quality, with major improvement in case of lower resolution screens (Spencer *et al.*, 2013). This way, the high-resolution screens did not get an obvious advantage. Also, using antialiasing is closer to the real-world scenario, as modern displays support anti-aliasing.

Another choice made in the moment of image export was image format. It was possible to export the image in JPEG file, but PNG file was chosen, as a more appropriate for high-contrast and high-frequency tested patterns.

Exported images had slightly different (+/- 2 pixels) dimensions. To match the display grid in the same way, they were cut to match exactly the same size.

Cropped images were ready to be used in the online survey. This form of a survey was supposed to enable effective collection of the results, using many images of different shapes and sizes. The platform chosen was "LimeSurvey" as it was available at the department, and offered tools for image display (Figure 24). The survey is an HTML file (a website), with a default layout and possibility of customizing it with CSS. In order to display the images in expected sizes, the images size in pixels was divided by pixel ratio. This value is used for high-resolution screens to display contents in similar sizes to lower resolution screens.

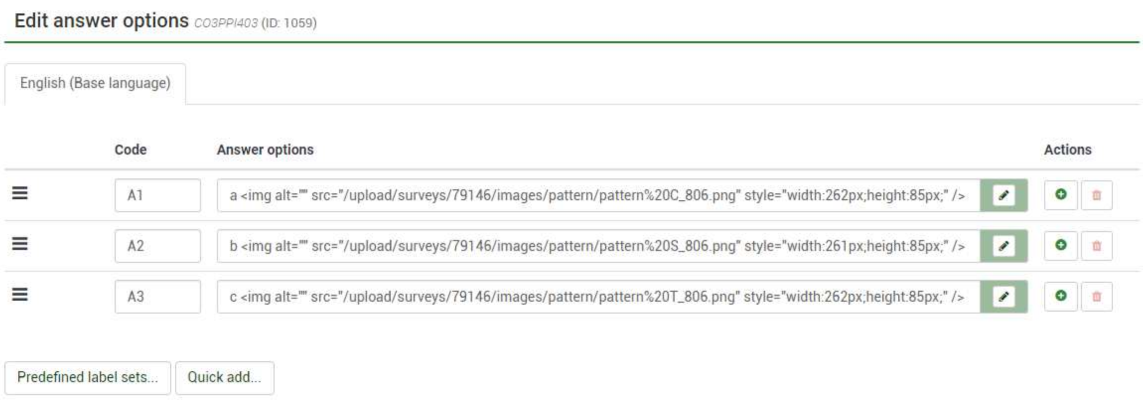


Figure 24 Capabilities of LimeSurvey – adding image files as alternative answers

Images used in the online tool LimeSurvey were scaled to the proper size with CSS using image width and image height properties.

3.3. Survey Structure

The survey was composed of several tasks – legibility of point and line symbols, with and without the map context. The main focus was on shape differentiation, applied for line symbols. The survey was designed to test legibility of line symbols in different resolutions. The tested symbol sizes were chosen based on the minimal possible rendering.

1 a. Legibility of point symbols

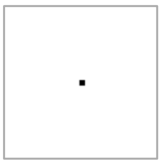
At the beginning, the point symbols legibility was tested in native screen resolutions of 217 ppi and 806 ppi. Three shapes – circle, square and triangle were tested in 0.1 to 0.6 mm width for a phone screen, and in 0.3 to 0.7 mm for a computer screen (Table 5). The computer version of a survey included additional images: pentagon 0.5, 0.6 and 0.7 mm; star 0.5, 0.6 and 0.7 mm; rotated triangle 0.6 mm; rotated square 0.5 mm; dinosaur 0.7 and 1.5 mm. Additional images for Phone version of a survey: pentagon 0.4, 0.5 mm; star 0.4, 0.5 mm; rotated triangle 0.6 mm; rotated square 0.4 and 0.5 mm; dinosaur 0.5, 0.6 and 1.5 mm. For both devices, these symbol sizes were the smallest possible to render. The order of images in the question group was random, in order to prevent the influence of order on expected answer.

Table 5 Tested point symbol sizes (triangles, circles and squares) in survey task 1a

device	computer	phone
resolution	217 ppi	806 ppi
symbol width (in mm)	0.3	0.1
	0.4	0.2
	0.5	0.3
	0.6	0.4
	0.7	0.5
		0.6

1 a. question with a sample image is presented below.

You will see several images with a small, black symbol in the centre. What shape do you see? Choose one of the available options.



- triangle
- circle
- square
- I can't recognise the shape
- Other: ______

1 b. Legibility of point symbols in map context

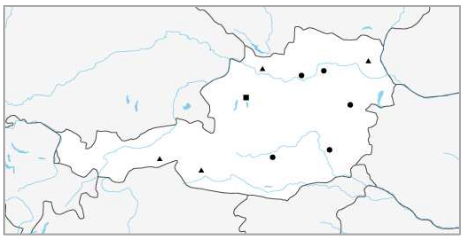
Point symbols were also applied in the map symbolization. The survey participant was supposed to count how many circles, squares or triangles appeared in the map. This task is more complex than just recognizing a solitary shape, but legibility should have an influence on task results. The survey participants could also make decision based rather on the similarity or dis-similarity between shapes, rather than their ability to recognize the shape.

Table 6 Tested symbol sizes in survey task 1b

device	computer	phone
resolution	217 ppi	806 ppi
symbol width (in mm)	0.3	0.2
	0.4	0.3
	0.5	0.4
	0.6	0.5

Task 1 b text and sample image is presented below.

Point symbols are often used to mark location of events, natural resources, industrial regions etc. You will see 4 maps with point symbols. For each map try to count, how many symbols of different shapes appeared.



Circles

Squares

Triangles

How difficult was it, to count shapes in this map?

1 star means very easy, 5 stars mean very difficult

☆☆☆☆☆

2a. Line symbolization legibility

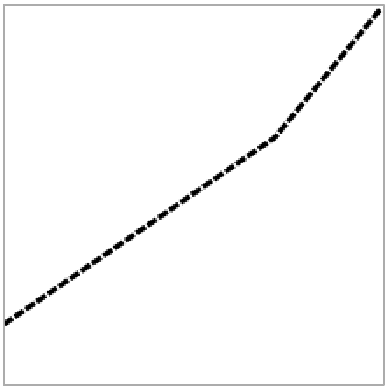
Images in this section were in varying resolutions. For a computer screen it was 217 ppi (native screen resolution) and 109 ppi (twice lower). For a phone screen, the used image resolutions were 806 ppi (native phone resolution), 403 ppi (twice lower resolution) and 202 ppi (four times lower than native resolution). Table 7 shows tested line widths for every resolution.

Table 7 Line width for symbols used in task 2a (in mm)

device	computer		phone		
resolution	217 ppi	109 ppi	806 ppi	403 ppi	202 ppi
line symbol width (in mm)	0.3	0.6	0.2	0.2	0.4
	0.4	0.7	0.3	0.3	0.5
	0.5	0.8	0.4	0.4	0.6

Survey task description and an example image:

Try to match the symbol in the image with a corresponding enlarged symbol. Choose "no answer" if you are not sure which option to choose.



- ○ a
- ○ b
- ○ c
- ○ No answer

2 b. Line symbolization in map context

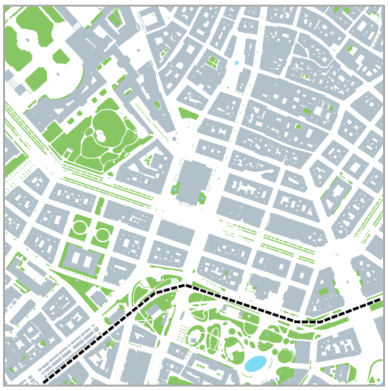
This task was essentially the same as the 2a task, but it incorporated a simple basemap, with only 2-3 additional colors for buildings, greenery and water bodies. The tested black pattern still appears on the white background. Table 8 shows the used symbol sizes for different image resolutions.

Table 8 Line width for symbols used in survey task 2b (in mm)

device	computer		phone		
resolution	217 ppi	109 ppi	806 ppi	403 ppi	202 ppi
line symbol width (in mm)	0.3	0.6	0.2	0.2	0.4
	0.4	0.7	0.3	0.3	0.5
	0.5	0.8	0.4	0.4	0.6

Task 3 description with a sample image:

Try to match the symbol in the image with a corresponding enlarged symbol. Choose "no answer" if you are not sure which option to choose.



- ○ a
- ○ b
- ○ c
- ○ No answer

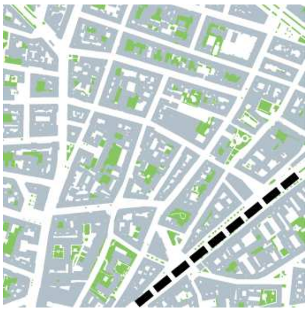
3. Line symbolization in map context

In this task, survey participants needed to find the enlarged symbol in one or more available images. The example for task 3 is shown below.

Next two tasks of this survey will follow the same pattern:
You will see the enlarged linear symbol, try to match it with corresponding map fragments.
Try to be as fast as you can!
Be careful, multiple answers are possible!

In which map section do you see this symbol?

☐ 

☐ 

☐ 

☐ 

For this tasks images in five resolutions were shown (Table 9), for a computer screen in native resolution of 217 ppi, and twice lower resolution of 109 ppi. For a phone screen images in 806, 403, and 202 ppi were used. All symbols had the same widths, which was chosen large enough in order to make it render in lower resolution (109 ppi).

Table 9 Symbol width for survey task 3

device	computer		phone		
resolution	217 ppi	109 ppi	806 ppi	403 ppi	202 ppi
linear symbol width (in mm)	0.6				
	0.8				
	1.0				

3.4. Experiment set-up

All the experiments took place in Cartography Research Division office at TU Wien.

Every participant took two surveys, answering questions about cartographic symbols legibility, viewing images rendered on two devices – mobile phone and computer screen.

Participants were asked if they wish to take part in the study and if they agree to be recorded with a video camera while taking the surveys. They signed a consent form (see appendix) and took a seat at the desk. They could ask questions before and during the experiment and their questions were answered by the assisting student, the author of this thesis.

Half of the participants were asked to start with a computer version of a survey and half were asked to start with a phone version.

The computer screen was placed around 45 cm from the table edge. Participants were allowed to take comfortable position and they were neither encouraged nor forbidden to adjust their viewing distance and move closer to the computer screen. During performing tasks on the phone, they were informed, that they can hold the phone in their hands.

The experiment was planned to take around 25 minutes but there was no time constraint. Participants could spend more time on performing tasks if they wished to do so.

The survey was conducted in English, making the assumption that the survey participants had sufficient knowledge of English language to be able to understand the questions and answer them according to their abilities.

4. Results

The survey was conducted between 21st of June and 14th of August 2019 in the office of the Research Division Cartography, TU Wien.

In the survey 29 participants took part. Due to the technical problem that occurred, saving answers for some of questions for two first participants was not possible. The problem was noticed early, and solved, but the answers of the first two participants were excluded from further analysis.

The experiments took place during the day, with a natural light in the background. Due to the office window location, north-west and to the backyard, there was no direct sunlight entering the room.

The computer screen surface was perpendicular to the window, and the screen was placed around 45 cm from the desk edge.

In this chapter, selected survey results are presented in already aggregated form. Raw survey results are featured in the Appendix.

4.1. Participants

There were 27 participants (10 males, 17 females), who took part in the experiment. The average age was 27 years, and median also 27 years. The youngest participant was 18 years old, and the oldest was 51 years old. The age distribution was not normal, the group was dominated by young people, with only 4 participants older than 30.

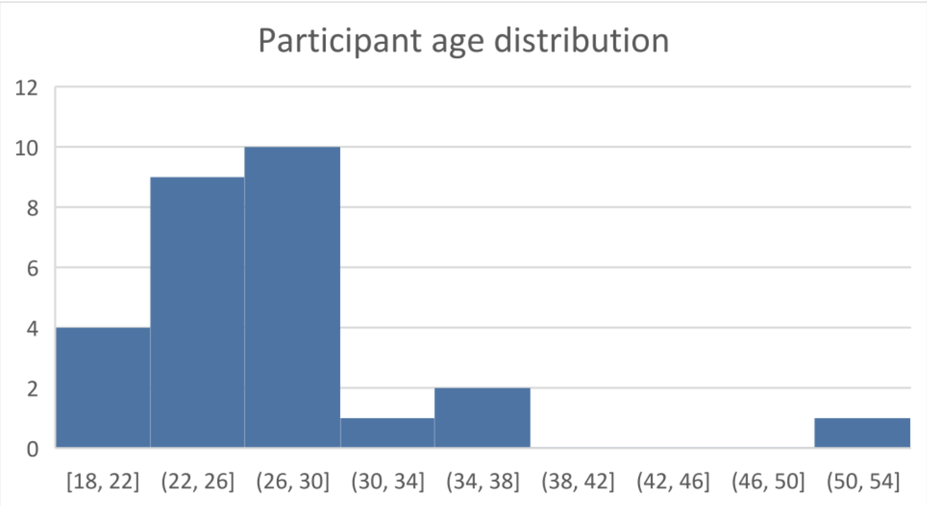


Figure 25 Participant age distribution

Out of 27 survey participants 17 persons admitted to be short-sighted, 2 were far sighted and 9 had astigmatism. Among the participants 3 persons assessed their vision as excellent, 14 as good, 7 as fair, 1 as poor and 1 as very poor. One person did not give any answer about the subjective assessment of vision. 17 participants were wearing glasses during the experiment.

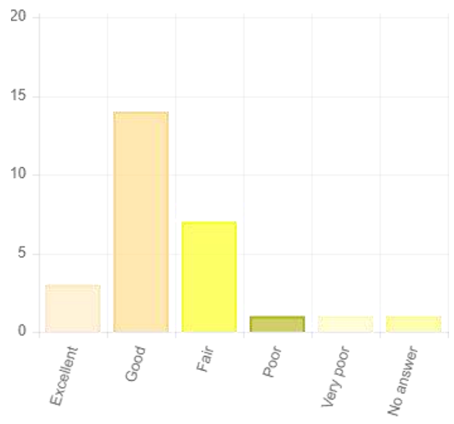


Figure 26 Subjective vision assessment of survey participants

4.2. Survey results

In this chapter the survey results will be shortly described, providing the context of expected outcome and the actual test results.

The created survey was divided in three tasks. Task one was investigating the legibility of point symbols isolated (task 1a) and with map context (task 1b), in the native resolutions of tested screens, which were 217 and 806 ppi. The second part was line symbolization test, with shape variation based on 3 shapes (circle, square, triangle). In the second task resolution lower-than-native screen resolution was imitated by rendering lower resolution images. Tasks 2 was divided in two parts – with isolated map symbols (task 2a) and in map context (2b). Tasks 1 and 2 had symbol sizes varying depending on the computer pixel density limitations and expected vision limits. This is to say, that the tested symbol sizes on a computer screen were larger than on a phone screen. Task 3 was testing the same line symbols as in task 2, but symbols in this task had the same width, independent from imitated resolution. Therefore, the tested images had the same symbol sizes of 0.6, 0.8, and 1.0 mm width.

Task 1a – legibility of point symbols

Survey participants were asked to recognize point symbols of different shapes. They were given an option to state that they are unable to answer the question. As already mentioned, minimal dimensions for point symbols are different depending on shape (Rytz *et al.*, 1980). According to that source, the square should have the highest legibility rate, followed by the circle, and the triangle with the lowest. For the computer screen, the tested symbols are expected to be only legible when in larger sizes, due to the larger viewing distance and lower pixel density comparing to the phone screen.

On the computer screen there were 5 symbol sizes tested between 0.3 mm and 0.7 mm. The 0.3 mm width was the smallest size to properly render the three investigated shapes on the 217 ppi screen. Table 10 shows the test results for a computer screen as a percentage of correct answers.

For this task, the analysis of the results focused on the percentage of correct answers for the circle, the square, and the triangle, rather than on additional symbols results for the silhouette of the dinosaur, star or pentagon. The percentage of right answers for varying shapes and sizes in task 1a with a computer screen is shown in table 10 and figure 27.

Table 10 Legibility of point symbols at 217 ppi computer screen, percentage of correct answers in task 1a

shape	0.3 mm	0.4 mm	0.5 mm	0.6 mm	0.7 mm
circle	40.7	63.0	88.9	96.3	100.0
square	37.0	66.7	92.6	92.6	96.3
triangle	33.3	66.7	92.6	92.6	92.6

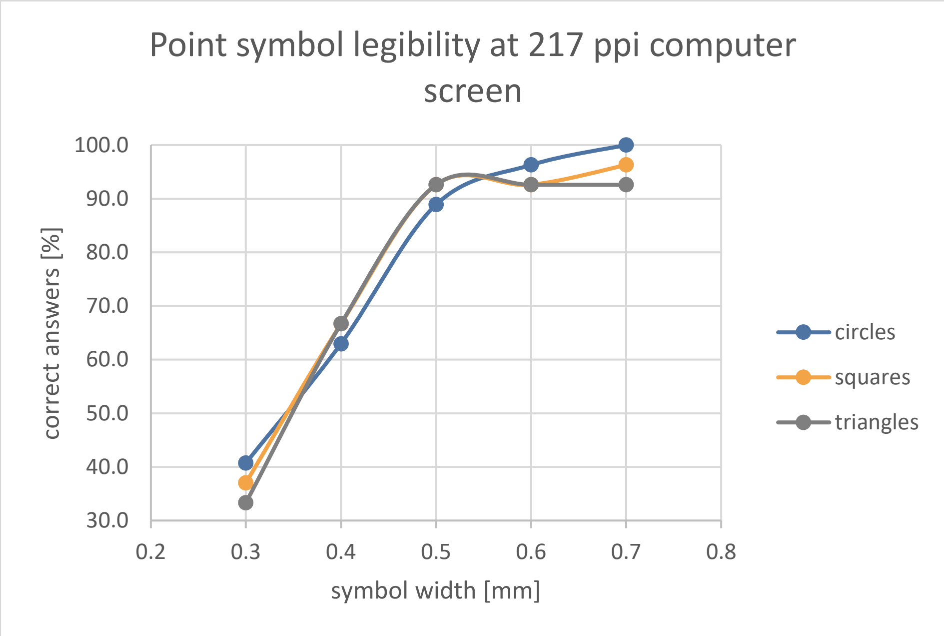


Figure 27 Legibility of point symbols at 217 ppi computer screen, percentage of correct answers in task 1a

While designing the symbol sizes for the survey, it was assumed that 0.6 mm and 0.7 mm wide symbols should be legible for all or almost all people. The survey results show that only one symbol (circle) had a maximum of 100% correct answers for the size of 0.7 mm. Interestingly, the circle was not the most legible shape for sizes 0.4 mm and 0.5 mm.

From visual analysis of results in table 10 and Figure 27, we can observe the following: the legibility of different shapes seems to be similar for all the tested symbol sizes. Legibility rates vary less than 8 percentage points. No shape obtains scores placing it as the highest or lowest consistently. Legibility of point symbols rapidly increases from 0.3 mm, which was the smallest possible to render on the 217 ppi computer screen, and the percentage of correct answers grows until the maximum measured size of 0.7 mm. Between 0.3 mm and 0.5 mm for all shapes there is a rapid increase in correct answers count, by more than 20 percentage points between consecutive sizes. Between 0.5 mm and 0.7 mm there is still a general trend for more correct answers, but the differences are smaller. For a triangle, the legibility rate remained the same, equal 92.6 %, which means that 2 survey participants failed to recognize this symbol correctly.

There was a statistical significance test conducted on the survey results, performed with the SPSS software. Before proceeding, survey answers were aggregated to the binary (nominal) form, and every answer was assigned 1 if a participant chose the correct answer, and otherwise 0. For chosen variable pairs McNemar's test[8] for 2 related samples was performed, using pre-selected pairs of variables. The chosen test is recommended for paired nominal data. This option was chosen, as the measured values were not independent – the same participants were asked to answer questions about legibility of two paired symbols. A non-parametric test was chosen, as there was no information about the expected distribution of answers.

The outputs for McNemar test include the p-value with $p < 0.05$ indicating statistically significant differences between paired responses. For such pairs, we can reject the null hypothesis that there is no significant difference between samples distribution.

Attributes with the following characteristics were compared – the same shape consecutively larger, or, equal size of different shape. The results of the test revealed that the distribution of 4 symbol pairs have statistically significant difference (Table 11). The only significant differences were between square sizes 0.3 mm – 0.4 mm, 0.4 mm – 0.5 mm, and triangles sizes 0.3 mm – 0.4 mm, 0.4 mm – 0.5 mm. This goes in line with observed tendency, that the. The difference in circle legibility for varying sizes was not significant.

Table 11 Exact significance value in McNemar's test for chosen pairs of variables with binomial two-tailed test for task 1a, computer. P-value<0 indicates statistically significant difference.

		circle					square					triangle				
		0.3	0.4	0.5	0.6	0.7	0.3	0.4	0.5	0.6	0.7	0.3	0.4	0.5	0.6	0.7
circle	0.3		0.109				1.000					0.774				
	0.4			0.092				1.000					1.000			
	0.5				0.500				1.000					1.000		
	0.6					1.000				1.000					1.000	
	0.7										1.000					0.500
square	0.3							0.008				1.000				
	0.4								0.016				1.000			
	0.5									1.000				1.000		
	0.6										1.000				1.000	
	0.7															1.000
triangle	0.3												0.004			
	0.4													0.016		
	0.5														1.000	
	0.6															1.000
	0.7															

Similarly, the point symbol legibility task was a part of the phone version of the survey. Due to higher screen resolution (806 ppi) it was possible to render even smaller symbols than on the computer screen. It was also expected that these symbols can have a higher legibility rate because of closer viewing distance, typical for handheld devices. The online survey featured symbols as small as 0.1 mm wide, which was practically impossible to see. These additional images were to determine 1) whether survey participants are guessing answers, and 2) if 0.2 mm size will get much higher score, or will be based on a random guess.

[8]Analysis of Paired Dichotomous Data: A Gentle Introduction to the McNemar Test in SPSS http://journals.sfu.ca/jmde/index.php/jmde_1/article/download/336/337/

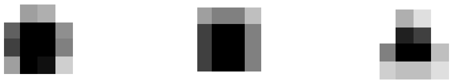


Figure 28 Circle square and triangle 0.1 mm wide in 806 ppi, enlarged

Phone screen experiment results (Table 12, Figure 29), reveal similar tendency to previously discussed computer screen results. Legibility of symbols grows from nearly 0% for 0.1 mm wide symbols, to almost 100% for 0.6 mm wide symbols. The maximum legibility of 100% was not reached by any symbol. The correct answers rate grows rapidly for triangles and squares 0.1 mm to 0.4 mm wide and remains on the same level from 0.4 mm to 0.6 mm. For the circle, it seems that the increase of legibility with size is nearly linear throughout the tested size range from 0.1 mm to 0.6 mm width.

Table 12 Legibility of point symbols at 806 ppi phone screen, percentage of correct answers in task 1a

Symbol size	0.1 mm	0.2 mm	0.3 mm	0.4 mm	0.5 mm	0.6 mm
circle	7.4	25.9	59.3	74.1	85.2	92.6
square	0.0	59.3	88.9	96.3	96.3	96.3
triangle	3.7	48.1	77.8	96.3	96.3	96.3

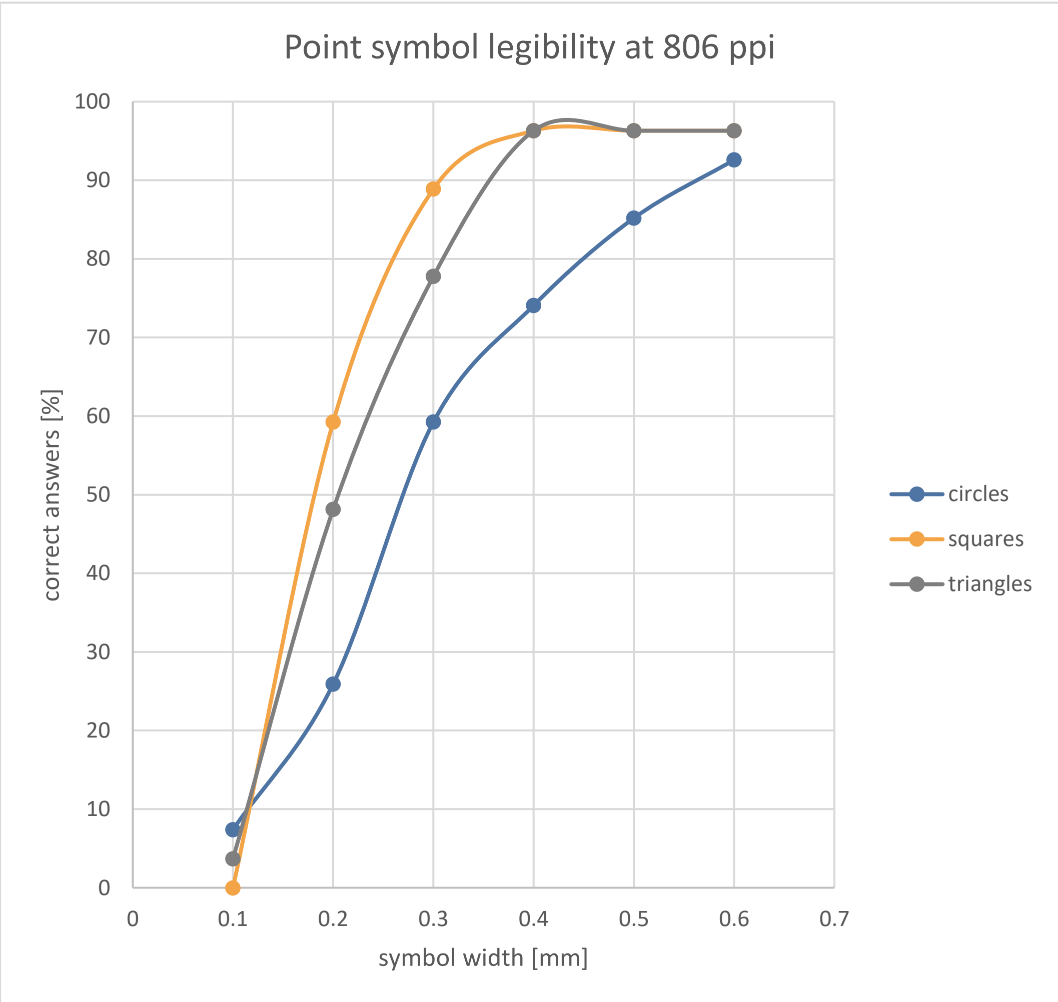


Figure 29 Legibility of point symbols at 806 ppi phone screen, percentage of correct answers in task 1a

The McNemar‘s test was performed on the results of chosen symbol pairs, with respect to size or shape difference. The test results revealed significant differences for size the changes 0.1 mm - 0.2 mm and 0.2 mm - 0.3 mm for all shapes. Also the difference in legibility between circles and squares at 0.2, 0.3, and 0.4 mm appeared to be significant. The exact significance values for chosen symbol pairs are presented in table 13. Significant difference p-values are marked with green.

Table 13 Exact significance value (McNemar‘s test) of chosen variables pairs with binomial two-tailed test for task 1a, phone. P-value<0 indicates statistically significant difference.

		circle						square						triangle					
		0.1	0.2	0.3	0.4	0.5	0.6	0.1	0.2	0.3	0.4	0.5	0.6	0.1	0.2	0.3	0.4	0.5	0.6
circle	0.1		0.063					0.500						1.000					
	0.2			0.012					0.022						0.109				
	0.3				0.344					0.039						0.180			
	0.4					0.453					0.031						0.310		
	0.5						0.625					0.250						0.250	
	0.6												1.000						1.000
square	0.1								0.000					1.000					
	0.2									0.039					0.549				
	0.3										0.500					0.453			
	0.4											1.000					1.000		
	0.5												1.000					1.000	
	0.6																		1.000
triangle	0.1														0.000				
	0.2															0.008			
	0.3																0.063		
	0.4																	1.000	
	0.5																		1.000
	0.6																		

Task 1b – legibility of point symbols in the map context

In this part of the survey, participants were given an atlas-like image, with country borders. They were asked to count how many symbols of different shapes appeared on the map. The task was more complex, requiring not only seeing and perceiving symbol shapes, as well as the ability to count them, which could be another source of error. On the other hand, it was possible that the map viewer makes the decision based on similarity (or dissimilarity) of shapes, rather than proper recognizing them one by one.

In this part of survey, only pictures in native screen resolution were tested.

Computer results are featured in table 14 and figure 30. Triangles had much better performance than circles and squares. The legibility rate seems to increase steadily for all shapes.

Table 14 Legibility of point symbols in map context at 217 ppi computer screen, percentage of correct answers in task 1b

Symbol size	0.3 mm	0.4 mm	0.5 mm	0.6 mm
circles	18.5	44.4	59.3	81.5
squares	18.5	44.4	63.0	81.5
triangles	44.4	66.7	81.5	92.6

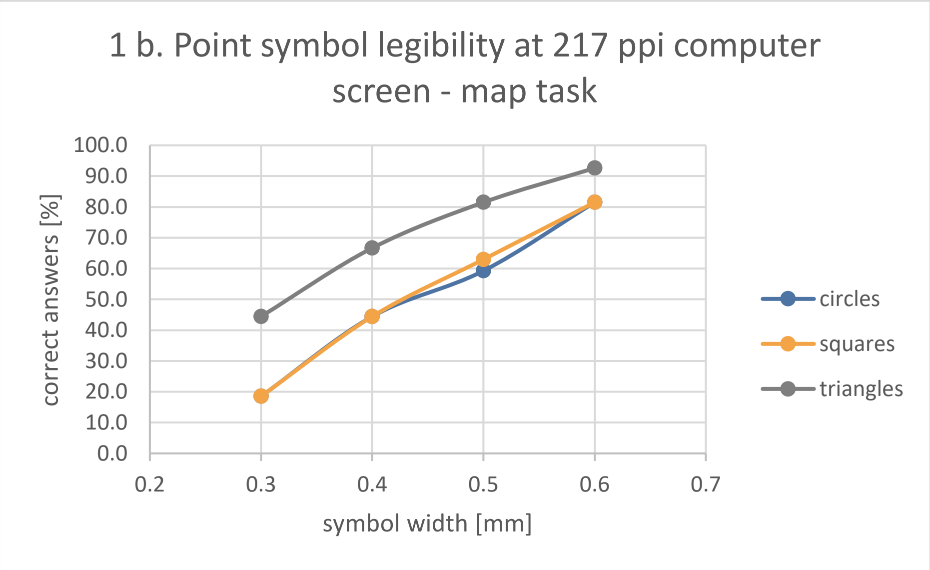


Figure 30 Legibility of point symbols in map context at 217 ppi computer screen, percentage of correct answers in task 1b

For every featured map, the survey participants were asked to estimate the difficulty of the task on a 1 to 5 scale. The results show that the vast majority of participants found the task with 0.3 mm symbols to be very difficult. Only 7 participants out of 27 found counting 0.6 mm wide shapes very easy. Aggregated answers for a question about difficulty are presented in Table 15.

Table 15 Difficulty estimation in 1 to 5 scale, average values for task 1b computer screen

	0.3 mm	0.4 mm	0.5 mm	0.6 mm
difficulty	4.7	4.1	3.3	2.5

Task 1b – legibility of point symbols in the map context, was also a part of the phone screen version of the experiment. The percentage of correct answers for symbols tested on a phone screen are shown in table 16 and figure 31. Similarly to the results of the experiment with a computer screen, the triangles had the best performance. Triangles got the highest legibility rate in all tested symbol sizes, reaching the 100% result for the largest 0.5 mm wide symbols. Circles had very similar result to squares in 0.2 mm width, somewhat higher than squares for middle values off 0.3 and 0.4 mm and the same as squares 92.6 % of correct answers for 0.5 mm symbol width. Squares had the worst performance for all the sizes.

Table 16 Legibility of point symbols in map context at 806 ppi phone screen, percentage of correct answers in task 1b

1b phone	0.2 mm	0.3 mm	0.4 mm	0.5 mm
circles	18.5	74.1	88.9	92.6
squares	14.8	63.0	74.1	92.6
triangles	48.1	88.9	92.6	100.0

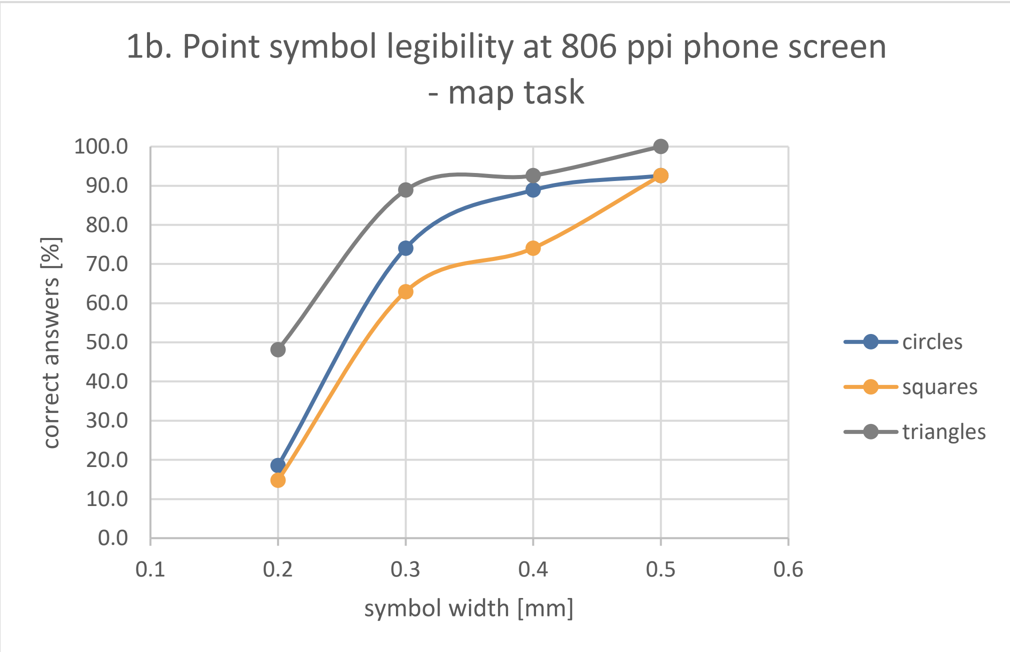


Figure 31 Legibility of point symbols in map context at 806 ppi phone screen, percentage of correct answers in task 1b

Figure 31 shows, that for the triangle had major growth in legibility rate between 0.2 mm and 0.3 mm. After 0.3 mm the performance was still improving but with lower rate. Squares had improved the legibility with nearly linear tendency. The average difficulty result shows the table 17.

Table 17 Difficulty estimation in 1 to 5 scale, average values for task 1b phone screen

	0.2 mm	0.3 mm	0.4 mm	0.5 mm
difficulty	4.7	3.2	2.2	1.9

Task 2a – line symbol legibility

In this part of the survey, three line symbolizations were tested. The line pattern was inspired by three shapes – circle (a), square (b) and triangle (c), as shown in figure 32. In the results analysis these shapes are refered to as answer **a, b, c,** or as the circle, square, and triangle pattern/cap.

Images within the question group were randomized. Possible answers included only the three previously mentioned options and “no answer” in case the participant was unable to answer.

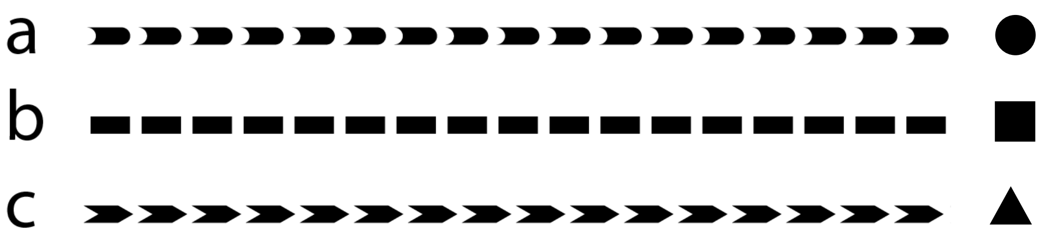


Figure 32 Three linear symbols tested in the survey parts 2a, 2b, and 3

One of the initial ideas was to compare different resolutions. This was implemented in the survey by imitating lower screen resolution by using lower resolution images.

For the computer screen, cartographic visualizations in native screen resolution of 217 ppi and half resolution of 109 ppi were tested. It was not possible to render in 109 ppi the same symbols sizes as in 217 ppi, therefore for 217 ppi the smallest tested symbol was 0.3 mm wide and for 109 ppi it was 0.3 mm. The test results for tested line symbol widths are aggregated in table 18 and Figure

Table 18 Line symbol legibility rates for task 2a, 217 ppi computer screen and reduced resolution of 109 ppi

resolution	217 ppi			109 ppi		
size	0.3 mm	0.4 mm	0.5 mm	0.6 mm	0.7 mm	0.8 mm
a	29.6	70.4	74.1	88.9	88.9	96.3
b	74.1	92.6	96.3	100.0	100.0	100.0
c	40.7	74.1	88.9	70.4	88.9	100.0

It was expected that lower resolution will get much worse results. Instead, 0.6 mm wide line pattern had improved legibility in 109 ppi in comparison to 0.5 mm in 217 ppi, for both symbols a) the line pattern with rounded cap, and b) square cap. The legibility of the third, triangular shape c) was worse at lower resolution (0.6 mm width) in comparison to slightly smaller 0.5 mm in 217 ppi.

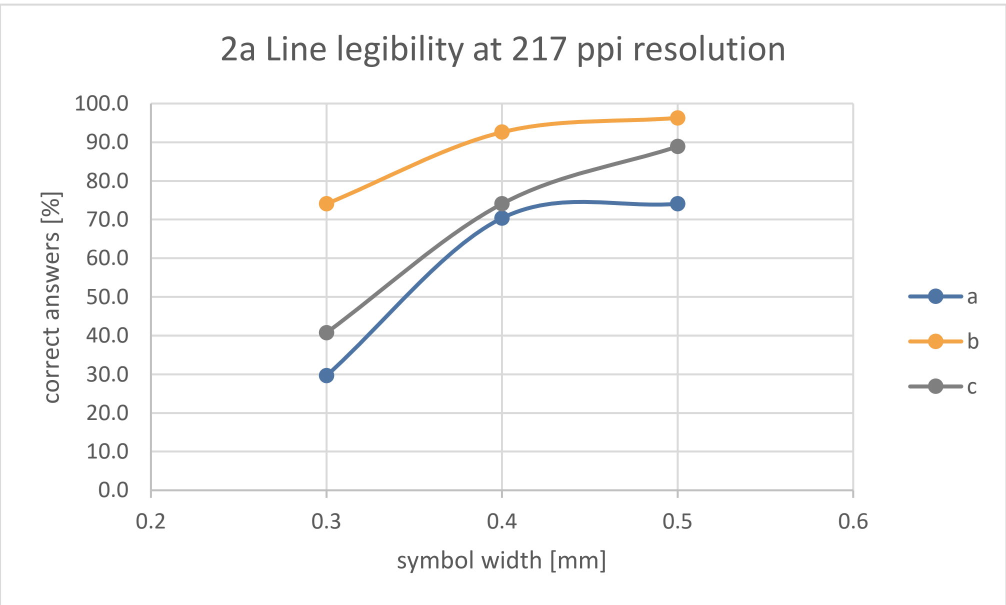


Figure 33 Legibility of linear symbols at 217 ppi, percentage of correct answers in task 2a

The results show (Figure 33, Figure 34), that the best performance in both cases had the square cap symbol, reaching 100% legibility for symbol width 0.6 mm-0.8 mm in lower resolution of 109 ppi.

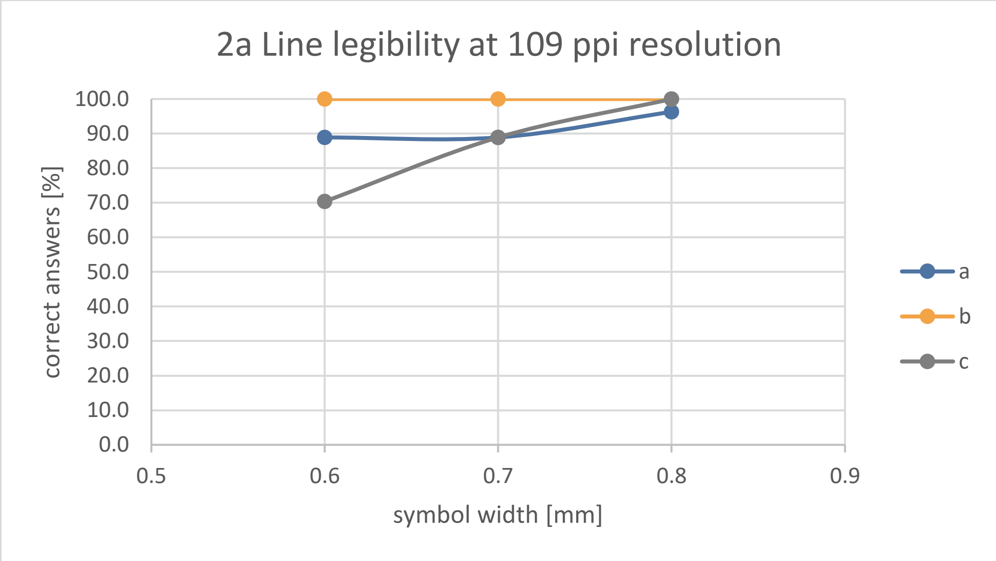


Figure 34 Legibility of linear symbols at 109 ppi, percentage of correct answers in task 2a

The conducted significance test (Table 19) revealed only significant difference in legibility between 5 pair of variables – 109 ppi 0.6 mm wide shape b) versus shape c). In 217 ppi resolution significant difference appeared for shape difference a-b and b-c, 0.3 mm width, between 0.3 mm shape a) and 0.4 mm wide same shape, as well as 0.3 c) and 0.4 the same shape. N/a value in the table appears for those pairs that had the same legibility rate of 100%.

Table 19 Exact significance value (McNemar test) of chosen variables pairs with binomial two-tailed test for task 2a, computer screen. P-value<0 indicates statistically significant difference

			109									217								
			0.6 mm			0.7 mm			0.8 mm			0.3 mm			0.4			0.5		
			a	b	c	a	b	c	a	b	c	a	b	c	a	b	c	a	b	c
109	0.6	a		0.25	0.06	1.00														
		b			0.01		n/a													
		c						0.06												
	0.7	a					0.25	1.00	0.50											
		b						0.25		n/a										
		c									0.25									
	0.8	a								1.00	1.00									
		b									n/a									
		c																		
217	0.3	a											0.00	0.55	0.00					
		b												0.01		0.06				
		c															0.02			
	0.4	a														0.11	0.18	1.00		
		b															0.18		1.00	
		c																		0.29
	0.5	a																	0.07	0.22
		b																		0.63
		c																		

The same three symbols: a) rounded cap, b) square cap and c) triangular, were tested on the 806 ppi phone screen in three different resolutions 202 ppi, 403 ppi, and 806 ppi (Table 20, Figure 35-37). The 202 ppi resolution was limiting the size of symbols, but 403 ppi and 806 ppi resolutions enabled rendering of the same symbol width.

Table 20 Line symbol legibility rates for task 2a, 806 ppi phone screen and reduced resolution of 403 ppi and 202 ppi

resolution	202 ppi			403 ppi			806 ppi		
size	0.4 mm	0.5 mm	0.6 mm	0.2 mm	0.3 mm	0.4 mm	0.2 mm	0.3 mm	0.4 mm
a	85.2	96.3	96.3	44.4	85.2	85.2	44.4	74.1	92.6
b	92.6	100.0	100.0	92.6	96.3	96.3	88.9	96.3	100.0
c	85.2	100.0	100.0	37.0	96.3	88.9	66.7	88.9	100.0

The results show, that the maximal legibility of 100% was achieved in 202 ppi by shapes b) and c) in 0.5 mm width, and 0.6 mm width. Similarly, the same shapes b) and c) were legible for 100% survey participants when displayed in 806 ppi and 0.4 mm wide. What is interesting, it was not achieved for the same shapes and sizes in 403 ppi.

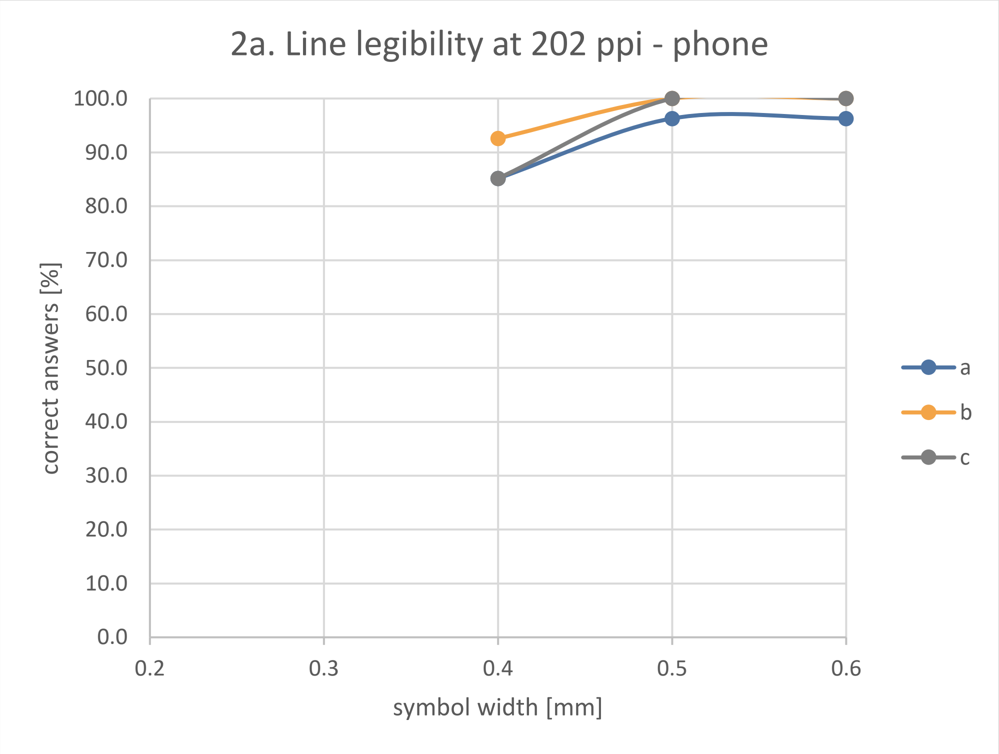


Figure 35 Legibility of linear symbols at 202 ppi, percentage of correct answers in task 2a

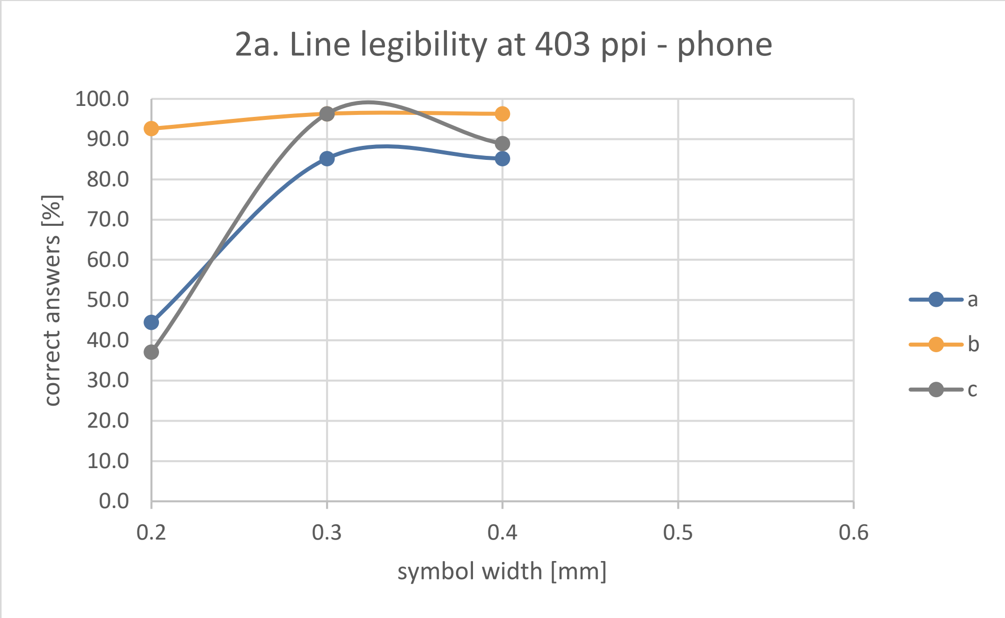


Figure 36 Legibility of linear symbols at 403 ppi, percentage of correct answers in task 2a

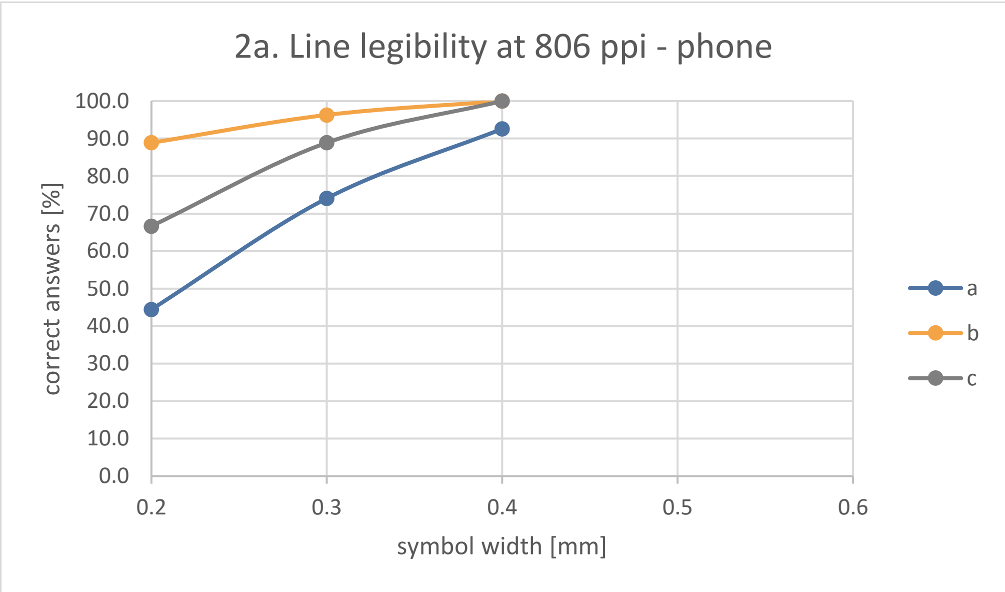


Figure 37 Legibility of linear symbols at 806 ppi, percentage of correct answers in task 2a

The survey results suggest (figure 35-37) that the 0.4 mm wide symbol is where good legibility rate starts, with around 90% correct answer ratio. Also, 0.3 mm wide line symbol in 403 ppi has similar results to 0.4 mm in 403 ppi. It seems that symbol a) and c) 0.3 mm wide had slightly worse legibility in 806 ppi than in 403 ppi. For those resolutions, only symbol c (triangular) clearly improved the result from 37% to almost 67%.

To see if the above-mentioned differences are statistically significant, the McNemar test for paired observations was conducted (Table 21). The statistical test revealed that the differences were significant for: 403 ppi 0.2 mm shape variation a-b, and b-c, as well as for both shapes “a” and “c” in the same resolution with size variation 0.2 mm-0.3 mm. Also, the difference in 0.2 mm wide symbol “c” in resolution of 403 ppi compared to 806 ppi, was significant. In 806 ppi, the difference in legibility between symbol “a” and “c”, 0.2 mm wide, was significant, but also between “a” 0.2 and 0.3 mm wide in the same resolution of 806 ppi.

Table 21 Exact significance value (McNemar test) of chosen variables pairs with binomial two-tailed test for task 2a, phone. P-value<0 indicates statistically significant difference.

			202									403									806								
			0.4			0.5			0.6			0.2			0.3			0.4			0.2			0.3			0.4		
			a	b	c	a	b	c	a	b	c	a	b	c	a	b	c	a	b	c	a	b	c	a	b	c	a	b	c
202	0.4	a		0.50	1.00	0.38												1.00									0.50		
		b			0.50		0.50												1.00									0.50	
		c						0.13												1.00									0.13
	0.5	a					1.00	1.00	1.00																				
		b						n/a		n/a																			
		c																											
	0.6	a								1.00	1.00																		
		b									n/a																		
		c																											
403	0.2	a											0.00	0.73	0.00						1.00								
		b												0.00		1.00						1.00							
		c															0.00						0.04						
	0.3	a														0.38	0.38	1.00						0.25					
		b															1.00		1.00						1.00				
		c																		0.50						0.50			
	0.4	a																	0.25	1.00							0.50		
		b																		0.50								1.00	
		c																											0.25
806	0.2	a																				0.00	0.07	0.04					
		b																					0.07		0.50				
		c																								0.07			
	0.3	a																							0.03	0.22	0.06		
		b																								0.50		1.00	
		c																											
	0.4	a																										0.50	0.50
		b																											n/a
		c																											

Task 2b – line symbol legibility in map context

The same line patterns as in 2a, were tested in the map context, with imitated lower resolution. Survey results for a computer screen are shown in table 22.

Table 22 Line symbol legibility rates for task 2b, 217 ppi computer screen and reduced resolution of 109 ppi

resolution	**217ppi**			**109 ppi**		
size	0.3 mm	0.4 mm	0.5 mm	0.6 mm	0.7 mm	0.8 mm
a	29.6	51.9	77.8	92.6	88.9	96.3
b	81.5	92.6	92.6	100.0	100.0	100.0
c	44.4	74.1	96.3	70.4	81.5	96.3

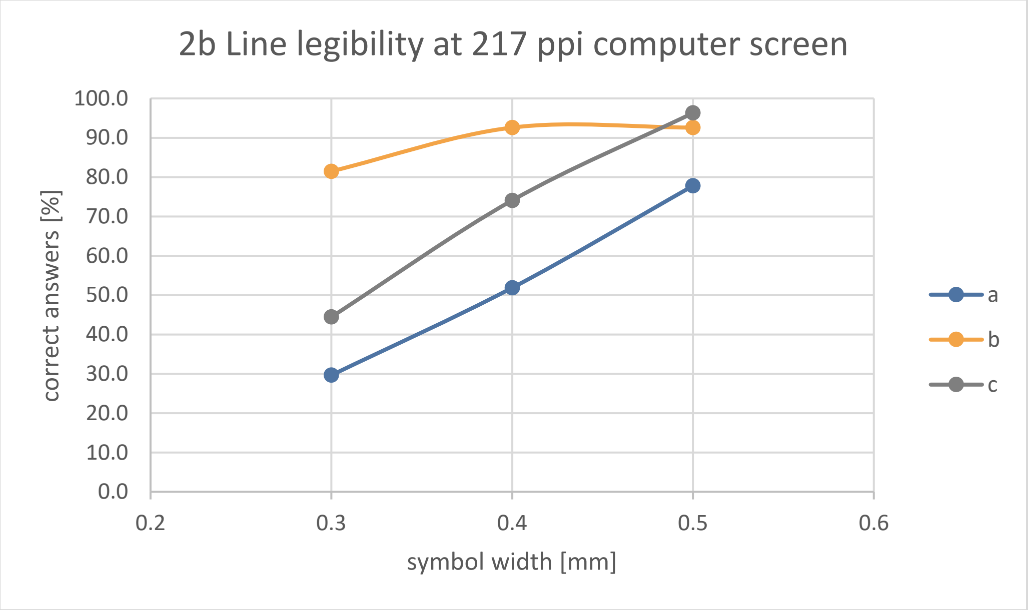


Figure 38 Legibility of linear symbols at 217 ppi, percentage of correct answers in task 2b

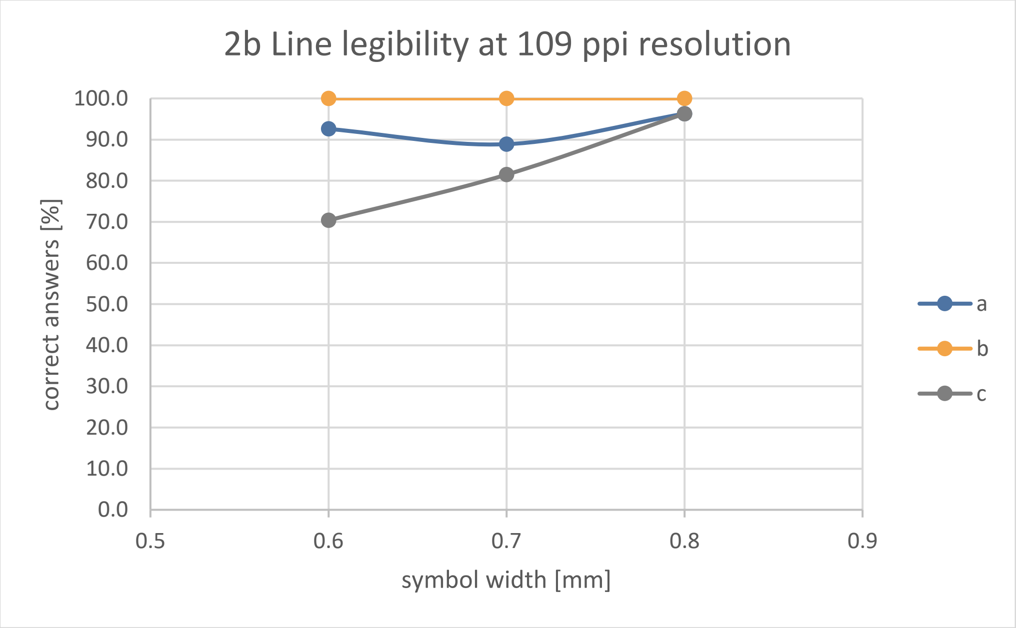


Figure 39 Legibility of linear symbols at 109 ppi, percentage of correct answers in task 2b

Table 23 Exact significance value (McNemar test) of chosen variables pairs with binomial two-tailed test for task 2b, computer screen. P-value<0 indicates statistically significant difference

			109									217								
			0.6			0.7			0.8			0.3			0.4			0.5		
			a	b	c	a	b	c	a	b	c	a	b	c	a	b	c	a	b	c
109	0.6	a		0.50	0.03	1.00														
		b			0.01		n/a													
		c						0.38												
	0.7	a					0.25	0.69	0.50											
		b						0.06		n/a										
		c									0.13									
	0.8	a								1.00	1.00									
		b									1.00									
		c																		
217	0.3	a											0.00	0.29	0.03					
		b												0.00		0.25				
		c															0.02			
	0.4	a														0.00	0.11	0.09		
		b															0.13		1.00	
		c																		0.03
	0.5	a																	0.22	0.13
		b																		1.00
		c																		

Task 2b was also performed on the phone screen revealing interesting results (Table 24). Some of the 806 ppi images got the highest 100% legibility score, having results better than 403 ppi resolution. Surprisingly, 0.2 mm wide pattern in native resolution had the same or worse results, than compared 403 ppi. Shape “b” had the same percentage of correct answers (92.59%), but shape “a” (rounded) dropped by almost 15 percentage points, and shape “c” (triangular) dropped by more than 20 percentage points.

Table 24 Line symbol legibility rates for task 2b, 806 ppi phone screen and reduced resolution of 403, and 202 ppi

resolution	202 ppi			403 ppi			806 ppi		
size	0.4 mm	0.5 mm	0.6 mm	0.2 mm	0.3 mm	0.4 mm	0.2 mm	0.3 mm	0.4 mm
a	96.30	96.30	96.30	66.67	88.89	92.59	51.85	85.19	88.89
b	96.30	100.00	100.00	92.59	96.30	96.30	92.59	100.00	100.00
c	81.48	100.00	96.30	70.37	88.89	96.30	48.15	88.89	100.00

Further analysis are possible with Figures 40-42, showing legibility rates for map task with line symbolization in three different resolutions.

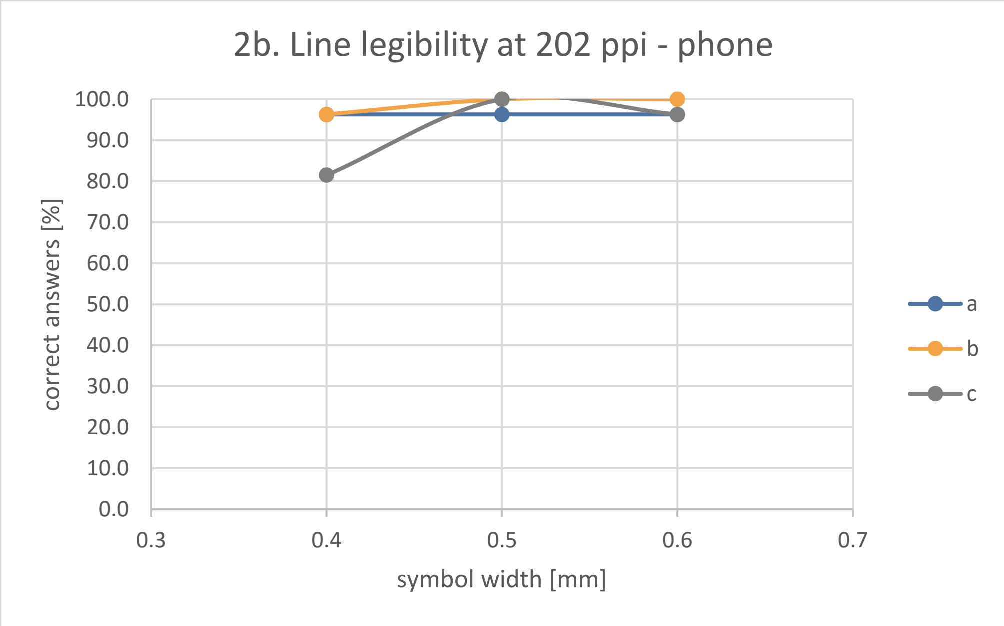


Figure 40 Legibility of linear symbols at 202 ppi, percentage of correct answers in task 2b

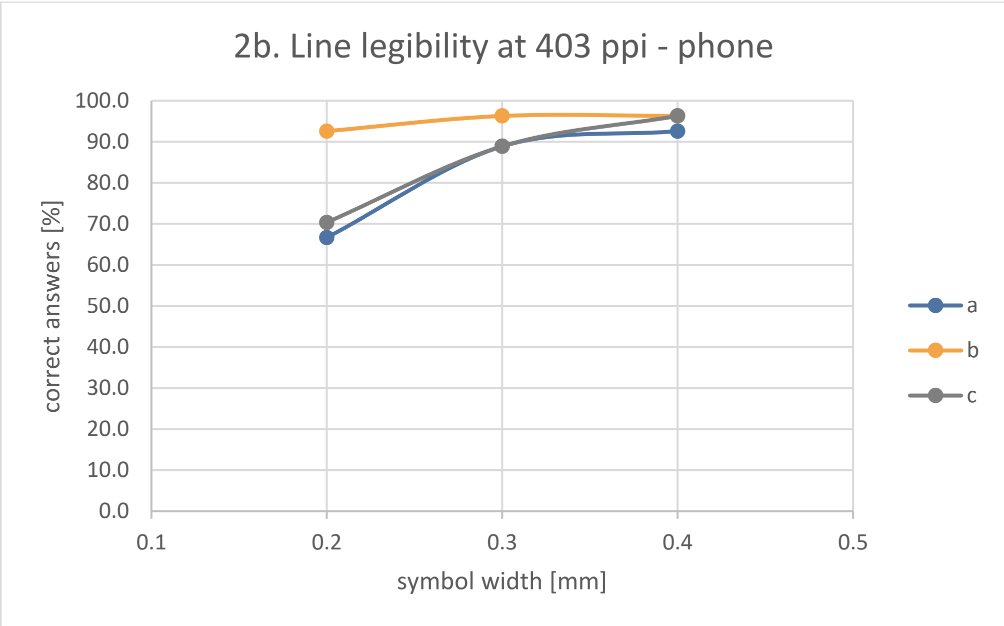


Figure 41 Legibility of linear symbols at 403 ppi, percentage of correct answers in task 2b

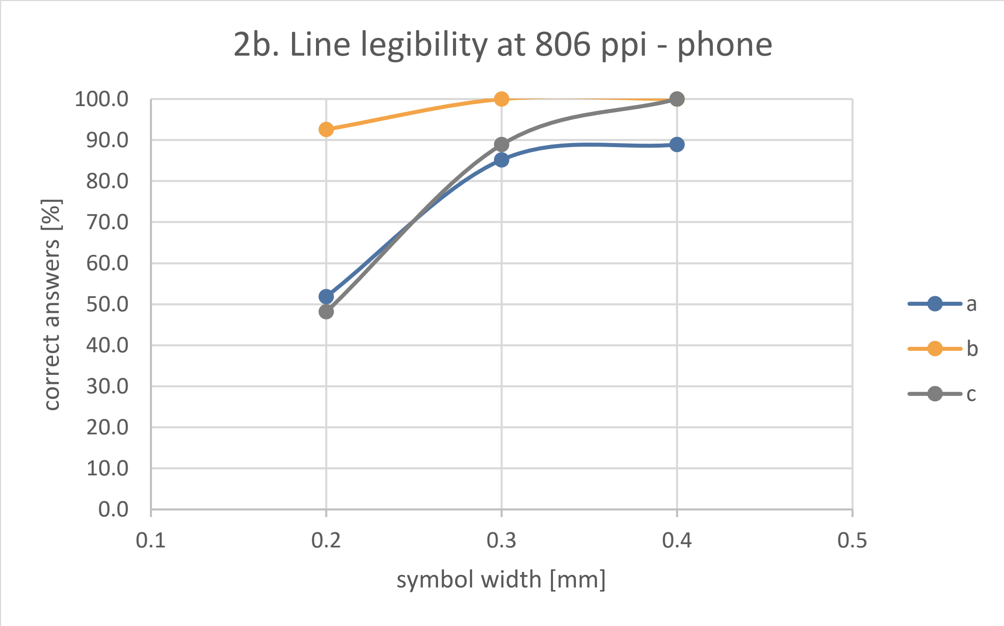


Figure 42 Legibility of linear symbols at 806 ppi, percentage of correct answers in task 2b

Microscopic photographs of survey images show (Figure 43), that the rendering of images was not perfect. It seems that the symbol that had better legibility rate (left side, 403 ppi) was also more sharp under the microscope, while in the 806 ppi image the investigated symbol had somewhat blurred edges and the symbol parts seem to be slightly curved. It can be said, that lower legibility was dues to lower quality of rendering.

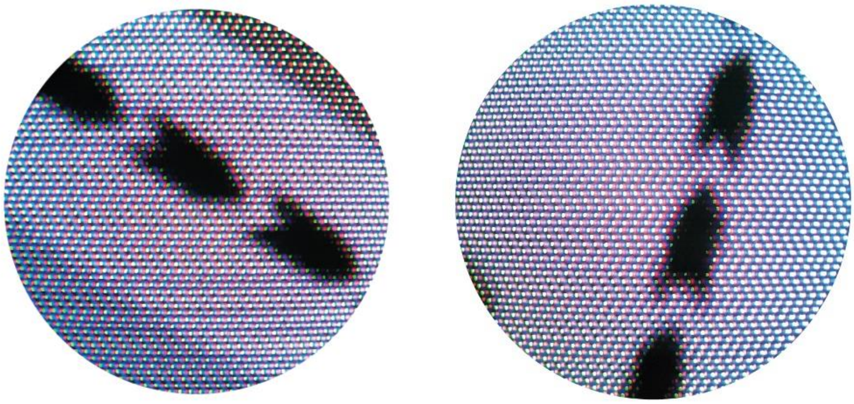


Figure 43 Line symbolization with triangle cap and 0.2 mm width. Left side: 403 ppi image, right side: 806 ppi

McNemar's statistical significance test was done for pairs of images having one variable fixed - either size, or shape, or resolution (Table 25). The test revealed statistically significant differences between shapes a-b, and b-c, 0.2 mm wide for both resolutions 403 and 806 ppi. Also for these resolutions, difference in pattern a) legibility between 0.2 and 0.3 mm was significant. Additionally in 806 ppi, there was a significant increased legibility between 0.2 and 03 mm wide shape c), and 0.3 mm wide a) – b). The previously described drop in legibility for line pattern a) and c), in 403 ppi and 806 ppi resolutions was not statistically significant.

Table 25 Exact significance value (McNemar test) of chosen variables pairs with binomial two-tailed test for task 2b, phone screen. P-value<0 indicates statistically significant difference

			202									403									806								
			0.4			0.5			0.6			0.2			0.3			0.4			0.2			0.3			0.4		
			a	b	c	a	b	c	a	b	c	a	b	c	a	b	c	a	b	c	a	b	c	a	b	c	a	b	c
202	0.4	a		1.00	0.13	1.00												1.00									0.50		
		b			0.13		1.00												1.00									1.00	
		c						0.06												0.13									0.06
	0.5	a					1.00	1.00	1.00																				
		b						n/a		n/a																			
		c									1.00																		
	0.6	a								1.00	1.00																		
		b									1.00																		
		c																											
403	0.2	a											0.02	1.00	0.03						0.29								
		b												0.03		1.00						1.00							
		c															0.13						0.18						
	0.3	a													0.50	1.00	1.00							1.00					
		b														0.50		1.00							1.00				
		c																	0.50							1.00			
	0.4	a																1.00	1.00								1.00		
		b																	1.00									1.00	
		c																											1.00
806	0.2	a																			0.00	1.00	0.00						
		b																				0.00		0.50					
		c																							0.00				
	0.3	a																						0.13	1.00	1.00			
		b																							0.25		n/a		
		c																											0.25
	0.4	a																										0.25	0.25
		b																											n/a
		c																											

Task 3 – line symbol legibility in map context

For this task, symbols had width that was supposed to render well in all tested resolutions, for both computer and phone screen. Also, when properly rendered, the images were expected to be legible for all the test participants. This task was supposed to show, if there is a significant difference in time taken for completing the task, when viewing images in different resolutions.

The survey participants were informed that they were supposed to do this task as fast as possible. The questions were divided in groups depending on image resolution, and in every group there were the same number of right answers to mark. That was to ensure, that the survey participants will need the same amount of time for clicking at the right answers.

Even though checking the ratio of correct answers was not the main purpose of this task, the results were compared (Table 26). The question group had multiple answers, and for every symbol, the participants could choose one or more map sections, with the particular symbol. It seems that even 1 mm wide symbols were not totally legible. It seems that either the task was more difficult, or participants could not answer that well, as they were under pressure of time.

Table 26 Line symbol legibility rates for task 3, 217 ppi computer screen and reduced resolution of 109 ppi

	109 ppi			217 ppi		
	0.6 mm	**0.8 mm**	**1.0 mm**	**0.6 mm**	**0.8 mm**	**1.0 mm**
a	63.0	85.2	88.9	88.9	81.5	96.3
b	92.6	96.3	96.3	88.9	92.6	92.6
c	85.2	96.3	92.6	77.8	88.9	96.3

Average time for taking the survey task 3 was 54.6 seconds for 217 ppi and 55.4 seconds for 109 ppi (Table 27). With the maximum time of 143 seconds, and the standard deviation of around 20 seconds, it seems that the average time difference between the two compared resolutions is too small to be considered a relevant discovery.

Table 27 Timing statistics for task 3 on the computer screen, in seconds

	109 ppi	217 ppi
Average	55.4	54.6
Min	31.5	33.4
Max	143.0	123.3
Std dev	21.3	17.8

Table 28 Line symbol legibility rates for task 3, 806 ppi phone screen and reduced resolution of 403, and 202 ppi

	202 ppi			403 ppi			806 ppi		
	0.6 mm	**0.8 mm**	**1.0 mm**	**0.6 mm**	**0.8 mm**	**1.0 mm**	**0.6 mm**	**0.8 mm**	**1.0 mm**
a	96.3	100.0	92.6	88.9	88.9	92.6	96.3	88.9	100.0
b	96.3	100.0	100.0	92.6	96.3	96.3	96.3	96.3	92.6
c	92.6	100.0	96.3	100.0	96.3	96.3	92.6	96.3	100.0

Table 29 Timing statistics for task 3 on the phone screen, in seconds

	806 ppi	403 ppi	202 ppi
Average	54.6	52.4	52.1
Min	39.6	37.9	37.1
Max	105.0	115.6	126.2
Standard deviation	16.5	18.7	19.8

Additional remarks

During the experiment the posture of survey participants was observed (Figure 44). In most cases, viewing distance for the computer screen was around 40 cm. There were a few participants, who were really close to the computer screen, far closer than the standard viewing distance. They were doing so in order to be able to recognize smaller symbols, that were not legible from their usual viewing distance.

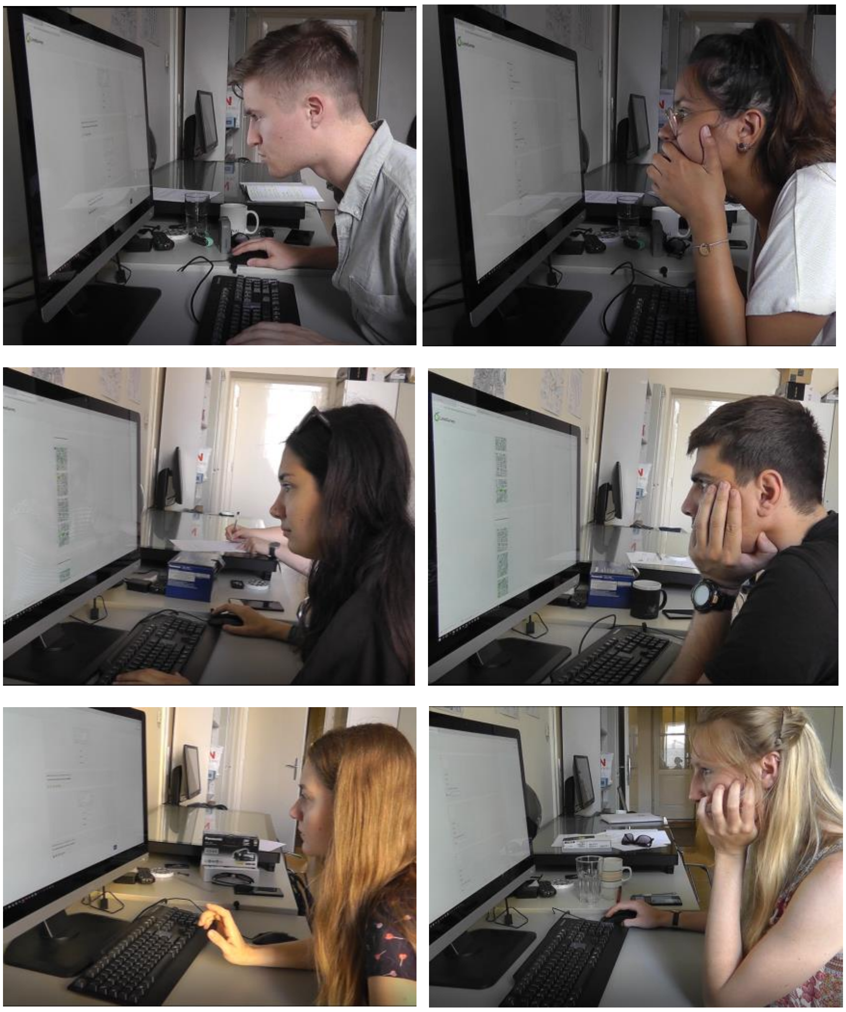


Figure 44 Selected survey participants performing the survey on the computer screen

Even though the survey participants were not forbidden from getting closer to the computer screen, only a few of them chose to do so. For a phone screen it was more natural to keep it closer to eyes – almost all participants had a viewing distance between 20 and 25 centimeters (Figure 45).

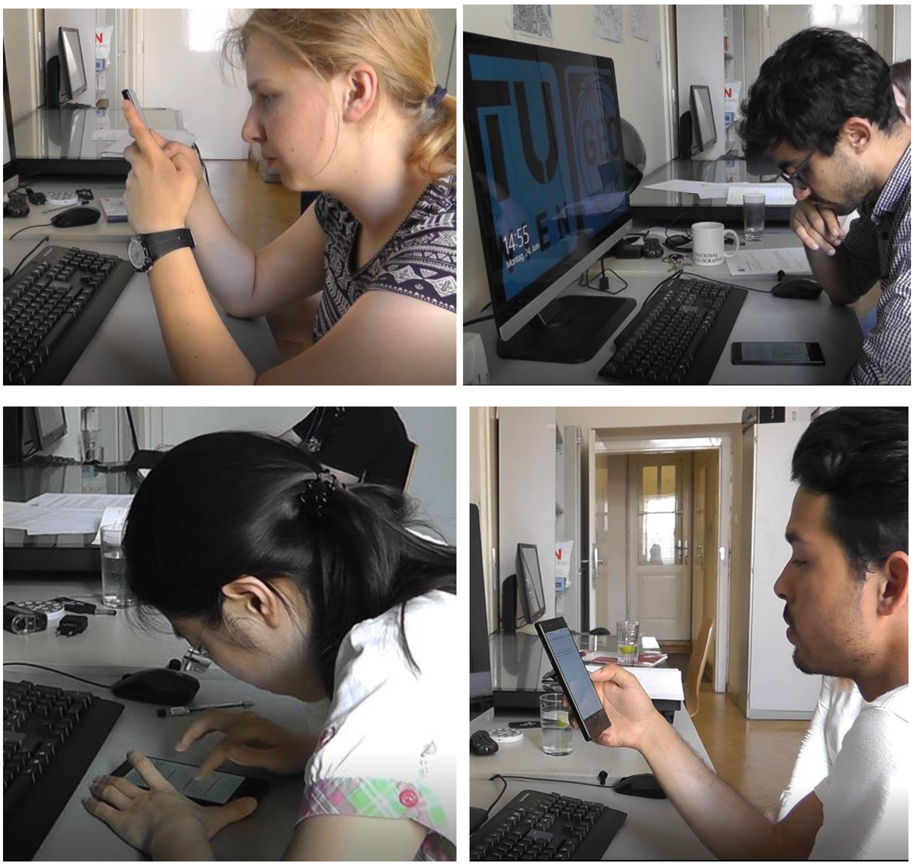


Figure 45 Photos of chosen survey participants doing the survey on a phone screen

Survey participants were recorded with a video camera while performing tasks. They could ask questions during the experiment and they were allowed to express themselves freely. A few experiment participants asked what to mark when they saw "a dot". This could mean that they were most likely unable to recognize the shape. It seemed to be more likely, that such person would mark a circle, as its association with "a dot" was stronger.

One of the participants made a remark, that they would come closer to the screen to see better, if the screen was not so bright. The survey was all on the white background, and it might have made some participants stay further from the display.

All survey questions had had an option for the participant to state that they are not able to recognize the shape shown in the sample image. In the experiment evidence of a psychological bias was found. Some survey participants wanted to perform "the best" and they were trying to guess the shape, despite being unable to confidently recognize it. Some others confessed that they would like to have an option to indicate "degree of confidence in their answer", as they stated a leaning towards one or two answer options, rather than stating an inability to correctly read the symbol. Therefore, these survey results should be interpreted with limited trust. Social studies tend to have this bias – people want to answer in a way that would give "good results" which actually cause errors in the results.

4.3. Results interpretation

Task 1a. legibility of point symbols

The first part of the experiment was attempting to estimate the participants' vision acuity and establish the minimal symbol sizes for point symbols. This task failed to find the "perfect legibility" threshold, as 0.7 mm wide circle was 100% legible and this size was only tested on a computer screen. Study participants had varying visual acuity, and the experiment was not limited to testing only people with perfect vision. There is also a possibility of random errors, for example when a participant accidentally omits a question. Nevertheless, this part of the study provided interesting results, that provide values comparable with previous research.

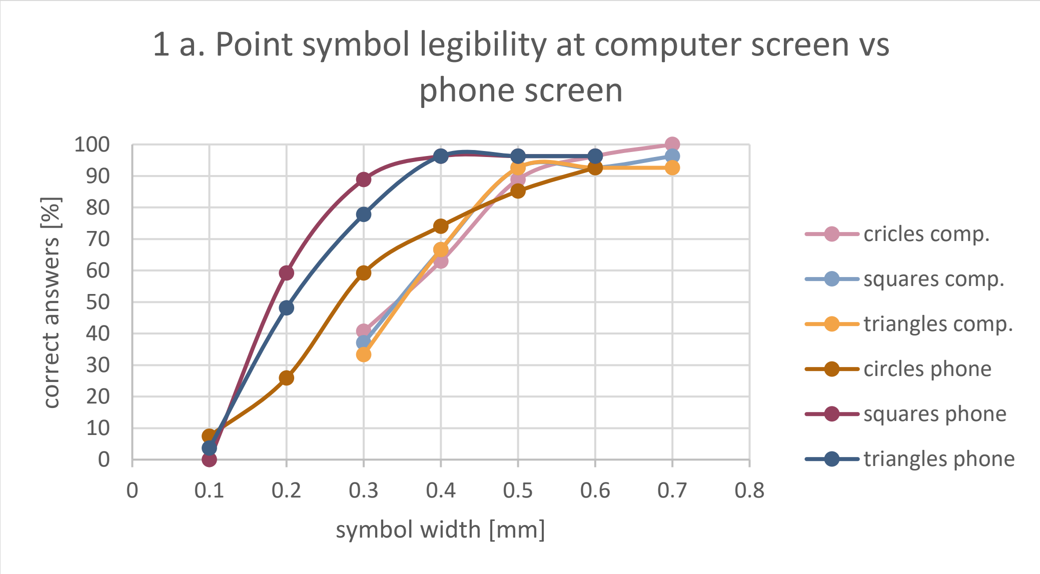


Figure 46 Point symbol legibility computer (217 ppi) and phone (806 ppi) results

Swiss Cartographic Society (Rytz *et al.*, 1980) claimed that the legibility of point symbols for printed maps differs with shape. Those authors recommended 0.35 mm minimum size for a square, 0.5 mm for a circle (hollow), and 1 mm for a triangle. These values can be partially confirmed by results of an experiment conducted within this master thesis (Figure 46). The results show that already 0.4 mm wide squares and triangles are very well legible on a high-resolution phone screen. Circles must be at least 0.6 mm wide to be legible[9]. In this comparison triangle is more legible than a circle, and the difference for 0.4 mm width is statistically significant[10]. Also Malić (1998) found evidence, that circles rendered on screens need to be larger than triangles or rectangles, in order to be legible.

In the computer screen results all shapes had very small differences in legibility throughout the experiment. To reach more than 90% legibility rate, a square or a triangle must be at least 0.5 mm wide, and a circle 0.6 mm wide. For a phone screen, this conservative approach brings the same 0.6 mm width for a circle, and 0.4 mm for the square and the triangle.

[9] Assuming that 90% of correct answers means that the symbol was legible

[10] McNemar's nonparametric test of binomial distribution

Neudeck (2001) expressed minimum dimensions in pixels (6 for square, 10 for a circle or triangle). The results of this experiment do not quite confirm dimensions proposed by Neudeck. It seems that on a computer screen, legible symbols (90%) had 5 pixels width, which is close to Neudeck. For an 806 ppi phone screen, 0.5 mm would be represented by 16 pixels width, and 0.6 mm by 19 pixels. These values exceed Neudeck's recommendations.

Task 1b. Map task with point symbols

Counting symbols on a map was a task different than asking about the single shape. It could introduce errors coming from counting itself or for example making the decision basing on another symbols count. In all cases, the triangle was getting the best result. The reason could be that triangles were recognized due to their smaller area, while circles were easier to confuse with squares.

Visual analysis of both tasks 1a and 1b answers show that the results are not fully consistent. First, if a survey participant was able to recognize the shape of a 0.3 wide circle in task 1a, we would expect them to be able to count the circle in the same size and larger, in task 1b. This was not always the case (Table 30). Second of all, two survey participants got much worse results, they were able to answer correctly only few questions. Those two participants were making about 7.4% of the data. With only 2 such cases out of 27, it is difficult to say if they are outliners that should be left out int the data analysis. As the survey participants were mostly recruited from university students, almost all younger than 30, it can mean that the chosen statistical sample had better vision characteristics than the whole population.

Table 30 Right (1) and wrong (0) answers in tasks 1a and 1b, computer screen.

task	1a															1b											
shape	circle					square					triangle					circles				squares				triangles			
size	0.3	0.4	0.5	0.6	0.7	0.3	0.4	0.5	0.6	0.7	0.3	0.4	0.5	0.6	0.7	0.3	0.4	0.5	0.6	0.3	0.4	0.5	0.6	0.3	0.4	0.5	0.6
right/wrong answer	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	0	1	1	1	0	1	1	1	1	1	0	1
	1	0	1	1	1	1	1	1	1	1	0	0	1	1	1	0	1	1	1	1	0	1	1	0	1	1	1
	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	1	0	1	0	1	0	1	1	1
	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	0	1	1	1	1	1	1	1
	0	1	1	1	1	0	1	1	1	1	0	0	1	1	1	0	1	1	1	0	1	1	1	1	1	1	1
	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	0	1	1	1	0	1	1	1	1	1	1	1
	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	0	1	1	1	1	1	1	1
	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	1	1	0	1	1	1	1	1	1	1
	0	0	1	1	1	0	0	1	1	1	0	1	1	1	1	1	0	1	1	1	0	1	1	1	1	1	1
	1	1	1	1	1	0	0	1	1	1	0	1	1	1	1	1	0	1	1	0	0	1	1	1	1	1	1
	0	1	0	1	1	0	1	1	1	1	0	0	1	1	1	0	1	1	1	0	1	1	1	0	1	1	1
	0	0	1	1	1	0	1	1	1	1	0	1	1	1	1	0	0	1	1	0	0	1	1	0	0	1	1
	1	1	1	1	1	0	1	1	1	1	0	0	1	1	1	1	0	0	0	1	1	0	0	0	1	1	1
	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	1	0	0	1	1	1	1	1	1
	1	1	1	1	1	0	0	1	1	1	0	0	1	1	1	0	0	1	1	0	0	1	1	0	0	1	1
	0	1	0	1	1	0	0	1	1	1	0	0	1	1	1	0	0	0	1	0	0	0	1	0	0	0	1
	0	1	1	1	1	0	1	1	1	1	0	1	1	1	1	0	1	1	1	0	1	1	1	0	1	1	1
	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1
	0	0	1	1	1	0	1	1	1	1	0	1	1	1	1	0	0	0	1	0	0	0	1	0	0	0	1
	0	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	0	1	0	0	0	1	0	0	0	1
	0	1	1	1	1	0	0	1	1	1	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	0	0	0	1	1	1	1	1
	1	0	1	1	1	1	1	1	1	1	0	1	1	1	1	0	0	0	1	0	0	0	1	0	1	1	1
	0	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	0	1	1	1	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1
	1	1	0	0	1	0	0	1	1	1	0	1	1	1	1	0	0	0	0	0	0	0	0	0	0	1	0
	0	0	1	1	1	0	0	1	1	1	0	1	1	1	1	0	0	0	0	0	0	1	0	0	0	1	1
Σ	11	17	24	26	27	10	18	25	25	26	9	18	25	25	25	5	12	16	22	5	12	17	22	12	18	22	25

Task 2a. Legibility of line symbols – varying resolutions

In this and following tasks, shape variation in line pattern was applied (Figure 47). Tested line patterns had different orientation in the tested images.

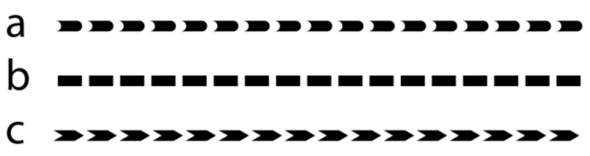


Figure 47 line symbolization in tasks 2a, 2b, 3

Pattern with a square cap b) had the highest legibility in comparison to a) and c), with a difference statistically significant for some of the tested sizes.

Task 2b. Legibility of line symbols in map context – different resolutions

The square cap symbol (b) had the highest legibility rate as in 2a, with nearly 90% legibility for even as little as 0.2 mm wide patterns.

Investigating linear symbols' legibility in map context did not reveal major differences in comparison to 2a. Nevertheless, the results of the experiment have shown, that the used images did not render as well as expected, which was the cause of worse question result. The reason could be the default smoothing algorithm in the browser which could influence final rendering. It is not sure if it was the reason, as the image was exported in the native resolution of the device, and in such a case smoothing algorithm should not be applied.

Task 3. Legibility of line symbols in map context – different resolutions

This task was attempting to show the time difference while performing tasks with images of different resolutions. Line symbols had such width, that was enabling rendering for all tested resolutions. This is why it was assumed that all the participants will be able to correctly identify images presenting the tested pattern.

The initial idea to investigate the time difference between tasks performed with pictures of different resolutions did not provide expected results. The difference of the average time spent on a group of questions was much smaller than its standard deviation. Therefore, this result is not valuable.

Additional remarks

Tested images were rendered in LimeSurvey with a default image rendering, that smooths the edges, which may make low resolution images rendered on high resolution displays less legible. Keeping the symbols crispy can be done with a single line of CSS code:

```
image-rendering: pixelated;
```

Alternative rendering methods to solve this problem were discovered only during result collection, so these solutions were not implemented.

Results summary

Overall, the survey results show, that the visual acuity differs over individuals, and there is clear tendency in the results. Most people could distinguish between the three tested shapes when they were 0.4 mm wide on a computer screen. For a phone screen, used with a shorter viewing distance, majority of survey participants could see and recognize a square, when it was 0.2 mm, the circle and the triangle had to be at least 0.3 mm wide.

For a computer screen the differences in legibility between those basic shapes were very small, hence insignificant. For a handheld 806 ppi device, a circle had a significantly worse results than the square or triangle.

The proposed line symbolization test shows, that the line with a square cap has a much higher legibility rate than the triangle or rounded cap. More than 90% of participants could read the square cap correctly, even when the pattern was only 0.2 mm wide.

The designed study failed to show significant differences in legibility of the same size symbols in at different resolutions. The difference in time taken to do the task at different resolutions also did not bring statistically significant results.

5. Discussion

5.1. Conclusions

This study aimed to address following questions:

- Is the point symbol legibility dependent on the screen pixel density?
- What are the smallest point symbols sizes that can be visually perceived on screens?
- Are these sizes different for different screen resolutions?
- How can the insights from three previous questions be relevant for creating a new line symbolization?

In order to answer those questions, the following objectives were chosen:

- Establishing minimum dimensions of point symbols for different screen resolutions
- Conducting a study with around 30 participants to confirm the minimum dimensions
- Designing a line symbol and testing its legibility

To meet these objectives, a study for a computer screen and a phone screen was designed, testing legibility of point and line symbols. The influence of screen resolution was approximated using raster images in varying resolutions.

The study differentiated between two common use cases for modern maps - phone and computer screens. These two cases differ in available pixel density, and viewing distance, the latter being much shorter for handheld devices such as a mobile phone.

The study was constrained by the number of experiment participants, due to the format of the master programme.

The results of the study did not provide clear answers for all research questions, as visual acuity is not a single value and differs from individual to individual. There were a few study participants who were able to distinguish shapes 0.2 mm in width. On the other hand, there were few participants for whom tested symbols were too small to recognize. This is why, the decision was made to focus rather on overall tendencies, rather than attempting to authoritatively derive the legibility threshold values.

Nevertheless, the 90% correct answer threshold was met on the computer screen[11] by the 0.6 mm wide circle, 0.5 mm wide square or 0.5 mm wide triangle. For a phone screen[12] 90% legibility threshold was met by the 0.6 mm wide circle, 0.4 mm wide square or 0.4 mm wide triangle. The study has shown that the smallest legible symbols have different sizes for different screen resolutions.

This does not completely confirm the previous studies, as some of them state, that minimum sizes for a circle and square are smaller than for a triangle (Rytz *et al.*, 1980; Neudeck, 2001).

[11] 5K computer display, 217 ppi

[12] 4K phone display, 806 ppi

It is clear that the minimum dimensions for point symbols are not the same as those of the guidelines for good map design. Nevertheless, it is important to know what are the minimum sizes to add a necessary reserve.

Furthermore, the experiment was concerned with determining if a symbol would have better legibility if rendered at a higher resolution. This study has found no such correlation, as the differences in results were very small and statistically insignificant.

Part of the experiment was testing line legibility, while the shape differentiation was inspired by circle, square and triangle. Interestingly, it appeared that square cap line has much better legibility than the other two.

5.2. Study Limitations

The study was conducted with only 27 participants, most of them under 30, and vast majority affiliated with Cartography MSc. Thus, we can expect that they should have good, natural or corrected vision. It is not certain if the results could be similar if the experiment was done with bigger group of people, with more diverse background and varying age.

In the survey, the viewing distance was not enforced. The experiment participants could get closer to the screen if they wanted. Viewing distance was also not measured, so the results are not directly comparable with visual acuity tests.

In this study only simple cartographic visualizations were created and tested. In web mapping, very often several layers of information are included. Cartographic symbols are overlapping or intersecting, which makes the cognitive load bigger and certain symbols less legible. This is to say that in this thesis the most optimal case of simplified map design was implemented.

The way the symbols were rendered was not fully controlled. The used images were displayed in the web browser with default raster CSS/HTML rendering, which may not be the most optimal solution for cartography.

Neither illumination of the room, nor the brightness and contrast of visual displays was measured.

Only high contrast and high frequency patterns – black symbols on the white background were tested. For lower contrast patterns larger symbols need to be used.

5.3. Recommendations for future research

The conducted experiment could be extended by focusing on subjects with good vision (natural or corrected). Alternatively, wider range of people with different vison should include wider range of symbol sizes.

Further topics related to the eye acuity are establishing the minimal line width, minimal line separation distance, and font sizes.

In future investigations it might be possible to create an adaptive map design, adjusting symbol sizes according to such information as device type, screen width, screen height or device pixel ratio.

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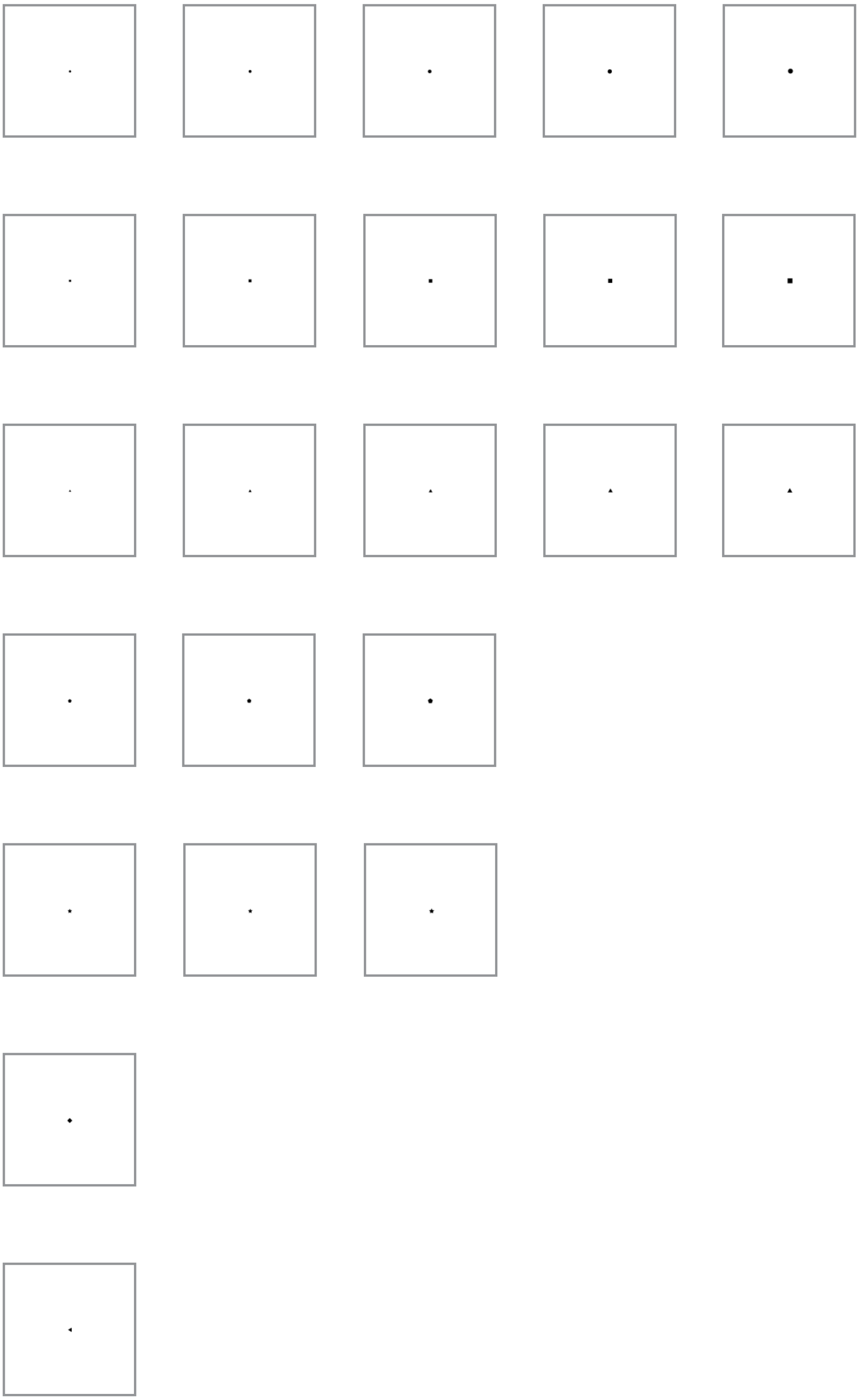
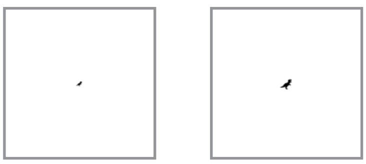
Appendix

Tested Images

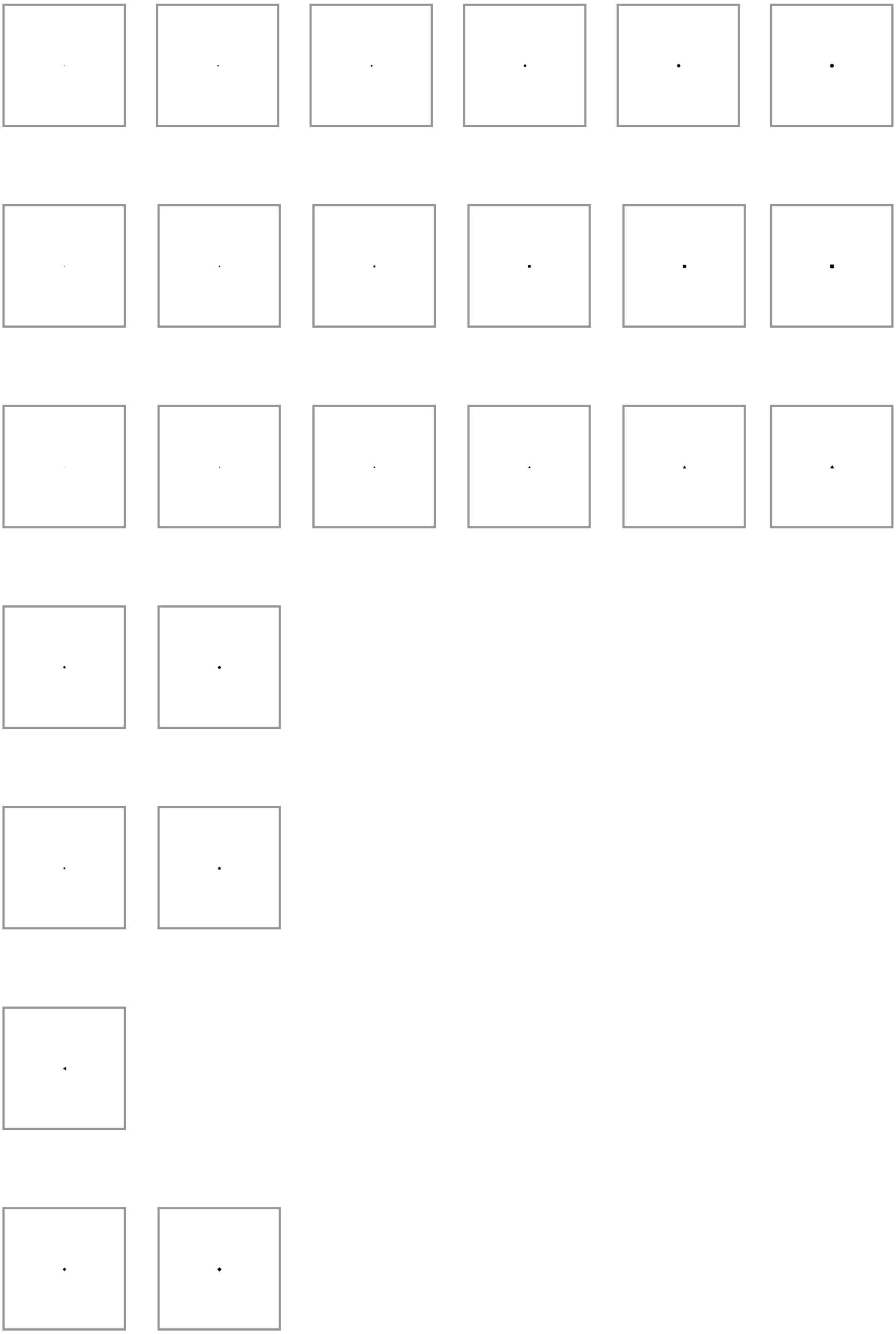
Task 1 a computer screen

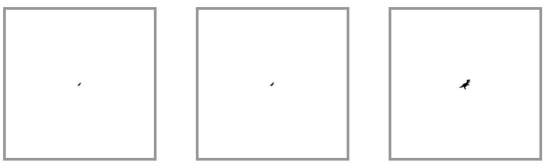




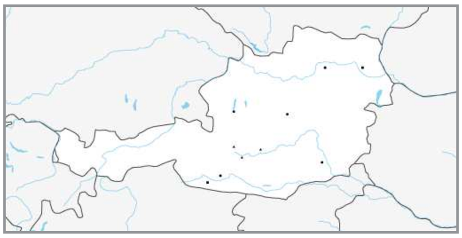
Tested Images

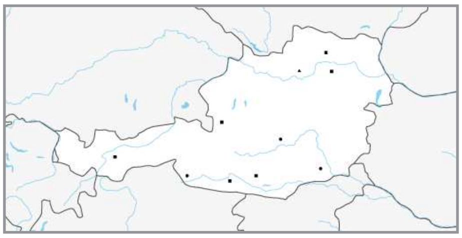
Task 1 a phone screen

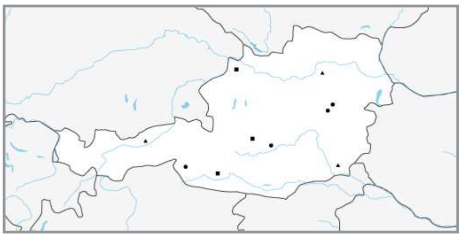


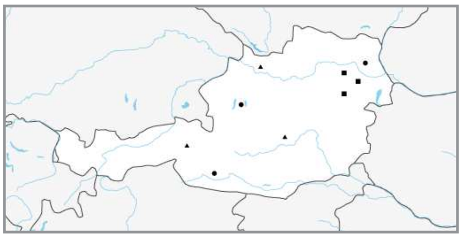


Tested Images
Task 1b computer screen

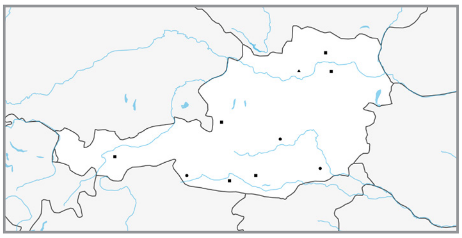








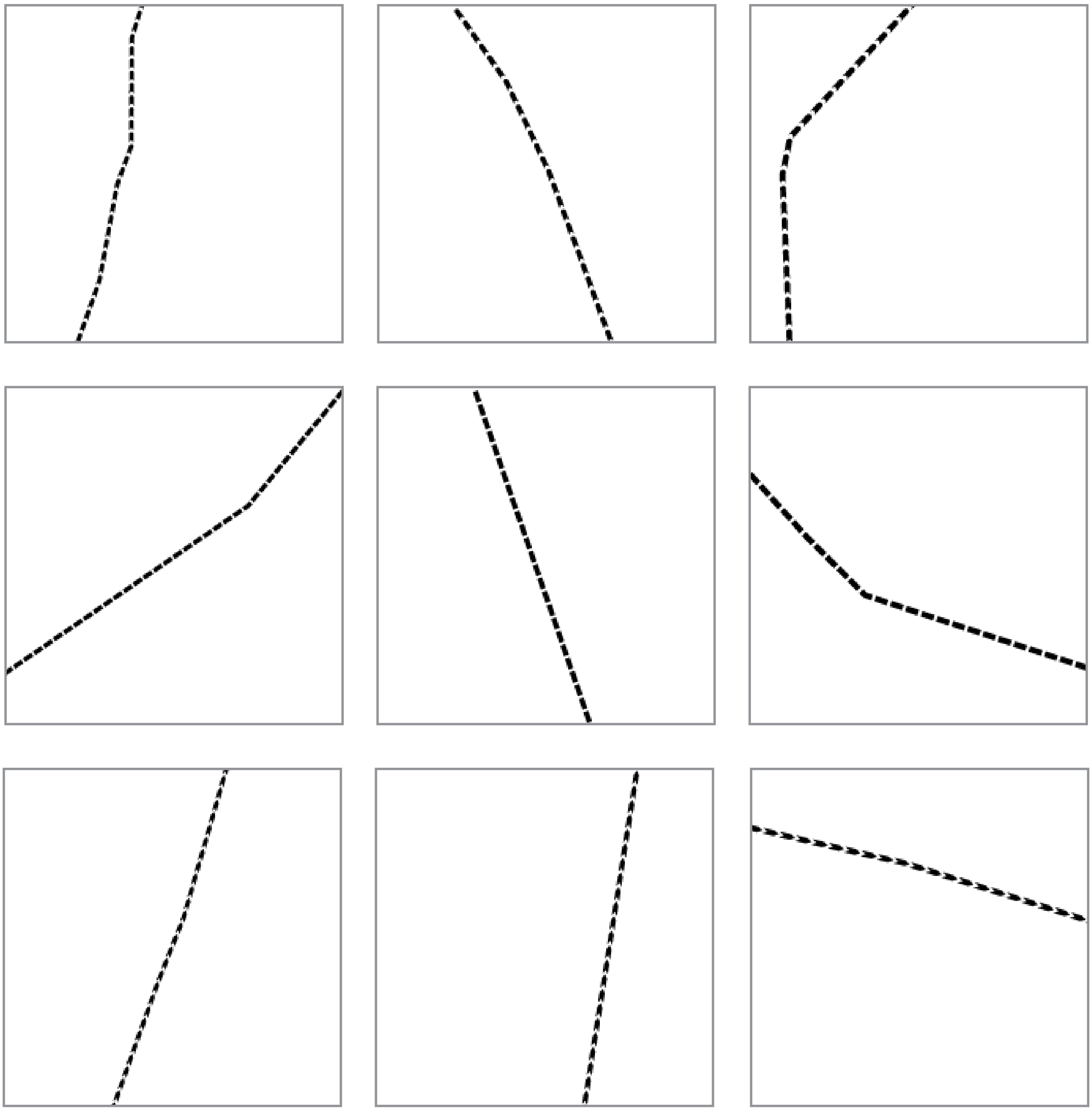
Tested Images
Task 1b phone screen



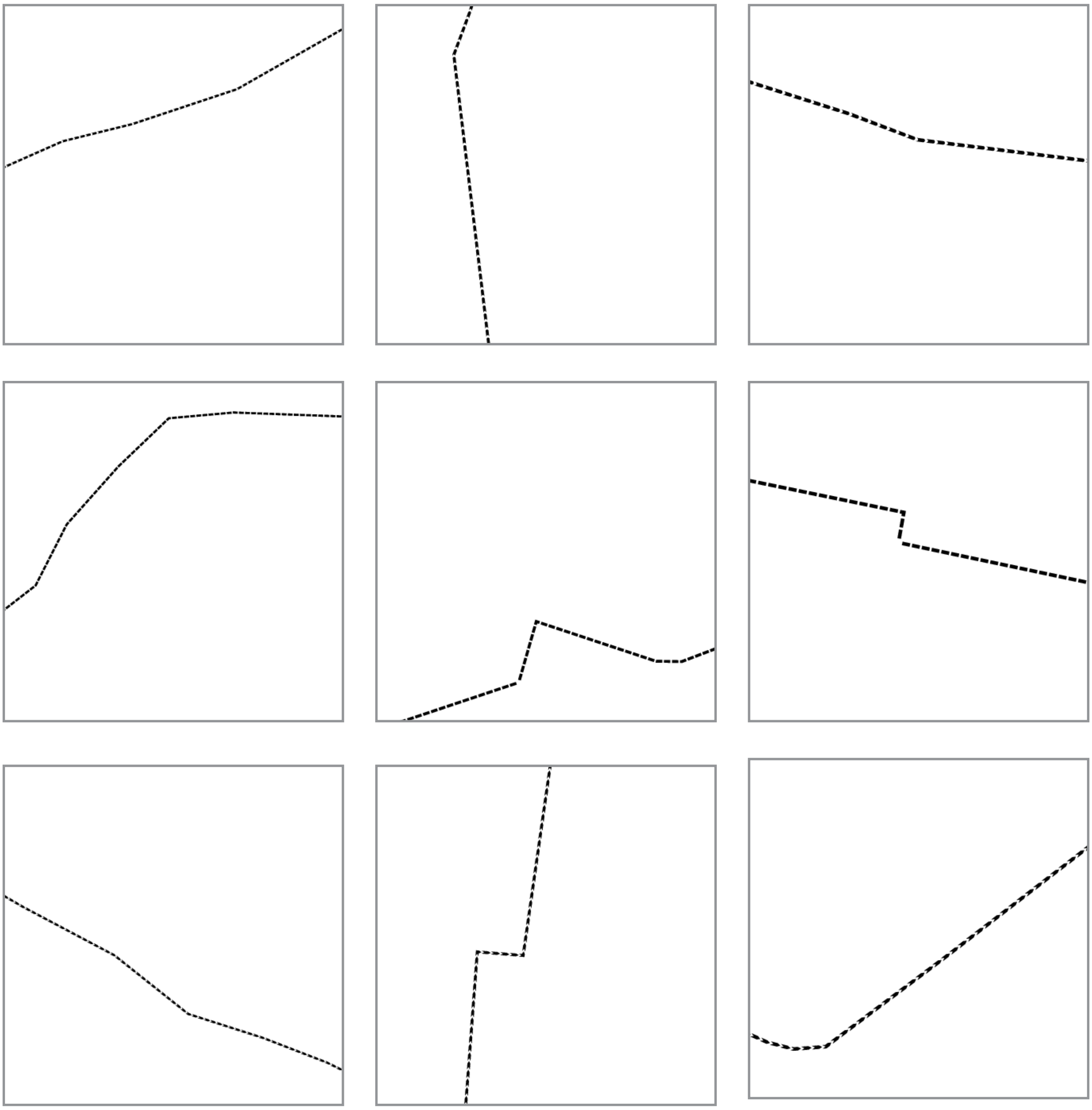
Tested Images

Task 2a computer screen

109 ppi



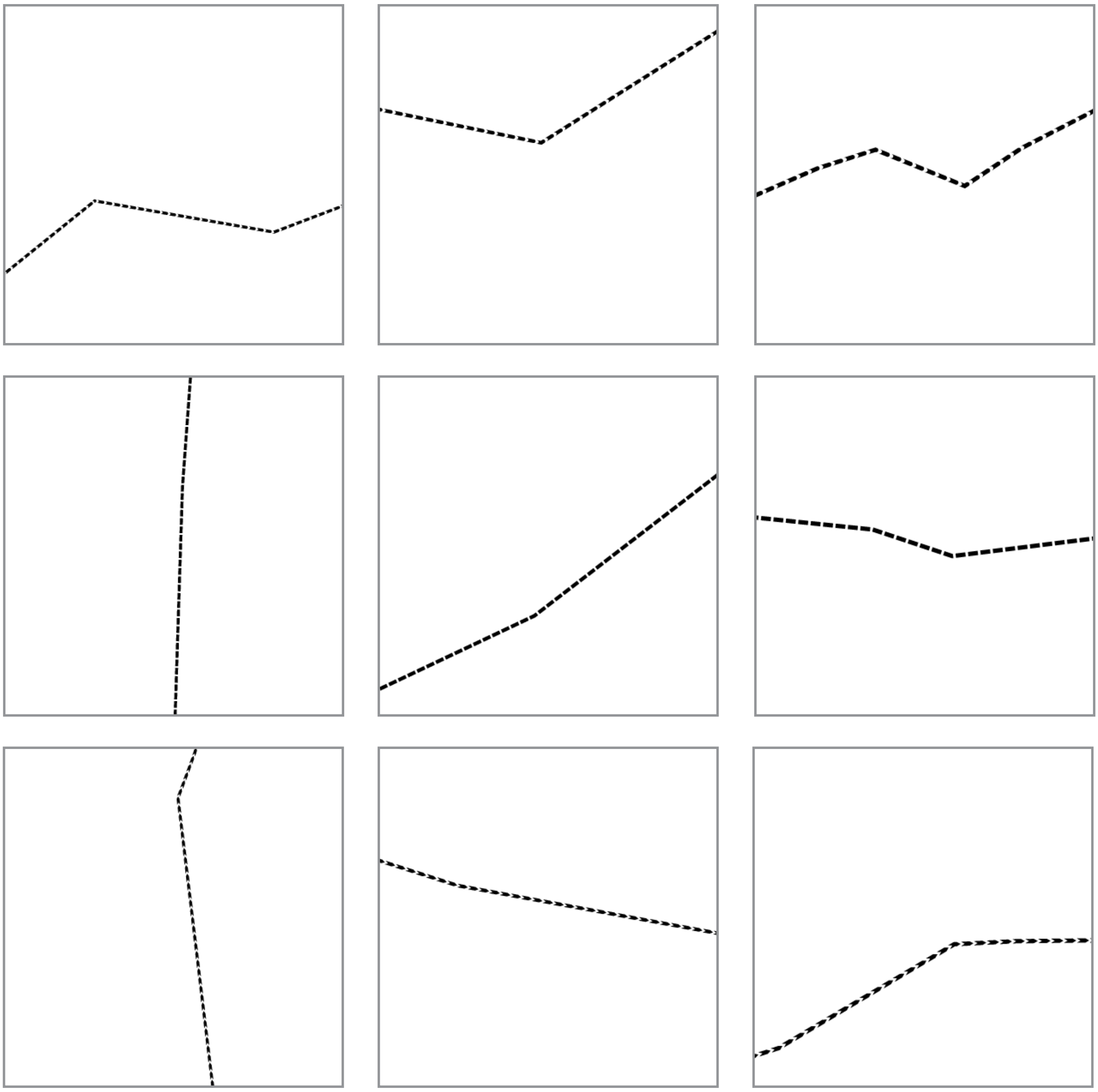
217 ppi



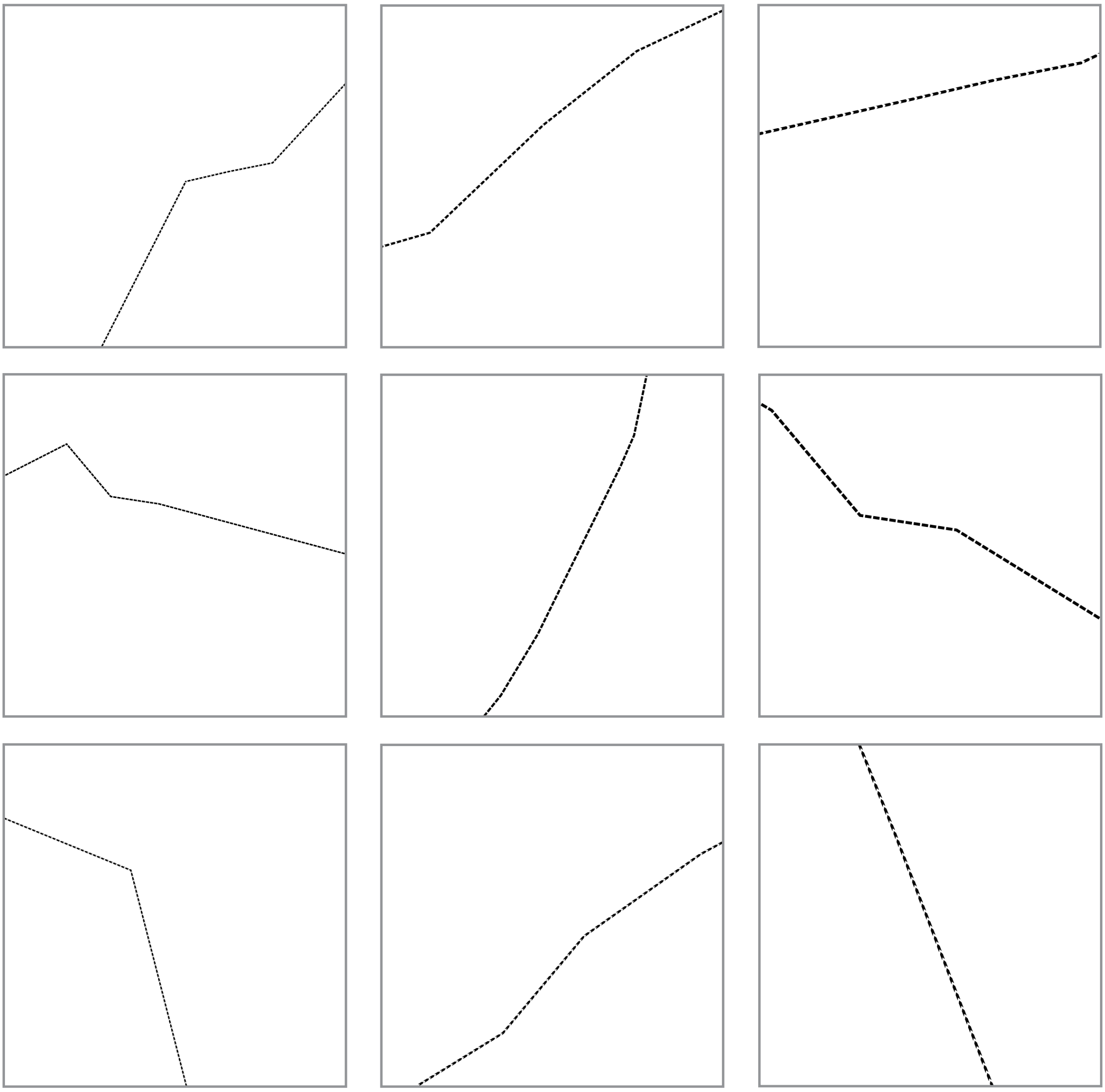
Tested Images

Task 2a phone screen

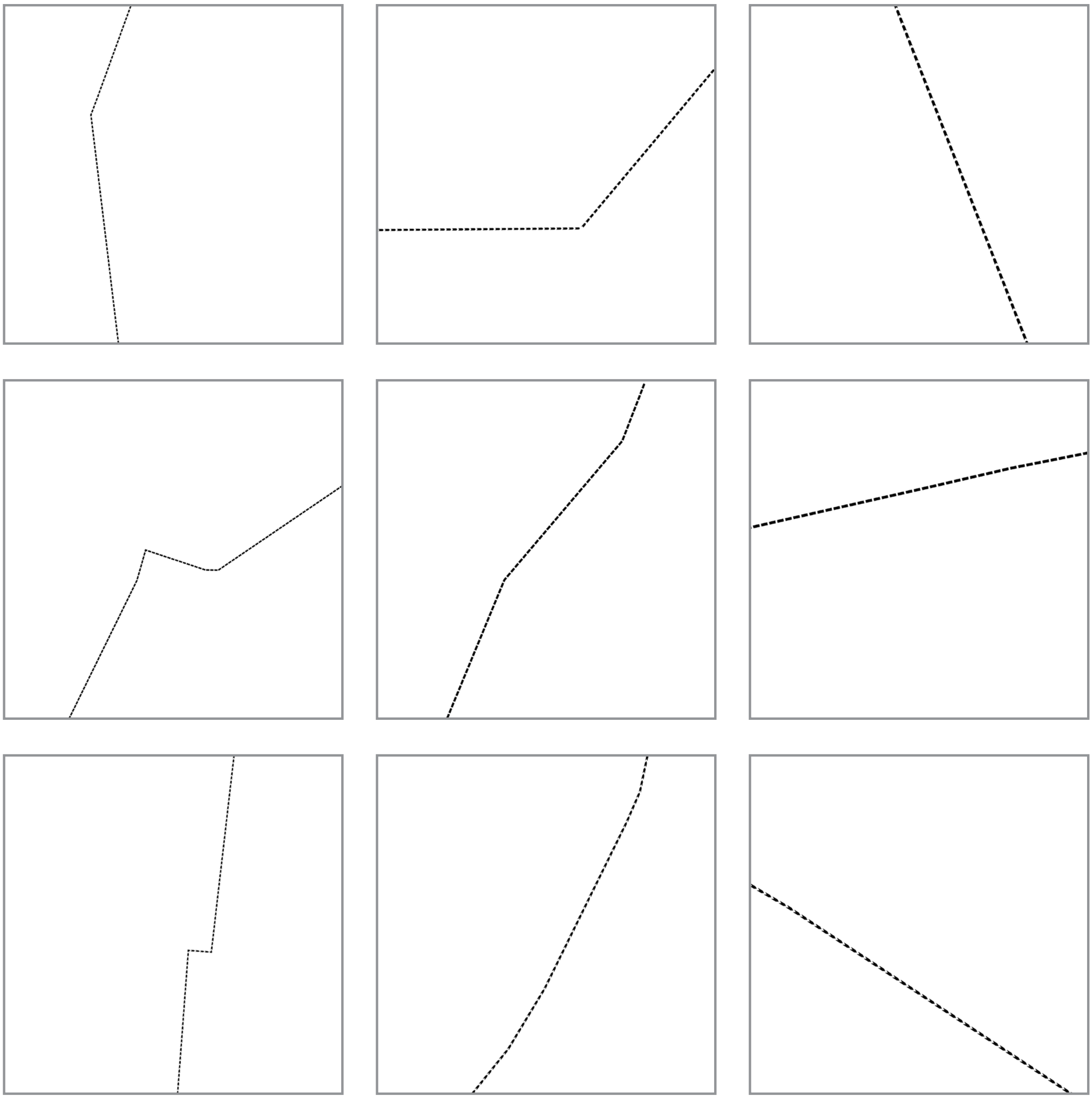
202 ppi



403 ppi



806 ppi



Tested Images
Task 2b computer screen

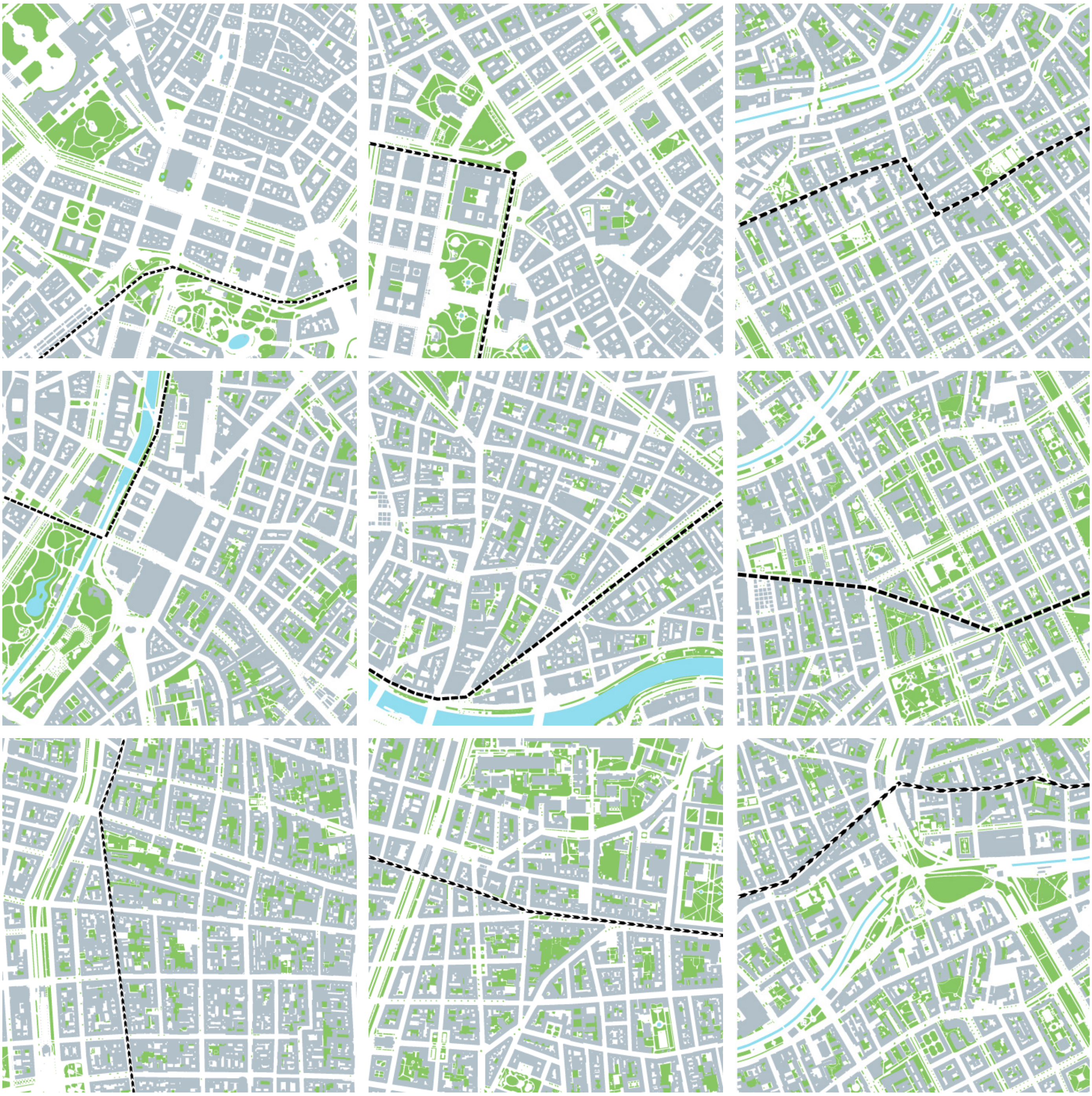
109 ppi

217 ppi

Tested Images

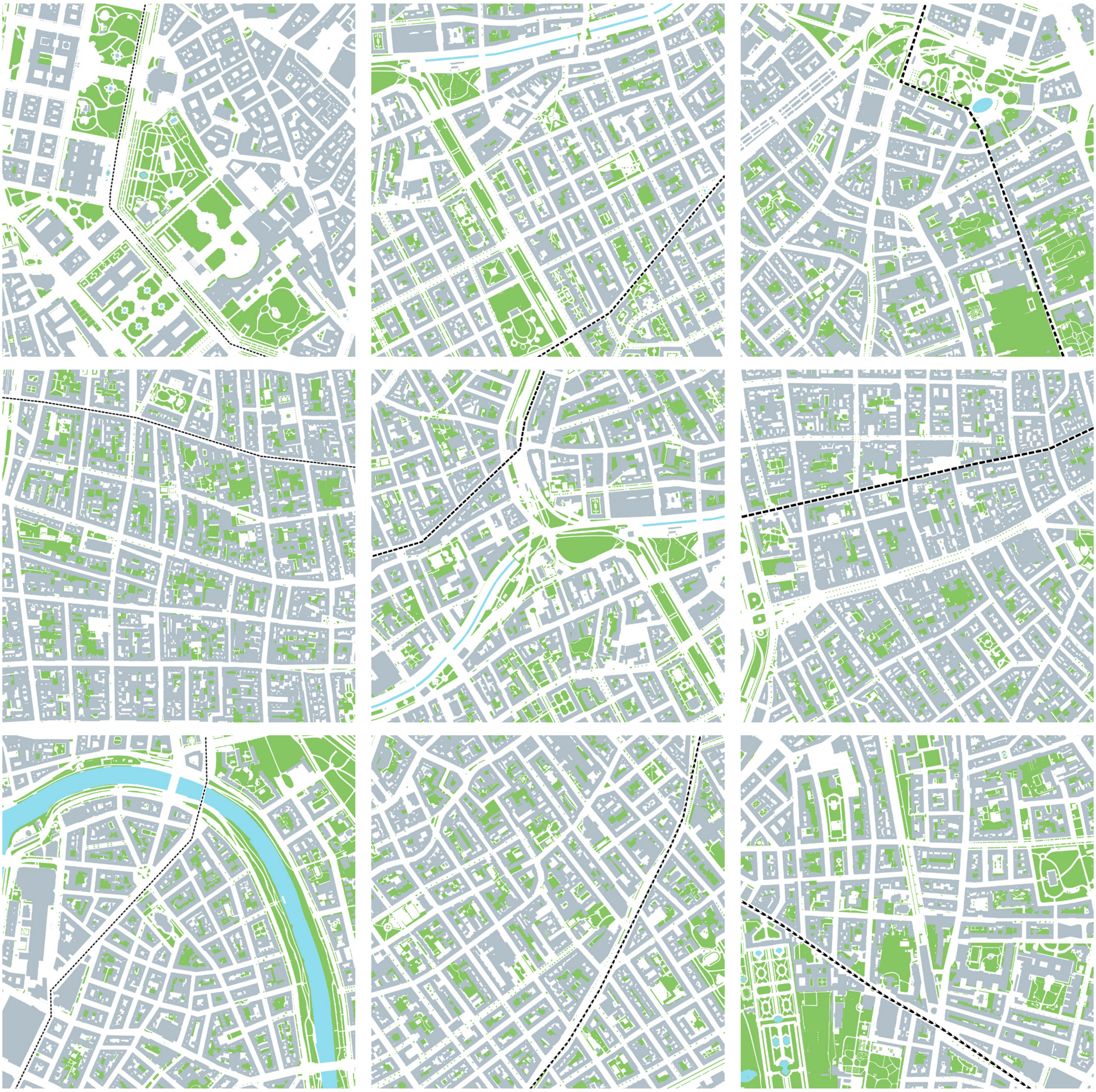
Task 2b phone screen

202 ppi



403 ppi

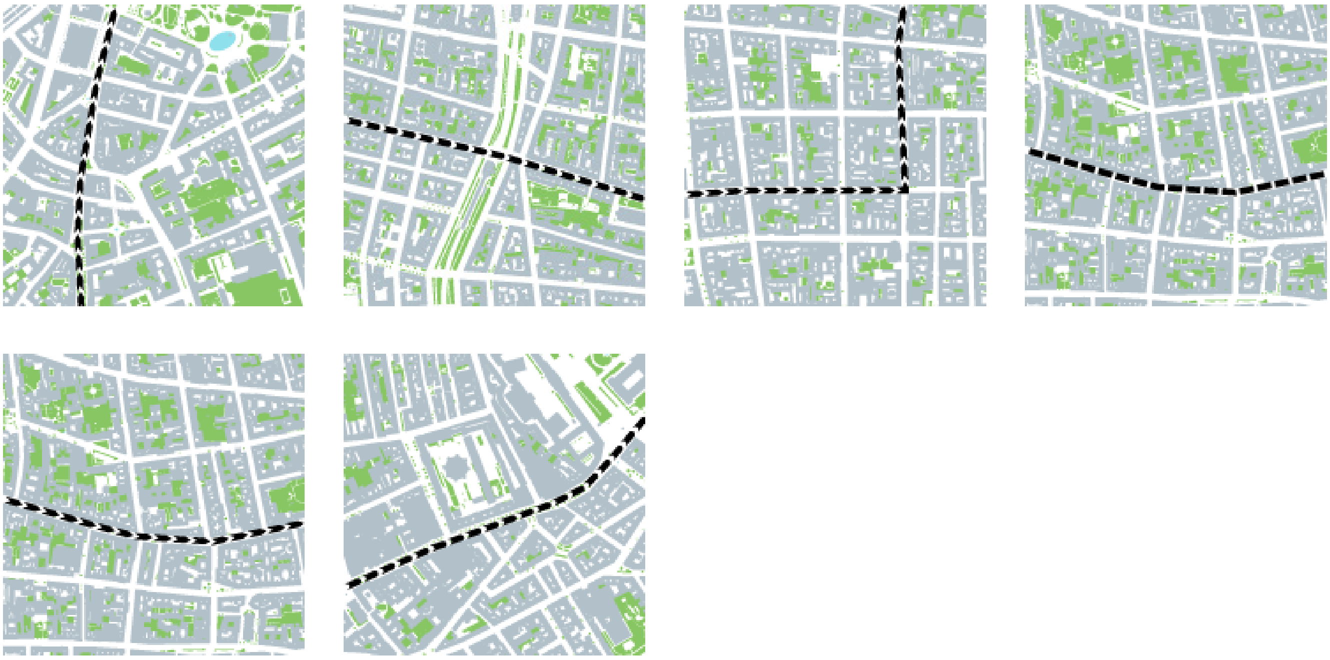
806 ppi



Tested Images

Task 3 computer screen

109 ppi



217 ppi





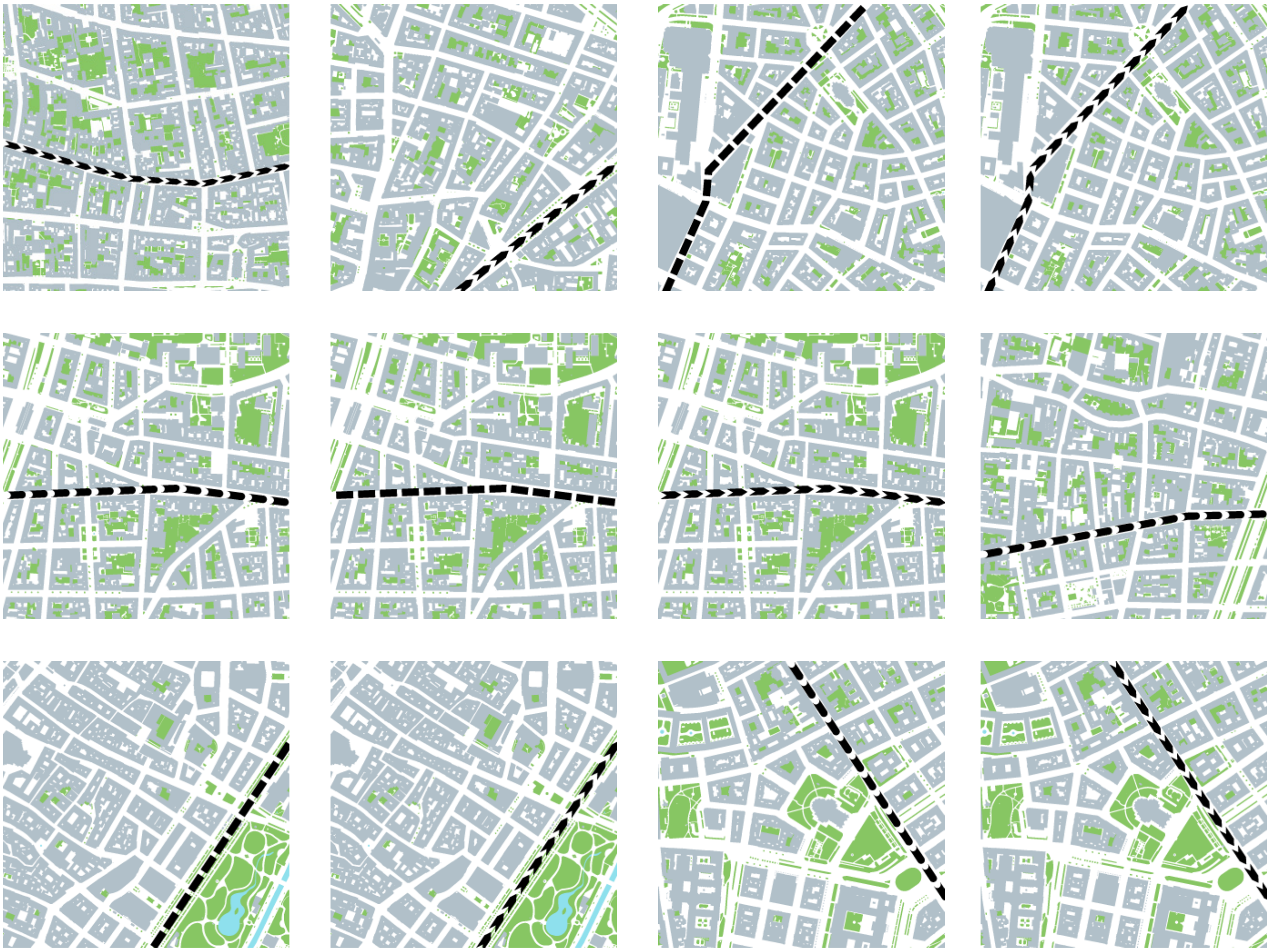




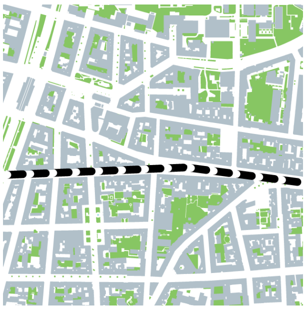
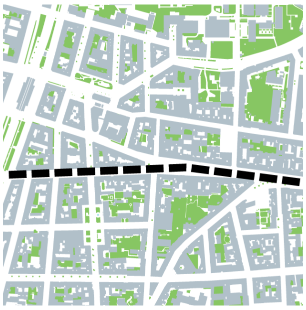
Tested Images

Task 3 phone screen

202 ppi



403 ppi



806 ppi






TECHNISCHE UNIVERSITÄT WIEN

Research Group Cartography

Department of Geodesy and Geoinformation

CARTOGRAPHIC SYMBOLIZATION FOR DIGITAL DISPLAYS

1.1 EXPERIMENT INFORMATION SHEET

Introduction

This experiment is a part of a Master thesis research and it was designed to develop better understanding of how the display resolution affects the perception of cartographic symbols.

Procedure

After a short introduction you will be asked to complete a survey on two devices – computer and phone. The experiment will take place in Research Group Cartography office. Throughout the experiment you will be assisted by a Master of Cartography student, who will give you instructions and answer your questions if you have any. The survey should be self-explanatory, but participants may also ask questions also during the experiment.

Duration

This experiment will take around 25 minutes.

Right to Refuse or Withdraw

Your participation in this research is entirely voluntary. It is your choice whether to participate or not. You may change your mind later and stop participating even if you agreed earlier.

Confidentiality

All the information you provide will be strictly confidential. The experiment may be recorded with a video camera. All data and will be anonymous. Any information about you will have a number on it instead of your name. I will not be sharing information about you to anyone outside of the research team. Video recording will be available if you request them. You may contact me at any time in the future to alter or delete any statements made.

Who to contact

If you have any questions, please contact Agnieszka Mańk (agnes.mank@gmail.com)

Research Group Cartography

Department of Geodesy
and Geoinformation

1.2 CERTIFICATE OF CONSENT

Statement by the participant

I have read information about the experiment. My questions about the study have been answered to my satisfaction and I understand that I may ask further questions at any point. I consent voluntarily to be a participant in this study.

Signature of Participant ________________________________ **Date** _______________________

Statement by the researcher

I confirm that the participant was given an opportunity to ask questions about the study, and all the questions asked by the participant have been answered to the best of my ability. I confirm that the participant agreed to take part in the experiment freely and voluntarily. I provided the information sheet and a copy of this certificate to the participant.

Signature of Researcher ________________________________ **Date** ________________________

Survey results

Task 1a, computer screen

ID	circle 0.3	circle 0.4	circle 0.5	circle 0.6	circle 0.7	square 0.3	square 0.4	square 0.5	square 0.6	square 0.7	traingle 0.3	triangle 0.4	triangle 0.4 [other]
1	circle	circle	circle	circle	circle	circle	square	square	square	square	triangle	triangle	
2	circle	0	circle	circle	circle	square	square	square	square	square	0	0	
3	circle	circle	circle	circle	circle	square	square	square	square	square	triangle	triangle	
4	0	circle	circle	circle	circle	square	square	square	square	square	triangle	triangle	
5	0	circle	circle	circle	circle	0	square	square	square	square	0	Other	star
6	circle	circle	circle	circle	circle	square	square	square	square	square	0	triangle	
7	circle	circle	circle	circle	circle	square	square	square	square	square	triangle	triangle	
8	circle	circle	circle	circle	circle	square	square	square	square	square	triangle	triangle	
9	0	0	circle	circle	circle	circle	circle	square	square	square	0	triangle	
10	circle	circle	circle	circle	circle	circle	circle	square	square	square	0	triangle	
11	0	circle	triangle	circle	circle	triangle	square	square	square	square	0	0	
12	0	0	circle	circle	circle	circle	square	square	square	square	0	triangle	
13	circle	circle	circle	circle	circle	circle	square	square	square	square	circle	circle	
14	0	0	circle	circle	circle	square	square	square	square	square	triangle	triangle	
15	circle	circle	circle	circle	circle	circle	circle	square	square	square	circle	circle	
16	0	circle	0	circle	circle	circle	circle	square	square	square	0	0	
17	0	circle	circle	circle	circle	circle	square	square	square	square	0	triangle	
18	0	0	circle	circle	circle	square	square	square	square	square	triangle	triangle	
19	0	0	circle	circle	circle	0	square	square	square	square	0	triangle	
20	triangle	circle	circle	circle	circle	0	square	square	square	square	triangle	triangle	
21	0	circle	circle	circle	circle	0	triangle	square	square	square	0	0	
22	0	square	circle	circle	circle	square	square	square	square	square	triangle	triangle	
23	circle	0	circle	circle	circle	square	square	square	square	square	0	triangle	
24	0	square	circle	circle	circle	0	circle	circle	triangle	circle	0	circle	
25	0	circle	circle	circle	circle	circle	circle	circle	circle	square	0	circle	
26	circle	circle	square	square	circle	0	triangle	square	square	square	0	triangle	
27	0	0	circle	circle	circle	triangle	0	square	square	square	0	triangle	
correct answer	circle	circle	circle	circle	circle	square	square	square	square	square	triangle	triangle	
count	11	17	24	26	27	10	18	25	25	26	9	18	

numbers in the columns names refer to the symbol width in mm
every question in this group had an option "Other". The column with "other" input apears in this table where at least one participant chose the option "other"
In the results 0 appears where the participant chose the option "I can't recognise the shape"

ID	triangle 0.5	triangle 0.6	triangle 0.7	pentagon 0.5	pentagon 0.5 [other]	pentagon 0.6	pentagon 0.6 [other]	pentagon 0.7	pentagon 0.7 [other]	dino 1.5	dino 1.5[other]	traingle 0.6 rotatated.
1	triangle	triangle	triangle	circle		circle		Other	star	Other	dinasor	triangle
2	triangle	triangle	triangle	0		0		Other	hex	Other	dino	triangle
3	triangle	triangle	triangle	circle		Other	house	Other	pentagon	Other	t-rex	triangle
4	triangle	triangle	triangle	Other	maaybe pentagon	circle		Other	pentagon	Other	tyrannosaurus rex	triangle
5	triangle	triangle	triangle	circle		Other	star	Other	star	0		triangle
6	triangle	triangle	triangle	circle		circle		Other	pentagon	Other	dinosaur	triangle
7	triangle	triangle	triangle	circle		circle		circle		Other	dinosaur	triangle
8	triangle	triangle	triangle	circle		Other	pentagon	Other	pentagon	Other	dinosaur	triangle
9	triangle	triangle	triangle	circle		0		Other	pentagon	Other	dinosaurus	triangle
10	triangle	triangle	triangle	circle		circle		circle		Other	bird	triangle
11	triangle	triangle	triangle	circle		circle		circle		0		triangle
12	triangle	triangle	triangle	circle		circle		Other	pentagon	Other	t-rex	triangle
13	triangle	triangle	triangle	circle		circle		circle		Other	dinosaur	triangle
14	triangle	triangle	triangle	0		circle		Other	house	Other	dinosaur	triangle
15	triangle	triangle	triangle	circle		circle		circle		Other	dinosaur	triangle
16	triangle	triangle	triangle	circle		0		0		0		triangle
17	triangle	triangle	triangle	circle		circle		circle		Other	dinosaur	triangle
18	triangle	triangle	triangle	0		0		Other	pentagon	Other	dinsoaur	triangle
19	triangle	triangle	triangle	0		circle		circle		Other	dinosaur	triangle
20	triangle	triangle	triangle	circle		square		circle		Other	dinosaurus	triangle
21	triangle	triangle	triangle	circle		circle		0		Other	animal	triangle
22	triangle	triangle	triangle	circle		circle		circle		Other	dinasour	triangle
23	triangle	triangle	triangle	circle		circle		0		0		triangle
24	circle	circle	square	circle		circle		circle		triangle		0
25	0	circle	circle	0		0		circle		Other	bird/dinosaur	circle
26	triangle	triangle	triangle	circle		square		square		Other	t-rex	triangle
27	triangle	triangle	triangle	triangle		square		circle		Other	Dinosaur	triangle
correct answer	triangle	triangle	triangle		pentagon		pentagon		pentagon		dinosaur	triangle
count	25	25	25		1		1		7		21	25

Survey results - Task 1a, computer screen

ID	square 0.5 rotated	square 0.5 rotated[other]	star 0.5	star 0. 5 [other]	star 0.6	star0.6 [other]	star 0.7	star 0.7[other]	dino 0.7	dino 0.7[other]
1	square		Other	star	Other	star	Other	star	Other	chicken
2	square		Other	star	Other	star	Other	star	Other	dino
3	square		Other	star	Other	star	Other	star	Other	T-Rex
4	Other	raute	Other	star	Other	star	Other	star	Other	cookie
5	square		Other	star	Other	star	Other	star	0	
6	square		Other	star	Other	star	Other	star	Other	dinosaur
7	Other	rhomb	Other	star	Other	star	Other	star	Other	bird
8	square		Other	star	Other	star	Other	star	Other	dinosaur
9	square		Other	star	circle		Other	star	Other	bird
10	circle		Other	star	circle		Other	star	Other	bird
11	Other	route	circle		square		Other	star	0	
12	Other	diamond	0		0		Other	star	Other	t-rex
13	square		Other	star	Other	star	Other	star	Other	dinosaur
14	square		Other	star	Other	star	Other	star	Other	dinosaur
15	circle		triangle		circle		circle		Other	moon
16	square		0		0		Other	star	0	
17	Other	raute	Other	star	Other	star	Other	star	0	
18	Other	diamond	Other	star	Other	star	Other	star	Other	dinosaur
19	circle		0		circle		0		triangle	
20	Other	romb	Other	star	0		Other	star	Other	dinosaurus
21	square		0		0		Other	star	0	
22	square		Other	star	Other	star	Other	star	Other	dinasour
23	square		0		circle		triangle		0	
24	circle		square		square		circle		0	
25	circle		0		circle		circle		Other	
26	circle		circle		triangle		circle		0	
27	circle		triangle		triangle		0		Other	Dinosaur
correct answer	square			star		star		star		dinosaur
count	13			16		13		20		11

Survey results - Task 1a, computer screen

Survey results

Task 1a, phone screen

ID	circle 0.1	circle 0.2	circle 0.2 [other]	circle 0.3	circle 0.3 [other]	circle 0.4	circle 0.4 [other]	circle 0.5	circle 0.6	square 0.1	square 0.2	square 0.2 [other]	square 0.3	square 0.4	square 0.5	square 0.6
1	0	0		circle		circle		circle	circle	0	square		square	square	square	square
2	0	0		0		circle		square	circle	0	0		square	square	square	square
3	triangle	0		circle		circle		circle	circle	0	square		circle	square	square	square
4	0	0		circle		circle		circle	circle	circle	square		square	square	square	square
5	0	0		Other	Star	circle		circle	circle	0	square		square	square	square	square
6	0	circle		circle		circle		circle	circle	0	0		square	square	square	square
7	0	square		circle		circle		square	circle	0	square		square	square	square	square
8	square	circle		circle		circle		circle	circle	circle	square		square	square	square	square
9	0	Other	Star	0		circle		circle	circle	triangle	0		square	square	square	square
10	circle	circle		square		circle		circle	circle	circle	square		square	square	square	square
11	0	circle		circle		circle		circle	triangle	0	square		square	square	square	square
12	0	square		circle		square		circle	circle	0	0		square	square	square	square
13	0	0		circle		square		circle	circle	0	square		square	square	square	square
14	0	0		0		Other	Square with round edges	circle	circle	0	0		square	square	square	square
15	triangle	circle		circle		circle		circle	circle	triangle	square		square	square	square	square
16	circle	circle		circle		circle		circle	circle	circle	circle		square	square	square	square
17	0	0		circle		circle		circle	circle	0	square		triangle	square	square	square
18	0	0		0		circle		circle	circle	0	square		square	square	square	square
19	0	0		circle		circle		circle	circle	0	0		square	square	square	square
20	0	circle		circle		square		circle	circle	circle	square		square	square	square	square
21	0	0		circle		circle		circle	circle	0	square		square	square	square	square
22	0	0		square		square		circle	circle	circle	0		square	square	square	square
23	0	0		0		0		square	circle	0	0		square	square	square	square
24	0	0		square		0		0	0	0	Other	2 points	0	0	circle	0
25	0	0		0		circle		circle	circle	0	square		square	square	square	square
26	0	0		circle		circle		circle	circle	circle	square		square	square	square	square
27	0	square		0		circle		circle	circle	0	0		square	square	square	square
correct answer	circle	circle		circle		circle		circle	circle	square	square		square	square	square	square
count	2	7		16		20		23	25	0	16		24	26	26	26

numbers in the columns names refer to the symbol width in mm

every question in this group had an option "Other". The column with "other" input apears in this table where at least one participant chose the option "other"

In the results 0 appears where the participant chose the option "I can’t recognise the shape"

ID	triangle 0.1	triangle 0.2	traingle 0.3	triangle 0.4	triangle 0.5	triangle 0.6	dino 1.5	dino 1.5 [other]	dino 0.5	dino 0.5 [other]	dino 0.6	dino 0.6 [other]	star 0.4	star 0.4 [other]
1	0	triangle	triangle	triangle	triangle	triangle	Other	Dinosaur	Other	Dinosaur or chicken	Other	Dinosaur	Other	Star
2	0	0	0	triangle	triangle	triangle	Other	Dinosaur	Other	Dinosaur	Other	Dinosaur	0	
3	0	0	triangle	triangle	triangle	triangle	Other	T-Rex	Other	T-Rex	Other	T-Rex	Other	star
4	0	triangle	triangle	triangle	triangle	triangle	Other	Dinosaur	Other	Dinosaur	Other	Dinosaur	Other	Star
5	0	0	triangle	triangle	triangle	triangle	Other	Dinosaur	0		0		Other	Star
6	0	triangle	triangle	triangle	triangle	triangle	Other	Dinosaur	Other	Dinosaur	Other	Dinosaur	Other	Star
7	0	triangle	triangle	triangle	triangle	triangle	Other	Dinosaur	Other	Dinosaur	Other	Bird	Other	Star
8	circle	triangle	triangle	triangle	triangle	triangle	Other	Dinosaur	Other	Dinosaur	Other	Bird	Other	Star
9	0	triangle	triangle	triangle	triangle	triangle	Other	Dinosaurus	Other	Dinosaurus	Other	Dinosaurus	Other	Star
10	circle	circle	triangle	triangle	triangle	triangle	Other	Bird	Other	Bird	Other	Bird	circle	
11	0	triangle	triangle	triangle	triangle	triangle	Other	T-Rex	Other	T-Rex	Other	T-Rex	Other	Pentagon
12	0	0	circle	triangle	triangle	triangle	Other	T-rex	Other	Bird?	Other	T-Rex	0	
13	0	0	triangle	triangle	triangle	triangle	Other	Dinosaur	0		Other	Dinosaur	Other	Star
14	0	triangle	triangle	triangle	triangle	triangle	Other	Dinosaur	Other	Dinosaur	Other	Dinosaur	Other	Star
15	triangle	triangle	triangle	triangle	triangle	triangle	Other	Dinosaur	Other	Dinosaur	Other	Dinosaur	Other	Star
16	circle	circle	triangle	triangle	triangle	triangle	0		0		0		circle	
17	0	triangle	triangle	triangle	triangle	triangle	Other	Dinosaur	Other	Dinosaur	Other	Dinosaur	Other	Star
18	0	triangle	triangle	triangle	triangle	triangle	Other	dinosaur	Other	Dinosaur	Other	Dinosaur	Other	pentagon
19	0	0	0	triangle	triangle	triangle	Other	Dinosaur	Other	Dinosaur	Other	Dinosaur	Other	Star
20	0	triangle	triangle	triangle	triangle	triangle	Other	Dinosaurus	Other	Dinosaurus	Other	Bird	circle	
21	0	0	triangle	triangle	triangle	triangle	Other	Animal	Other	Animal	Other	Animal	0	
22	0	circle	0	triangle	triangle	triangle	Other	Dinausore	Other	Bird	Other	Dinosaur	0	
23	0	0	0	triangle	triangle	triangle	0		0		0		0	
24	0	0	0	0	circle	0	circle		circle		0		0	
25	0	0	triangle	triangle	triangle	triangle	Other	Dinosaur	Other	Dinosaur	Other	Dinosaur	Other	Star
26	circle	0	triangle	triangle	triangle	triangle	Other	T-rex	0		0		square	
27	0	triangle	triangle	triangle	triangle	triangle	Other	Dinosaur	0		Other	dinosaur	circle	
correct answer	triangle	triangle	triangle	triangle	triangle	triangle		dinosaur		dinosaur		dinosaur		star
count	1	13	21	26	26	26		22		16		17		14

Survey results - Task 1a, phone screen

ID	star 0.5	star 0.5 [other]	triangle 0.6 rotated	square 0.4 rotated	square 0.4 rotated [other]	square 0.5 rotated	square 0.5 rotated [other]	pentagon 0.4	pentagon 0.5	pentagon 0.5 [other]
1	Other	Star	triangle	square		square		circle	Other	Star
2	Other	✵	triangle	square		square		circle	Other	Hexagon
3	Other	star	triangle	square		square		circle	Other	Pentagon
4	Other	Star	triangle	Other	Raute	Other	Raute	circle	Other	Pentagon
5	Other	Star	triangle	square		square		circle	Other	Star
6	Other	Star	triangle	square		square		circle	Other	Pentagon
7	Other	Star	triangle	Other	Rhomb	square		circle	Other	Star
8	Other	Star	triangle	square		square		circle	Other	Pentagon
9	Other	Star	triangle	square		square		circle	Other	Pentagon
10	Other	Star	triangle	square		square		circle	circle	
11	Other	Star	triangle	Other	Route	Other	Route	circle	Other	Pentagon
12	Other	Star	triangle	Other	Diamond	Other	Diamond	circle	Other	Pentagon
13	Other	Star	triangle	Other	Rhombls	Other	Rhomb	square	Other	Star
14	Other	Star	triangle	square		square		circle	0	
15	Other	Star	triangle	square		square		circle	Other	Pentagon
16	Other	Star	triangle	0		square		circle	circle	
17	Other	Star	triangle	Other	Raute	Other	Raute	circle	0	
18	Other	Star	triangle	Other	diamond	Other	diamond	0	Other	Pentagon
19	Other	Star	triangle	square		square		circle	circle	
20	Other	Star	triangle	Other	Romb	Other	Romb	circle	Other	Pentagon
21	Other	Star	triangle	square		square		circle	Other	Star
22	Other	Star	triangle	circle		square		circle	circle	
23	triangle		triangle	square		square		0	triangle	
24	0		0	circle		circle		0	0	
25	Other	Star	triangle	Other		Other		circle	Other	Star
26	Other	Star	triangle	Other	Rhombus	Other	Rhombus	circle	circle	
27	Other	Star	triangle	Other	Diamond	Other	Diamond	circle	Other	Pentagram
correct answer		star	triangle	square		square		pentagon		pentagon
count		25	26	13		16	0	0		10

Survey results - Task 1a, phone screen

Survey results

Task 1b, computer screen

	0.3				0.4				0.5				0.6			
ID	circles	squares	triangles	difficulty	circles	squares	triangles	difficulty	circles	squares	triangles	difficulty	circles	squares	triangles	difficulty
1	5	2	3	3	3	6	1	3	4	3	4	2	3	3	3	1
2		3		5	3	5	1	4	4	3	3	4	3	3	3	3
3	2	5	1	4	2	6	1	1	3	4	3	3	3	3	3	2
4	3	4	3	5	3	6	1	4	4	3	3	2	3	3	3	2
5			3	4	3	6	1	4	4	3	3	3	3	3	3	3
6			3	5	3	6	1	5	4	3	3	1	3	3	3	2
7			3	4	3	6	1	2	4	3	3	2	3	3	3	1
8	3	4	3	5	4	6	1	3	4	3	3	4	3	3	3	3
9	4	3	3	4	4	5	1	5	4	3	3	3	3	3	3	2
10	4		3	5	5	4	1	5	4	3	3	4	3	3	3	1
11				5	3	6	1	4	4	3	3	2	3	3	3	2
12				5				5	4	3	3	5	3	3	3	3
13	4	3		5	4	6	1	4	3	5	3	3	2	4	3	1
14			3	4	4	4	1	3	3	3	3	3	3	3	3	2
15				5				5	4	3	3	5	3	3	3	4
16				5				5				5	3	3	3	4
17		4		5	3	6	1	3	4	3	3	3	3	3	3	2
18		3	3	4	3	6	1	4	4	3	3	2	3	3	3	2
19				5				5		5		4	3	3	3	3
20	4		4	5	3	4	2	4	3	5	2	3	3	3	3	1
21	4	3	3	5	3	6	1	5	4	3	3	2	3	3	3	1
22			3	5	3	7	1	4	4	4	3	3	3	3	3	4
23				5		3	1	3		4	3	3	3	3	3	1
24				5				5	5		5	4	2	4	4	4
25				5				5	6	1	3	4	2	4	3	4
26				5	5	2	3	5	2	4	3	4	2	4	2	4
27				5				5		3	3	5	4	4	3	5
correct answer	4	3	3		3	6	1		4	3	3		3	3	3	
count	5	5	12		12	12	18		16	17	22	0	22	22	25	

Survey results

Task 1b, phone screen

	0.2				0.3				0.4				0.5			
ID	circles	squares	triangles	difficulty	circles	squares	triangles	difficulty	circles	squares	triangles	difficulty	circles	squares	triangles	difficulty
1	6	4	2	4	4	3	3	2	3	6	1	2	4	3	3	1
2		3		5	4	3	3	5	3	5	1	3	4	3	3	3
3	5	4	2	4	4	3	3	3	3	6	1	1	4	3	3	1
4	3	5	2	5	3	4	3	4	3	6	1	2	4	3	3	3
5			2	5	4	3	3	4	3	5	1	2	4	3	3	2
6	3	5	2	5	4	3	3	3	3	6	1	1	4	3	3	1
7				5	4	3	3	4	3	6	1	1	4	3	3	1
8	3	5	2	4	4	3	3	3	3	5	3	2	4	3	3	1
9	3	4	3	5	3	4	3	4	3	6	1	1	3	4	3	2
10	4	3	2	4	4	3	3	3	3	6	1	1	4	3	3	2
11	4	4	2	4	4	3	3	2	3	6	1	2	4	3	3	2
12		2	2	5	4	3	3	4	3	5	1	2	4	3	3	2
13				5	4	4	3	1	3	6	1	1	4	3	3	1
14	2	4	2	4	3	2	2	3	3	6	1	1	4	3	3	1
15				5	4	3	3	4	3	6	1	4	4	3	3	2
16				5				5	3	6	1	4	4	3	3	3
17	4	4	2	4	4	3	3	2	6	3	1	1	4	3	3	1
18	4		5	5	4	3	3	4	3	6	1	4	4	3	3	3
19				5	4	3	3	3	3	6	1	3	4	3	3	2
20	4	4		5	4	4	3	2	3	6	1	1	4	3	3	1
21	3	5	2	5	4	3	3	3	3	6	1	2	4	3	3	1
22				5	5	2	3	3	3	6	1	4	4	3	3	3
23				5	2	3	3	3	2	3	1	3	4	3	3	1
24				5				5			10	5	2	5	3	5
25		4		4	4	3	3	2	3	6	1	2	4	3	3	2
26	6	2	2	4	4	1	3	3	3	6	1	2	4	3	3	2
27				5	4	4	3	3	3	6	1	3	4	3	3	1
correct answer	3	5	2		4	3	3		3	6	1		4	3	3	
count	5	4	13		20	17	24		24	20	25	0	25	25	27	

Survey results

Task 2a, computer screen

	217 ppi									109 ppi								
	0.3 mm			0.4 mm			0.5 mm			0.6 mm			0.7 mm			0.8 mm		
ID	a	b	c	a	b	c	a	b	c	a	b	c	a	b	c	a	b	c
1	a	b	a	a	b	c	a	b	c	a	b	c	a	b	c	a	b	c
2		b	c	a	b	c	a	b	c	a	b	c	a	b	c	a	b	c
3	a	b	c	a	b	a	a	b	c	a	b	a	a	b	c	a	b	c
4	a	b	c	a	b	c	a	b	c	a	b	c	a	b	c	a	b	c
5		b			b	c	a	b	c	a	b	c	a	b	c	a	b	c
6	a	b	c	a	b	c	a	b	c	a	b	c	a	b	c	a	b	c
7		b	c	a	b	c	a	b	c	a	b	c	a	b	c	a	b	c
8		b	c	a	b	c	a	b	c	a	b	c	a	b	c	a	b	c
9	b	b	a	a	b	c	a	b	c	a	b	c	a	b	c	a	b	c
10	b	b		a	b	c	c	b	c	a	b	c	c	b	c	a	b	c
11				a	b	c	a	b	c	a	b	c	a	b	c	a	b	c
12		b			b		a	b	c	a	b	c	a	b	c	a	b	c
13			c	c	b	c	a	b	c	a	b	c	a	b	c	a	b	c
14	a	b	c	a	b	c	a	b	c	a	b	c	a	b	c	a	b	c
15	b	b	c	b	b	b	a	b	c	a	b	c	a	b	c	a	b	c
16				a		c		b	c		b		a	b	c	a	b	c
17		b	c		b	c		b	c	a	b		a	b		a	b	c
18		b		a	b	c	a		c	a	b	c	a	b	c	a	b	c
19				a	b		a	b	c	a	b	c	a	b	c	a	b	c
20	a	b	a	a	b	c	a	b	c	a	b	a	a	b	c	a	b	c
21	a	b	a	a	b	c	a	b	c	a	b	a	a	b	c	a	b	c
22	c	b	c	a	b	c	c	b	c	a	b	c	a	b	c	a	b	c
23		b			b			b	c		b		c	b	c	c	b	c
24	a		b	a	b	a	a	b	a	a	b	a	b	b	a	a	b	c
25				b	b	c	c	b	a	b	b	a	a	b	a	a	b	c
26				a	a	c	b	b	a	a	b	c	a	b	c	a	b	c
27	b	b		b	b	a	a	b	c	a	b	c	a	b	c	a	b	c
correct answer	a	b	c	a	b	c	a	b	c	a	b	c	a	b	c	a	b	c
count	8	20	11	19	25	20	20	26	24	24	27	19	24	27	24	26	27	27

answers a, b, and c refer to line symbols with roud, square, and triangular cap

Survey results

Task 2a, phone screen

	202 ppi									403 pppi									806 ppi								
	0.4 mm			0.5 mm			0.6 mm			0.2 mm			0.3 mm			0.4 mm			0.2 mm			0.3 mm			0.4 mm		
ID	a	b	c	a	b	c	a	b	c	a	b	c	a	b	c	a	b	c	a	b	c	a	b	c	a	b	c
1	a	b	c	a	b	c	a	b	c	a	b	c	a	b	c	a	b	c	a	b	c	a	b	c	a	b	c
2	a	b	c	a	b	c	a	b	c	b	b	a	a	b	c	a	b	c		b	a		b	c	a	b	c
3	a	b	c	a	b	c	a	b	c	b	b	b	a	b	c	a	b	c	b	b	b	a	b	c	a	b	c
4	a	b	c	a	b	c	a	b	c	a	b	c	a	b	c	a	b	c	a	b	c	a	b	c	a	b	c
5	c	b	a	a	b	c	a	b	c		b		a	b	c	a	b	a		b	c	a	b	a	a	b	c
6	a	b	c	a	b	c	a	b	c	a	b	c	a	b	c	a	b	c		b	c	a	b	c	a	b	c
7	a	b	c	a	b	c	a	b	c	a	b	c	a	b	c	a	b	c	a	b		a	b	c	a	b	c
8	a	b	c	a	b	c	a	b	c		b	c	a	b	c	a	b	c		b	c	a	b	c	a	b	c
9	a	b	c	a	b	c	a	b	c	b	b	a	a	b	c	a	b	c	a	b	c	a	b	c	a	b	c
10	a	b	c	c	b	c	a	b	c	c	b	a	c	b	c	c	b	c	b	b	b	c	b	c	a	b	c
11	a	b	c	a	b	c	a	b	c		b		a	b	c	a	b	c	a	b	c	a	b	c	a	b	c
12	a	b	c	a	b	c	a	b	c		b		a	b	c	a	b	c	b	b	a	a	b	c	a	b	c
13	a	b	c	a	b	c	a	b	c			a	a	b	c	a	b	c		b	c	a	b	c	a	b	c
14	a	b	c	a	b	c	a	b	c	a	b	a	a	b	c	a	b	c	a	b	c	a	b	c	a	b	c
15	a	b	c	a	b	c	a	b	c	a	b	c	a	b	c	a	b	c	a	b	c	a	b	c	a	b	c
16		b		a	b	c	a	b	c				c	b	c	a	b		b			c	b		a	b	c
17	a	b	c	a	b	c	a	b	c	a	b		a	b	c	a	b	c		b	c	a	b	c	a	b	c
18	a	b	c	a	b	c	a	b	c	a	b	c	a	b	c	a	b	c		b	c	a	b	c	a	b	c
19	a	b	c	a	b	c	a	b	c	a	b	a	a	b	c	a	b	c	b	b	c	a	b	c	a	b	c
20	a	b	c	a	b	c	a	b	c	a	b	a	a	b	c	a	b	c	a	b	c	a	b	c	a	b	c
21	a	b	c	a	b	c	a	b	c	a	b	a	a	b	c	a	b	c	a	b	c	a	b	c	a	b	c
22	a	b	c	a	b	c	a	b	c	a	b	c	c	b	c	c	b	c	a	b	c	c	b	c	a	b	c
23				a	b	c	a	b	c		b	c	c	b	c	c	b	c		b			b	c	c	b	c
24	b		a	a	b	c	b	b	c		b		a		a	b	a	a	c							b	c
25	a	b	c	a	b	c	a	b	c	b	b	c	a	b	c	a	b	c	a	b	c	c	b	c	a	b	c
26	a	b	c	a	b	c	a	b	c		b	a	a	b	c	a	b	c	a		c	a	b	c	a	b	c
27	a	b	c	a	b	c	a	b	c	b	b	b	a	b	c	a	b	c	b	b	b	a	b	c	a	b	c
correct answer	a	b	c	a	b	c	a	b	c	a	b	c	a	b	c	a	b	c	a	b	c	a	b	c	a	b	c
count	23	25	23	26	27	27	26	27	27	12	25	10	23	26	26	23	26	24	12	24	18	20	26	24	25	27	27

answers a, b, and c refer to line symbols with roud, square, and triangular cap

Survey results

Task 2b, computer screen

	217 ppi									109 ppi								
	0.3 mm			0.4 mm			0.5 mm			0.6 mm			0.7 mm			0.8 mm		
ID	a	b	c	a	b	c	a	b	c	a	b	c	a	b	c	a	b	c
1	a	b	a	a	b	c	c	b	c	a	b	c	a	b	c	a	b	c
2		b	c	c	b	c	a	b	c	a	b	c	a	b	c	a	b	c
3	c	b	c	a	b	c	a	b	c	a	b	c	a	b	c	a	b	c
4	a	b	c	a	b	c	a	b	c	a	b	c	a	b	c	a	b	c
5	b	b			b	c	a	b	c	a	b	c	a	b	c	a	b	c
6	a	b	c	a	b	c	a	b	c	a	b	c	a	b	c	a	b	c
7	a	b	c	a	b	c	a	b	c	a	b	c	a	b	c	a	b	c
8		b	c		b	c	a	b	c	a	b	c	a	b	c	a	b	c
9	b	b			b	c	a	b	c	a	b	c	a	b	c	a	b	c
10		b		a	b	c	c	b	c	a	b	c	a	b	c	a	b	c
11	b	b		a	b	c	a	b	c	a	b	c	a	b	c	a	b	c
12					b	a	a	b	c	a	b	a	a	b	a	a	b	c
13	a	b	c	a	b		a	b	c	a	b	a	a	b	c	a	b	c
14	a	b	c	a	b	c	a	b	c	a	b	c	a	b	c	a	b	c
15	b	b	b	b	b	c	a	b	c	a	b	a	a	b	a	a	b	c
16		b			b			b	c	a	b			b	c	a	b	c
17		b	c		b	c	a	b	c	a	b		a	b	c	a	b	c
18		b	c	a	b	c	a	b	c	a	b	c	a	b	c	a	b	c
19						c	a	b	c	a	b	a	a	b	a	a	b	c
20	b	b	a	a	b	c	c	b	c	a	b	c	a	b	c	a	b	c
21	a	b	c	a	b	c	a	b	c	a	b	c	a	b	c	a	b	c
22		b	c	a	b	c	a	b	c	a	b	c	a	b	c	a	b	c
23	b	b	b		b	c	a	b	c	a	b	c	c	b	c	a	b	c
24					a		b	c	c	b	b	a	b	b	a	b	b	a
25	b				b	a		b	c	b	b	a	a	b	c	a	b	c
26	a			a	b	b	a	a	a	a	b	c	a	b	a	a	b	c
27	b	b	a		b	a	a	b	c	a	b	c	a	b	c	a	b	c
correct answer	a	b	c	a	b	c	a	b	c	a	b	c	a	b	c	a	b	c
count	8	22	12	14	25	20	21	25	26	25	27	19	24	27	22	26	27	26

answers a, b, and c refer to line symbols with roud, square, and triangular cap

Survey results

Task 2b, phone screen

	202 ppi									403 pppi									806 ppi								
	0.4 mm			0.5 mm			0.6 mm			0.2 mm			0.3 mm			0.4 mm			0.2 mm			0.3 mm			0.4 mm		
ID	a	b	c	a	b	c	a	b	c	a	b	c	a	b	c	a	b	c	a	b	c	a	b	c	a	b	c
1	a	b	c	a	b	c	a	b	c	a	b	c	a	b	c	a	b	c	a	b	c	a	b	c	a	b	c
2	a	b	c	a	b	c	a	b	c		b		a	b	c	a	b	c	a	b	c	a	b	c	a	b	c
3	a	b	c	a	b	c	a	b	c	b	b	c	a	b	c	a	b	c	b	b	a	a	b	c	a	b	c
4	a	b	c	a	b	c	a	b	c	a	b	c	a	b	c	a	b	c	a	b	c	a	b	c	a	b	c
5	a	b	a	a	b	c	a	b	c	b	b	c	a	b	a	a	b	c	b	b	a	a	b	a	a	b	c
6	a	b	c	a	b	c	a	b	c	a	b	c	a	b	c	a	b	c	a	b		a	b	c	a	b	c
7	a	b	c	a	b	c	a	b	c	a	b	c	a	b	c	a	b	c	b	b	a	a	b	c	a	b	c
8	a	b	c	a	b	c	a	b	c	a	b	c	a	b	c	a	b	c	a	b	c	a	b	c	a	b	c
9	a	b	c	a	b	c	a	b	c	a	b	c	a	b	c	a	b	c	b	b	a	a	b	c	a	b	c
10	a	b	c	c	b	c	a	b	c	c	b	c	a	b	c	a	b	c	a	b	a	a	b	c	a	b	c
11	a	b	c	a	b	c	a	b	c	a	b	c	a	b	c	a	b	c	a	b	c	a	b	c	a	b	c
12	a	b	c	a	b	c	a	b	c	a	b	c	a	b	c	a	b	c		b	a	a	b	c	a	b	c
13	a	b	c	a	b	c	a	b	c	a	b	c	a	b	c	a	b	c	c	b	c	a	b	c	a	b	c
14	a	b	c	a	b	c	a	b	c	a	b	c	a	b	c	a	b	c	a	b	c	a	b	c	a	b	c
15	a	b	c	a	b	c	a	b	c	a	b		a	b	c	a	b	c	b	b	c	a	b	c	a	b	c
16		b		a	b	c	a	b	c					b		a	b	c	b				b			b	c
17	a	b	c	a	b	c	a	b	c	a	b	c	a	b	c	a	b	c	a	b	a	a	b	c	a	b	c
18	a	b	c	a	b	c	a	b	c	a	b	c	a	b	c	a	b	c	a	b		a	b	c	a	b	c
19	a	b	c	a	b	c	a	b	c	a	b	c	a	b	c	a	b	c	a	b	c	a	b	c	a	b	c
20	a	b	c	a	b	c	a	b	c	a	b	c	a	b	c	a	b	c	a	b	c	a	b	c	a	b	c
21	a	b	c	a	b	c	a	b	c	a	b	a	a	b	c	a	b	c	a	b	c	a	b	c	a	b	c
22	a	b	c	a	b	c	a	b	c	c	b	c	a	b	c	c	b	c	c	b	c	c	b	c	a	b	c
23	a	b		a	b	c	a	b	c	b	b	b	c	b	c	a	b	c	b	b			b	c	a	b	c
24	a	a	a	a	b	c	b	b	a				b			b	a	a					b	b		b	c
25	a	b	c	a	b	c	a	b	c	a	b	c	a	b	c	a	b	c	a	b	a	a	b	c	a	b	c
26	a	b	a	a	b	c	a	b	c	a	b	a	a	b	c	a	b	c	b	b	c	a	b	c	a	b	c
27	a	b	c	a	b	c	a	b	c	b	b	a	a	b	c	a	b	c	b	b	b	a	b	c	b	b	c
correct answer	a	b	c	a	b	c	a	b	c	a	b	c	a	b	c	a	b	c	a	b	c	a	b	c	a	b	c
count	26	26	22	26	27	27	26	27	26	18	25	19	24	26	24	25	26	26	14	25	13	23	27	24	24	27	27

answers a, b, and c refer to line symbols with roud, square, and triangular cap

Survey results

Task 3, computer screen

	217 ppi																													
	0.6 mm															0.8 mm														
	a					b					c					a					b					c				
	a	b	c	c	right	b	c	a	a	right	c	a	a	b	right	b	a	a	a	right	b	c	c	a	right	c	c	a	a	right
1	Yes	No	No	No	1	Yes	No	No	No	1	Yes	No	No	No	1	No	Yes	Yes	Yes	1	Yes	No	No	No	1	Yes	Yes	No	No	1
2	Yes	No	No	No	1	Yes	No	No	No	1	Yes	Yes	No	No	0	No	Yes	Yes	Yes	1	Yes	No	No	No	1	Yes	Yes	No	No	1
3	Yes	No	No	No	1	Yes	No	No	No	1	Yes	No	No	No	1	No	Yes	Yes	Yes	1	Yes	No	No	No	1	Yes	Yes	No	No	1
4	Yes	No	No	No	1	Yes	No	No	No	1	Yes	No	No	No	1	No	Yes	Yes	Yes	1	Yes	No	No	No	1	Yes	Yes	No	No	1
5	Yes	No	No	No	1	Yes	No	No	No	1	Yes	No	No	No	1	No	Yes	No	Yes	0	Yes	No	No	No	1	Yes	Yes	No	No	1
6	Yes	No	No	No	1	Yes	No	No	No	1	Yes	No	No	No	1	No	Yes	Yes	Yes	1	Yes	No	No	No	1	Yes	Yes	No	No	1
7	Yes	No	No	No	1	Yes	No	No	No	1	Yes	No	No	No	1	No	Yes	Yes	Yes	1	Yes	No	No	No	1	Yes	Yes	No	No	1
8	Yes	No	No	No	1	Yes	No	No	No	1	Yes	No	No	No	1	No	Yes	Yes	Yes	1	Yes	No	No	No	1	Yes	Yes	No	No	1
9	Yes	No	No	No	1	Yes	No	No	No	1	Yes	No	No	No	1	No	Yes	Yes	Yes	1	Yes	No	No	No	1	Yes	Yes	No	No	1
10	Yes	No	No	Yes	0	Yes	No	No	No	1	Yes	No	No	No	1	No	Yes	Yes	Yes	1	Yes	No	No	No	1	Yes	Yes	No	No	1
11	Yes	No	No	No	1	Yes	No	No	No	1	Yes	No	No	No	1	No	Yes	Yes	Yes	1	Yes	No	No	No	1	Yes	Yes	No	No	1
12	Yes	No	No	No	1	Yes	No	No	No	1	Yes	No	No	No	1	No	Yes	Yes	Yes	1	Yes	No	No	No	1	Yes	Yes	No	No	1
13	Yes	No	No	No	1	Yes	No	No	No	1	Yes	No	No	No	1	No	Yes	Yes	Yes	1	Yes	No	No	No	1	Yes	Yes	No	No	1
14	Yes	No	No	No	1	Yes	No	No	No	1	Yes	No	No	No	1	No	Yes	Yes	Yes	1	Yes	No	No	No	1	Yes	Yes	No	No	1
15	Yes	No	No	No	1	Yes	No	Yes	No	0	Yes	Yes	No	No	0	No	Yes	Yes	Yes	1	Yes	No	No	Yes	0	Yes	Yes	No	No	1
16	Yes	No	No	No	1	Yes	No	No	No	1	Yes	No	No	No	1	No	Yes	Yes	Yes	1	Yes	No	No	No	1	Yes	Yes	No	No	1
17	Yes	No	No	No	1	Yes	No	No	No	1	Yes	No	No	No	1	No	Yes	Yes	Yes	1	Yes	No	No	No	1	Yes	Yes	No	No	1
18	Yes	No	No	No	1	Yes	No	No	No	1	Yes	No	No	No	1	No	Yes	Yes	Yes	1	Yes	No	No	No	1	Yes	Yes	No	No	1
19	Yes	No	No	No	1	Yes	No	No	No	1	No	Yes	Yes	No	0	No	Yes	Yes	Yes	1	Yes	No	No	No	1	No	No	Yes	Yes	0
20	Yes	No	No	No	1	Yes	No	No	No	1	Yes	No	No	No	1	No	Yes	No	Yes	0	Yes	No	No	No	1	Yes	Yes	No	No	1
21	Yes	No	No	No	1	Yes	No	No	No	1	Yes	No	No	No	1	No	Yes	Yes	Yes	1	Yes	No	No	No	1	Yes	Yes	No	No	1
22	Yes	No	No	No	1	Yes	No	No	No	1	Yes	No	No	No	1	No	Yes	Yes	Yes	1	Yes	No	No	No	1	Yes	Yes	No	No	1
23	No	No	No	No	0	Yes	No	No	No	1	Yes	No	No	No	1	No	Yes	No	No	0	Yes	No	No	No	1	Yes	Yes	No	No	1
24	Yes	No	No	Yes	0	No	Yes	Yes	Yes	0	Yes	Yes	No	Yes	0	No	Yes	No	No	0	Yes	No	Yes	Yes	0	Yes	Yes	No	Yes	0
25	Yes	No	No	No	1	Yes	No	No	No	1	Yes	No	No	No	1	No	Yes	Yes	Yes	1	Yes	No	No	No	1	No	No	Yes	Yes	0
26	Yes	No	No	No	1	Yes	No	No	Yes	0	Yes	No	Yes	No	0	No	Yes	Yes	Yes	1	Yes	No	No	No	1	Yes	Yes	No	No	1
27	Yes	No	No	No	1	Yes	No	No	No	1	Yes	No	Yes	No	0	No	Yes	Yes	No	0	Yes	No	No	No	1	Yes	Yes	No	No	1
correct answer	Yes	No	No	No		Yes	No	No	No		Yes	No	No	No		No	Yes	Yes	Yes		Yes	No	No	No		Yes	Yes	No	No	
count					24					24					21					22					25					24

	217 ppi															109 ppi														
	1.0 mm															0.6 mm														
	a					b					c					a					b					c				
	c	a	b	a	right	b	a	b	b	right	b	c	c	a	right	a	b	b	a	right	c	b	a	a	right	c	a	a	b	right
1	No	Yes	No	Yes	1	Yes	No	Yes	Yes	1	No	Yes	Yes	No	1	Yes	No	No	Yes	1	No	Yes	No	No	1	Yes	No	No	No	1
2	No	Yes	No	Yes	1	Yes	No	Yes	Yes	1	No	Yes	Yes	No	1	Yes	No	No	Yes	1	No	Yes	No	No	1	Yes	No	No	No	1
3	No	Yes	No	Yes	1	Yes	No	Yes	Yes	1	No	Yes	Yes	No	1	No	No	No	No	0	No	Yes	No	No	1	Yes	No	No	No	1
4	No	Yes	No	Yes	1	Yes	No	Yes	Yes	1	No	Yes	Yes	No	1	Yes	No	No	Yes	1	No	Yes	No	No	1	Yes	No	No	No	1
5	No	Yes	No	Yes	1	Yes	No	Yes	No	0	No	Yes	Yes	No	1	No	No	No	Yes	0	No	Yes	No	No	1	Yes	No	No	No	1
6	No	Yes	No	Yes	1	Yes	No	Yes	Yes	1	No	Yes	Yes	No	1	Yes	No	No	Yes	1	No	Yes	No	No	1	Yes	No	No	No	1
7	No	Yes	No	Yes	1	Yes	No	Yes	Yes	1	No	Yes	Yes	No	1	Yes	No	No	Yes	1	No	Yes	No	No	1	Yes	No	No	No	1
8	No	Yes	No	Yes	1	Yes	No	Yes	Yes	1	No	Yes	Yes	No	1	Yes	No	No	Yes	1	No	Yes	No	No	1	Yes	No	No	No	1
9	No	Yes	No	Yes	1	Yes	No	Yes	Yes	1	No	Yes	Yes	No	1	Yes	No	No	Yes	1	No	Yes	No	No	1	Yes	No	No	No	1
10	No	Yes	No	Yes	1	Yes	No	Yes	Yes	1	No	Yes	Yes	No	1	No	No	No	Yes	0	No	Yes	No	No	1	Yes	No	No	No	1
11	No	Yes	No	Yes	1	Yes	No	Yes	Yes	1	No	Yes	Yes	No	1	Yes	No	No	Yes	1	No	Yes	No	No	1	Yes	No	No	No	1
12	No	Yes	No	Yes	1	Yes	No	Yes	Yes	1	No	Yes	Yes	No	1	Yes	No	No	No	0	No	Yes	No	No	1	Yes	No	No	No	1
13	No	Yes	No	Yes	1	Yes	No	Yes	Yes	1	No	Yes	Yes	No	1	Yes	No	No	Yes	1	No	Yes	No	No	1	Yes	No	No	No	1
14	No	Yes	No	Yes	1	Yes	No	Yes	Yes	1	No	Yes	Yes	No	1	Yes	No	No	Yes	1	No	Yes	No	No	1	Yes	No	No	No	1
15	No	Yes	No	Yes	1	Yes	No	Yes	Yes	1	No	Yes	Yes	No	1	No	No	No	No	0	No	Yes	Yes	No	0	Yes	No	No	No	1
16	No	Yes	No	Yes	1	Yes	No	Yes	Yes	1	No	Yes	Yes	No	1	Yes	No	No	No	0	No	Yes	No	No	1	Yes	No	No	No	1
17	No	Yes	No	Yes	1	Yes	No	Yes	Yes	1	No	Yes	Yes	No	1	Yes	No	No	Yes	1	No	Yes	No	No	1	Yes	No	No	No	1
18	No	Yes	No	Yes	1	Yes	No	Yes	Yes	1	No	Yes	Yes	No	1	Yes	No	No	Yes	1	No	Yes	No	No	1	Yes	No	No	No	1
19	No	Yes	No	Yes	1	Yes	No	Yes	Yes	1	No	Yes	Yes	No	1	Yes	No	No	Yes	1	No	Yes	No	No	1	Yes	No	No	No	1
20	No	Yes	No	Yes	1	Yes	No	Yes	Yes	1	No	Yes	Yes	No	1	Yes	No	No	Yes	1	No	Yes	No	No	1	Yes	No	No	No	1
21	No	Yes	No	Yes	1	Yes	No	Yes	Yes	1	No	Yes	Yes	No	1	Yes	No	No	Yes	1	No	Yes	No	No	1	Yes	No	No	No	1
22	No	Yes	No	Yes	1	Yes	No	Yes	Yes	1	No	Yes	Yes	No	1	Yes	No	No	Yes	1	No	Yes	No	No	1	Yes	No	No	No	1
23	No	Yes	No	Yes	1	Yes	No	Yes	Yes	1	No	Yes	Yes	No	1	No	No	No	No	0	No	Yes	No	No	1	No	No	No	No	0
24	Yes	No	No	No	0	Yes	Yes	Yes	Yes	0	No	Yes	Yes	Yes	0	Yes	No	No	No	0	Yes	No	No	Yes	0	No	No	No	Yes	0
25	No	Yes	No	Yes	1	Yes	No	Yes	Yes	1	No	Yes	Yes	No	1	Yes	No	No	No	0	No	Yes	No	No	1	No	No	Yes	No	0
26	No	Yes	No	Yes	1	Yes	No	Yes	Yes	1	No	Yes	Yes	No	1	Yes	No	No	Yes	1	No	Yes	No	No	1	No	No	Yes	No	0
27	No	Yes	No	Yes	1	Yes	No	Yes	Yes	1	No	Yes	Yes	No	1	No	No	No	No	0	No	Yes	No	No	1	Yes	No	No	No	1
correct answer	No	Yes	No	Yes		Yes	No	Yes	Yes		No	Yes	Yes	No		Yes	No	No	Yes		No	Yes	No	No		Yes	No	No	No	
count					26					25					26					17					25					23

Survey results - Task 3, computer screen

	109 ppi																													
	0.8 mm															1.0 mm														
	a					b					c					a					b					c				
	c	a	b	a	c	b	a	c	a	right	b	a	c	c	right	c	a	a	a	right	a	c	b	b	right	b	c	a	c	right
1	No	Yes	No	Yes	1	Yes	No	No	No	1	No	No	Yes	Yes	1	No	Yes	Yes	Yes	1	No	No	Yes	Yes	1	No	Yes	No	Yes	1
2	No	Yes	No	Yes	1	Yes	No	No	No	1	No	No	Yes	Yes	1	No	Yes	Yes	Yes	1	No	No	Yes	Yes	1	No	Yes	No	Yes	1
3	No	Yes	No	Yes	1	Yes	No	No	No	1	No	No	Yes	Yes	1	No	Yes	Yes	Yes	1	No	No	Yes	Yes	1	No	Yes	No	Yes	1
4	No	Yes	No	Yes	1	Yes	No	No	No	1	No	No	Yes	Yes	1	No	Yes	Yes	Yes	1	No	No	Yes	Yes	1	No	Yes	No	Yes	1
5	No	Yes	No	Yes	1	Yes	No	No	No	1	No	No	Yes	Yes	1	No	Yes	Yes	Yes	1	No	No	Yes	Yes	1	No	Yes	No	Yes	1
6	No	Yes	No	Yes	1	Yes	No	No	No	1	No	No	Yes	Yes	1	No	Yes	Yes	Yes	1	No	No	Yes	Yes	1	No	Yes	No	Yes	1
7	No	Yes	No	Yes	1	Yes	No	No	No	1	No	No	Yes	Yes	1	No	Yes	Yes	Yes	1	No	No	Yes	Yes	1	No	Yes	No	Yes	1
8	No	Yes	No	Yes	1	Yes	No	No	No	1	No	No	Yes	Yes	1	No	Yes	Yes	Yes	1	No	No	Yes	Yes	1	No	Yes	No	Yes	1
9	No	Yes	No	Yes	1	Yes	No	No	No	1	No	No	Yes	Yes	1	No	Yes	Yes	Yes	1	No	No	Yes	Yes	1	No	Yes	No	Yes	1
10	No	Yes	No	Yes	1	Yes	No	No	No	1	No	No	Yes	Yes	1	No	Yes	Yes	Yes	1	No	No	Yes	Yes	1	No	Yes	No	Yes	1
11	No	Yes	No	Yes	1	Yes	No	No	No	1	No	No	Yes	Yes	1	No	Yes	Yes	Yes	1	No	No	Yes	Yes	1	No	Yes	No	Yes	1
12	Yes	Yes	No	No	0	Yes	No	No	No	1	No	No	Yes	Yes	1	No	Yes	Yes	Yes	1	No	No	Yes	Yes	1	No	Yes	No	Yes	1
13	No	Yes	No	Yes	1	Yes	No	No	No	1	No	No	Yes	Yes	1	No	Yes	Yes	Yes	1	No	No	Yes	Yes	1	No	Yes	No	Yes	1
14	No	Yes	No	Yes	1	Yes	No	No	No	1	No	No	Yes	Yes	1	No	Yes	Yes	Yes	1	No	No	Yes	Yes	1	No	Yes	No	Yes	1
15	No	Yes	No	Yes	1	Yes	No	No	No	1	No	No	Yes	Yes	1	No	Yes	Yes	Yes	1	No	No	Yes	Yes	1	No	Yes	No	Yes	1
16	No	Yes	No	Yes	1	Yes	No	No	No	1	No	No	Yes	Yes	1	No	Yes	Yes	Yes	1	No	No	Yes	Yes	1	No	Yes	No	Yes	1
17	No	Yes	No	Yes	1	Yes	No	No	No	1	No	No	No	Yes	0	No	Yes	Yes	Yes	1	No	No	Yes	Yes	1	No	Yes	No	Yes	1
18	No	Yes	No	No	0	Yes	No	No	No	1	No	No	Yes	Yes	1	No	Yes	Yes	Yes	1	No	No	Yes	Yes	1	No	Yes	No	Yes	1
19	No	Yes	No	Yes	1	Yes	No	No	No	1	No	No	Yes	Yes	1	No	Yes	Yes	Yes	1	No	No	Yes	Yes	1	No	Yes	No	Yes	1
20	No	No	No	Yes	0	Yes	No	No	No	1	No	No	Yes	Yes	1	No	Yes	Yes	Yes	1	No	No	Yes	Yes	1	No	Yes	No	Yes	1
21	No	Yes	No	Yes	1	Yes	No	No	No	1	No	No	Yes	Yes	1	No	Yes	Yes	Yes	1	No	No	Yes	Yes	1	No	Yes	No	Yes	1
22	No	Yes	No	Yes	1	Yes	No	No	No	1	No	No	Yes	Yes	1	No	Yes	Yes	Yes	1	No	No	Yes	Yes	1	No	Yes	No	Yes	1
23	No	Yes	No	Yes	1	Yes	No	No	No	1	No	No	Yes	Yes	1	No	Yes	No	Yes	0	No	No	Yes	Yes	1	No	Yes	No	Yes	1
24	Yes	Yes	No	No	0	Yes	Yes	No	No	0	No	No	Yes	Yes	1	No	No	Yes	No	0	Yes	No	Yes	Yes	0	No	Yes	Yes	Yes	0
25	No	Yes	No	Yes	1	Yes	No	No	No	1	No	No	Yes	Yes	1	No	Yes	Yes	Yes	1	No	No	Yes	Yes	1	No	Yes	No	No	0
26	No	Yes	No	Yes	1	Yes	No	No	No	1	No	No	Yes	Yes	1	No	Yes	Yes	Yes	1	No	No	Yes	Yes	1	No	Yes	No	Yes	1
27	No	Yes	No	Yes	1	Yes	No	No	No	1	No	No	Yes	Yes	1	No	Yes	Yes	No	0	No	No	Yes	Yes	1	No	Yes	No	Yes	1
correct answer	No	Yes	No	Yes		Yes	No	No	No		No	No	Yes	Yes		No	Yes	Yes	Yes		No	No	Yes	Yes		No	Yes	No	Yes	
count					23					26					26					24					26					25

Survey results - Task 3, computer screen

Survey results

Task 3, phone screen

	202 ppi																													
	0.6 mm															0.8 mm														
	a					b					c					c					b					c				
	c	b	a	a	right	c	b	b	a	right	b	c	c	a	right	b	a	b	c	right	c	c	a	b	right	c	a	a	b	right
1	No	No	Yes	Yes	1	No	Yes	Yes	No	1	No	Yes	Yes	No	1	No	No	No	Yes	1	No	No	No	Yes	1	Yes	No	No	No	1
2	No	No	Yes	Yes	1	No	Yes	Yes	No	1	No	Yes	Yes	No	1	No	No	No	Yes	1	No	No	No	Yes	1	Yes	No	No	No	1
3	No	No	Yes	Yes	1	No	Yes	Yes	No	1	No	Yes	Yes	No	1	No	No	No	Yes	1	No	No	No	Yes	1	Yes	No	No	No	1
4	No	No	Yes	Yes	1	No	Yes	Yes	No	1	No	Yes	Yes	No	1	No	No	No	Yes	1	No	No	No	Yes	1	Yes	No	No	No	1
5	No	No	Yes	Yes	1	No	Yes	Yes	No	1	No	Yes	Yes	No	1	No	No	No	Yes	1	No	No	No	Yes	1	Yes	No	No	No	1
6	No	No	Yes	Yes	1	No	Yes	Yes	No	1	No	Yes	Yes	No	1	No	No	No	Yes	1	No	No	No	Yes	1	Yes	No	No	No	1
7	No	No	Yes	Yes	1	No	Yes	Yes	No	1	No	Yes	Yes	No	1	No	No	No	Yes	1	No	No	No	Yes	1	Yes	No	No	No	1
8	No	No	Yes	Yes	1	No	Yes	Yes	No	1	No	Yes	Yes	No	1	No	No	No	Yes	1	No	No	No	Yes	1	Yes	No	No	No	1
9	No	No	Yes	Yes	1	No	Yes	Yes	No	1	No	Yes	Yes	No	1	No	No	No	Yes	1	No	No	No	Yes	1	Yes	No	No	No	1
10	No	No	Yes	Yes	1	No	Yes	Yes	No	1	No	Yes	Yes	No	1	No	No	No	Yes	1	No	No	No	Yes	1	Yes	No	No	No	1
11	No	No	Yes	Yes	1	No	Yes	Yes	No	1	No	Yes	Yes	No	1	No	No	No	Yes	1	No	No	No	Yes	1	Yes	No	No	No	1
12	No	No	Yes	Yes	1	No	Yes	Yes	No	1	No	Yes	Yes	No	1	No	No	No	Yes	1	No	No	No	Yes	1	Yes	No	No	No	1
13	No	No	Yes	Yes	1	No	Yes	Yes	No	1	No	Yes	Yes	No	1	No	No	No	Yes	1	No	No	No	Yes	1	Yes	No	No	No	1
14	No	No	Yes	Yes	1	No	Yes	Yes	No	1	No	Yes	Yes	No	1	No	No	No	Yes	1	No	No	No	Yes	1	Yes	No	No	No	1
15	No	No	Yes	Yes	1	No	Yes	Yes	No	1	No	Yes	Yes	No	1	No	No	No	Yes	1	No	No	No	Yes	1	Yes	No	No	No	1
16	No	No	Yes	Yes	1	No	Yes	Yes	No	1	No	Yes	Yes	No	1	No	No	No	Yes	1	No	No	No	Yes	1	Yes	No	No	No	1
17	No	No	Yes	Yes	1	No	Yes	Yes	No	1	No	Yes	Yes	No	1	No	No	No	Yes	1	No	No	No	Yes	1	Yes	No	No	No	1
18	No	No	Yes	Yes	1	No	Yes	Yes	No	1	No	Yes	Yes	No	1	No	No	No	Yes	1	No	No	No	Yes	1	Yes	No	No	No	1
19	No	No	Yes	Yes	1	No	Yes	Yes	No	1	No	Yes	Yes	No	1	No	No	No	Yes	1	No	No	No	Yes	1	Yes	No	No	No	1
20	No	No	Yes	Yes	1	No	Yes	Yes	No	1	No	Yes	Yes	No	1	No	No	No	Yes	1	No	No	No	Yes	1	Yes	No	No	No	1
21	No	No	Yes	Yes	1	No	Yes	Yes	No	1	No	Yes	Yes	No	1	No	No	No	Yes	1	No	No	No	Yes	1	Yes	No	No	No	1
22	No	No	Yes	Yes	1	No	Yes	Yes	No	1	No	Yes	Yes	Yes	0	No	No	No	Yes	1	No	No	No	Yes	1	Yes	No	No	No	1
23	No	No	Yes	Yes	1	No	Yes	Yes	No	1	No	No	Yes	No	0	No	No	No	Yes	1	No	No	No	Yes	1	Yes	No	No	No	1
24	Yes	No	No	Yes	0	Yes	Yes	No	No	0	No	Yes	Yes	No	1	No	No	No	Yes	1	No	No	No	Yes	1	Yes	No	No	No	1
25	No	No	Yes	Yes	1	No	Yes	Yes	No	1	No	Yes	Yes	No	1	No	No	No	Yes	1	No	No	No	Yes	1	Yes	No	No	No	1
26	No	No	Yes	Yes	1	No	Yes	Yes	No	1	No	Yes	Yes	No	1	No	No	No	Yes	1	No	No	No	Yes	1	Yes	No	No	No	1
27	No	No	Yes	Yes	1	No	Yes	Yes	No	1	No	Yes	Yes	No	1	No	No	No	Yes	1	No	No	No	Yes	1	Yes	No	No	No	1
correct	No	No	Yes	Yes		No	Yes	Yes	No		No	Yes	Yes	No		No	No	No	Yes		No	No	No	Yes		Yes	No	No	No	
count					26					26					25					27					27					27

	202 ppi															403 ppi														
	1..0 mm															0.6 mm														
	a					b					c					a					b					c				
	b	c	c	a	right	b	a	b	b	right	a	c	c	c	right	c	a	c	b	right	c	b	b	b	right	a	b	c	c	right
1	No	No	No	Yes	1	Yes	No	Yes	Yes	1	No	Yes	Yes	Yes	1	No	Yes	No	No	1	No	Yes	Yes	Yes	1	No	No	Yes	Yes	1
2	No	No	No	Yes	1	Yes	No	Yes	Yes	1	No	Yes	Yes	Yes	1	No	Yes	No	No	1	No	Yes	Yes	Yes	1	No	No	Yes	Yes	1
3	No	No	No	Yes	1	Yes	No	Yes	Yes	1	No	Yes	Yes	Yes	1	No	Yes	No	No	1	No	Yes	Yes	Yes	1	No	No	Yes	Yes	1
4	No	No	No	Yes	1	Yes	No	Yes	Yes	1	No	Yes	Yes	Yes	1	No	Yes	No	No	1	No	Yes	Yes	Yes	1	No	No	Yes	Yes	1
5	No	No	No	Yes	1	Yes	No	Yes	Yes	1	No	Yes	Yes	Yes	1	No	No	No	Yes	0	No	Yes	Yes	Yes	1	No	No	Yes	Yes	1
6	No	No	No	Yes	1	Yes	No	Yes	Yes	1	No	Yes	Yes	Yes	1	No	Yes	No	No	1	No	Yes	Yes	Yes	1	No	No	Yes	Yes	1
7	No	No	No	Yes	1	Yes	No	Yes	Yes	1	No	Yes	Yes	Yes	1	No	Yes	No	No	1	No	Yes	Yes	Yes	1	No	No	Yes	Yes	1
8	No	No	No	Yes	1	Yes	No	Yes	Yes	1	No	Yes	Yes	Yes	1	No	Yes	No	No	1	No	Yes	Yes	Yes	1	No	No	Yes	Yes	1
9	No	No	No	Yes	1	Yes	No	Yes	Yes	1	No	Yes	Yes	Yes	1	No	Yes	No	No	1	No	Yes	Yes	Yes	1	No	No	Yes	Yes	1
10	No	No	No	Yes	1	Yes	No	Yes	Yes	1	No	Yes	Yes	Yes	1	No	Yes	No	No	1	No	Yes	Yes	Yes	1	No	No	Yes	Yes	1
11	No	No	No	Yes	1	Yes	No	Yes	Yes	1	No	Yes	Yes	Yes	1	No	Yes	No	No	1	No	Yes	Yes	Yes	1	No	No	Yes	Yes	1
12	No	No	No	Yes	1	Yes	No	Yes	Yes	1	No	Yes	Yes	Yes	1	No	Yes	No	No	1	No	Yes	Yes	Yes	1	No	No	Yes	Yes	1
13	No	No	No	Yes	1	Yes	No	Yes	Yes	1	No	Yes	Yes	Yes	1	No	Yes	No	No	1	No	Yes	Yes	Yes	1	No	No	Yes	Yes	1
14	No	No	No	Yes	1	Yes	No	Yes	Yes	1	No	Yes	Yes	Yes	1	No	No	Yes	No	0	No	Yes	Yes	Yes	1	No	No	Yes	Yes	1
15	No	No	No	Yes	1	Yes	No	Yes	Yes	1	No	Yes	Yes	Yes	1	No	Yes	No	No	1	Yes	Yes	Yes	Yes	0	No	No	Yes	Yes	1
16	No	No	No	Yes	1	Yes	No	Yes	Yes	1	No	Yes	Yes	Yes	1	No	Yes	No	No	1	No	Yes	Yes	Yes	1	No	No	Yes	Yes	1
17	No	No	No	Yes	1	Yes	No	Yes	Yes	1	No	Yes	Yes	Yes	1	No	Yes	No	No	1	No	Yes	Yes	Yes	1	No	No	Yes	Yes	1
18	No	No	No	Yes	1	Yes	No	Yes	Yes	1	No	Yes	Yes	Yes	1	No	Yes	No	No	1	No	Yes	Yes	Yes	1	No	No	Yes	Yes	1
19	No	No	No	Yes	1	Yes	No	Yes	Yes	1	No	Yes	Yes	Yes	1	No	Yes	No	No	1	No	Yes	Yes	Yes	1	No	No	Yes	Yes	1
20	No	No	No	Yes	1	Yes	No	Yes	Yes	1	No	Yes	Yes	Yes	1	No	Yes	No	No	1	No	Yes	Yes	Yes	1	No	No	Yes	Yes	1
21	No	No	No	Yes	1	Yes	No	Yes	Yes	1	No	Yes	Yes	Yes	1	No	Yes	No	No	1	No	Yes	Yes	Yes	1	No	No	Yes	Yes	1
22	No	No	No	Yes	1	Yes	No	Yes	Yes	1	No	Yes	Yes	Yes	1	No	Yes	No	No	1	No	Yes	Yes	Yes	1	No	No	Yes	Yes	1
23	No	No	No	Yes	1	Yes	No	Yes	Yes	1	No	Yes	Yes	Yes	1	No	Yes	No	No	1	No	Yes	Yes	Yes	1	No	No	Yes	Yes	1
24	No	Yes	No	No	0	Yes	No	Yes	Yes	1	No	Yes	Yes	No	0	No	No	Yes	No	0	No	Yes	No	Yes	0	No	No	Yes	Yes	1
25	No	No	No	No	0	Yes	No	Yes	Yes	1	No	Yes	Yes	Yes	1	No	Yes	No	No	1	No	Yes	Yes	Yes	1	No	No	Yes	Yes	1
26	No	No	No	Yes	1	Yes	No	Yes	Yes	1	No	Yes	Yes	Yes	1	No	Yes	No	No	1	No	Yes	Yes	Yes	1	No	No	Yes	Yes	1
27	No	No	No	Yes	1	Yes	No	Yes	Yes	1	No	Yes	Yes	Yes	1	No	Yes	No	No	1	No	Yes	Yes	Yes	1	No	No	Yes	Yes	1
correct	No	No	No	Yes		Yes	No	Yes	Yes		No	Yes	Yes	Yes		No	Yes	No	No		No	Yes	Yes	Yes		No	No	Yes	Yes	
count					25					27					26					24					25					27

Survey results - Task 3, phone screen

	403 ppi																													
	0.8 mm															1.0 mm														
	a					b					c					a					b					c				
	c	a	c	b	right	a	b	a	b	right	a	b	c	c	right	b	a	c	b	right	b	c	a	c	right	b	c	c	c	right
1	No	Yes	No	No	1	No	Yes	No	Yes	1	No	No	Yes	Yes	1	No	Yes	No	No	1	Yes	No	No	No	1	No	Yes	Yes	Yes	1
2	No	Yes	No	No	1	No	Yes	No	Yes	1	No	No	Yes	Yes	1	No	Yes	No	No	1	Yes	No	No	No	1	No	Yes	Yes	Yes	1
3	No	Yes	No	No	1	No	Yes	No	Yes	1	No	No	Yes	Yes	1	No	Yes	No	No	1	Yes	No	No	No	1	No	Yes	Yes	Yes	1
4	No	Yes	No	No	1	No	Yes	No	Yes	1	No	No	Yes	Yes	1	No	Yes	No	No	1	Yes	No	No	No	1	No	Yes	Yes	Yes	1
5	No	No	No	Yes	0	No	Yes	No	Yes	1	No	No	Yes	Yes	1	No	No	No	Yes	0	Yes	No	No	No	1	No	Yes	Yes	Yes	1
6	No	Yes	No	No	1	No	Yes	No	Yes	1	No	No	Yes	Yes	1	No	Yes	No	No	1	Yes	No	No	No	1	No	Yes	Yes	Yes	1
7	No	Yes	No	No	1	No	Yes	No	Yes	1	No	No	Yes	Yes	1	No	Yes	No	No	1	Yes	No	No	No	1	No	Yes	Yes	Yes	1
8	No	Yes	No	No	1	No	Yes	No	Yes	1	No	No	Yes	Yes	1	No	Yes	No	No	1	Yes	No	No	No	1	No	Yes	Yes	Yes	1
9	No	Yes	No	No	1	No	Yes	No	Yes	1	No	No	Yes	Yes	1	No	Yes	No	No	1	Yes	No	No	No	1	No	Yes	Yes	Yes	1
10	No	Yes	No	No	1	No	Yes	No	Yes	1	No	No	Yes	Yes	1	No	Yes	No	No	1	Yes	No	No	No	1	No	Yes	Yes	Yes	1
11	No	Yes	No	No	1	No	Yes	No	Yes	1	No	No	Yes	Yes	1	No	Yes	No	No	1	Yes	No	No	No	1	No	Yes	Yes	Yes	1
12	No	Yes	No	No	1	No	Yes	No	Yes	1	No	No	Yes	Yes	1	No	Yes	No	No	1	Yes	No	No	No	1	No	Yes	Yes	Yes	1
13	No	Yes	No	No	1	No	Yes	No	Yes	1	No	No	Yes	Yes	1	No	Yes	No	No	1	Yes	No	No	No	1	No	Yes	Yes	No	0
14	No	Yes	No	No	1	No	Yes	No	Yes	1	No	No	Yes	Yes	1	No	Yes	No	No	1	Yes	No	No	No	1	No	Yes	Yes	Yes	1
15	No	Yes	No	No	1	No	Yes	No	Yes	1	No	No	Yes	Yes	1	No	Yes	No	No	1	Yes	No	No	No	1	No	Yes	Yes	Yes	1
16	No	Yes	No	No	1	No	Yes	No	Yes	1	No	No	Yes	Yes	1	No	Yes	No	No	1	Yes	No	No	No	1	No	Yes	Yes	Yes	1
17	No	Yes	No	No	1	No	Yes	No	Yes	1	No	No	Yes	Yes	1	No	Yes	No	No	1	Yes	No	No	No	1	No	Yes	Yes	Yes	1
18	No	Yes	No	No	1	No	Yes	No	Yes	1	No	No	Yes	Yes	1	No	Yes	No	No	1	Yes	No	No	No	1	No	Yes	Yes	Yes	1
19	No	Yes	No	No	1	No	Yes	No	Yes	1	No	No	Yes	Yes	1	No	Yes	No	No	1	Yes	No	No	No	1	No	Yes	Yes	Yes	1
20	No	No	No	Yes	0	No	Yes	No	Yes	1	No	No	Yes	Yes	1	No	Yes	No	No	1	Yes	No	No	No	1	No	Yes	Yes	Yes	1
21	No	Yes	No	No	1	No	Yes	No	Yes	1	No	No	Yes	Yes	1	No	Yes	No	No	1	Yes	No	No	No	1	No	Yes	Yes	Yes	1
22	No	Yes	No	No	1	No	Yes	No	Yes	1	No	No	Yes	Yes	1	No	Yes	No	No	1	Yes	No	No	No	1	No	Yes	Yes	Yes	1
23	No	Yes	No	No	1	No	Yes	No	Yes	1	No	No	Yes	Yes	1	No	Yes	No	No	1	Yes	No	No	No	1	No	Yes	Yes	Yes	1
24	Yes	No	Yes	No	0	No	Yes	Yes	Yes	0	Yes	No	Yes	Yes	0	No	Yes	Yes	No	0	Yes	No	Yes	No	0	No	Yes	Yes	Yes	1
25	No	Yes	No	No	1	No	Yes	No	Yes	1	No	No	Yes	Yes	1	No	Yes	No	No	1	Yes	No	No	No	1	No	Yes	Yes	Yes	1
26	No	Yes	No	No	1	No	Yes	No	Yes	1	No	No	Yes	Yes	1	No	Yes	No	No	1	Yes	No	No	No	1	No	Yes	Yes	Yes	1
27	No	Yes	No	No	1	No	Yes	No	Yes	1	No	No	Yes	Yes	1	No	Yes	No	No	1	Yes	No	No	No	1	No	Yes	Yes	Yes	1
correct	No	Yes	No	No		No	Yes	No	Yes		No	No	Yes	Yes		No	Yes	No	No		Yes	No	No	No		No	Yes	Yes	Yes	
count					24					26					26					25					26					26

Survey results - Task 3, phone screen

	806 ppi																													
	0.6 mm															0.8 mm														
	a					b					c					a					b					c				
	c	b	b	a	right	c	a	b	c	right	a	a	c	c	right	c	a	a	a	right	c	a	b	b	right	a	c	b	c	right
1	No	No	No	Yes	1	No	No	Yes	No	1	No	No	Yes	Yes	1	No	Yes	Yes	Yes	1	No	No	Yes	Yes	1	No	Yes	No	Yes	1
2	No	No	No	Yes	1	No	No	Yes	No	1	No	No	Yes	Yes	1	No	Yes	No	Yes	0	No	No	Yes	Yes	1	No	Yes	Yes	No	0
3	No	No	No	Yes	1	No	No	Yes	No	1	No	No	Yes	Yes	1	No	Yes	Yes	Yes	1	No	No	Yes	Yes	1	No	Yes	No	Yes	1
4	No	No	No	Yes	1	No	No	Yes	No	1	No	No	Yes	Yes	1	No	Yes	Yes	Yes	1	No	No	Yes	Yes	1	No	Yes	No	Yes	1
5	No	No	No	Yes	1	No	No	Yes	No	1	No	No	Yes	Yes	1	No	Yes	Yes	Yes	1	No	No	Yes	Yes	1	No	Yes	No	Yes	1
6	No	No	No	Yes	1	No	No	Yes	No	1	No	No	Yes	Yes	1	No	Yes	Yes	Yes	1	No	No	Yes	Yes	1	No	Yes	No	Yes	1
7	No	No	No	Yes	1	No	No	Yes	No	1	No	No	Yes	Yes	1	No	Yes	Yes	Yes	1	No	No	Yes	Yes	1	No	Yes	No	Yes	1
8	No	No	No	Yes	1	No	No	Yes	No	1	No	No	Yes	Yes	1	No	Yes	Yes	Yes	1	No	No	Yes	Yes	1	No	Yes	No	Yes	1
9	No	No	No	Yes	1	No	No	Yes	No	1	No	No	Yes	Yes	1	No	Yes	Yes	Yes	1	No	No	Yes	Yes	1	No	Yes	No	Yes	1
10	No	No	No	Yes	1	No	No	Yes	No	1	No	No	Yes	Yes	1	No	Yes	Yes	Yes	1	No	No	Yes	Yes	1	No	Yes	No	Yes	1
11	No	No	No	Yes	1	No	No	Yes	No	1	No	No	Yes	Yes	1	No	Yes	Yes	Yes	1	No	No	Yes	Yes	1	No	Yes	No	Yes	1
12	No	No	No	Yes	1	No	No	Yes	No	1	No	No	Yes	Yes	1	No	Yes	Yes	Yes	1	No	No	Yes	Yes	1	No	Yes	No	Yes	1
13	No	No	No	Yes	1	No	No	Yes	No	1	No	No	Yes	Yes	1	No	Yes	Yes	No	0	No	No	Yes	Yes	1	No	Yes	No	Yes	1
14	No	No	No	Yes	1	No	No	Yes	No	1	No	No	Yes	Yes	1	No	Yes	Yes	Yes	1	No	No	Yes	Yes	1	No	Yes	No	Yes	1
15	No	No	No	Yes	1	No	No	Yes	No	1	No	No	Yes	Yes	1	No	Yes	Yes	Yes	1	No	No	Yes	Yes	1	No	Yes	No	Yes	1
16	No	No	No	Yes	1	No	No	Yes	No	1	No	No	Yes	Yes	1	No	Yes	Yes	Yes	1	No	No	Yes	Yes	1	No	Yes	No	Yes	1
17	No	No	No	Yes	1	No	No	Yes	No	1	No	No	Yes	Yes	1	No	Yes	Yes	Yes	1	No	No	Yes	Yes	1	No	Yes	No	Yes	1
18	No	No	No	Yes	1	No	No	Yes	No	1	No	No	Yes	Yes	1	No	Yes	Yes	Yes	1	No	No	Yes	Yes	1	No	Yes	No	Yes	1
19	No	No	No	Yes	1	No	No	Yes	No	1	No	No	Yes	Yes	1	No	Yes	Yes	Yes	1	No	No	Yes	Yes	1	No	Yes	No	Yes	1
20	No	No	No	Yes	1	No	No	Yes	No	1	No	No	Yes	Yes	1	No	Yes	Yes	Yes	1	No	No	Yes	Yes	1	No	Yes	No	Yes	1
21	No	No	No	Yes	1	No	No	Yes	No	1	No	No	Yes	Yes	1	No	Yes	Yes	Yes	1	No	No	Yes	Yes	1	No	Yes	No	Yes	1
22	No	No	No	Yes	1	No	No	Yes	No	1	No	No	Yes	Yes	1	No	Yes	Yes	Yes	1	No	No	Yes	Yes	1	No	Yes	No	Yes	1
23	No	No	No	Yes	1	No	No	Yes	No	1	No	No	Yes	Yes	1	No	Yes	Yes	Yes	1	No	No	Yes	Yes	1	No	Yes	No	Yes	1
24	Yes	No	Yes	No	0	No	Yes	No	Yes	0	Yes	No	No	Yes	0	Yes	No	No	Yes	0	No	Yes	Yes	Yes	0	No	Yes	No	Yes	1
25	No	No	No	Yes	1	No	No	Yes	No	1	No	No	Yes	Yes	1	No	Yes	Yes	Yes	1	No	No	Yes	Yes	1	No	Yes	No	Yes	1
26	No	No	No	Yes	1	No	No	Yes	No	1	No	No	Yes	Yes	1	No	Yes	Yes	Yes	1	No	No	Yes	Yes	1	No	Yes	No	Yes	1
27	No	No	No	Yes	1	No	No	Yes	No	1	Yes	No	Yes	Yes	0	No	Yes	Yes	Yes	1	No	No	Yes	Yes	1	No	Yes	No	Yes	1
correct	No	No	No	Yes		No	No	Yes	No		No	No	Yes	Yes		No	Yes	Yes	Yes		No	No	Yes	Yes		No	Yes	No	Yes	
count					26					26					25					24					26					26

Survey results - Task 3, phone screen

	806 ppi														
	1..0 mm														
	c					b					c				
	c	a	a	b	right	b	a	c	b	right	c	b	a	a	right
1	Yes	No	No	No	1	Yes	No	No	Yes	1	Yes	No	No	No	1
2	Yes	No	No	No	1	Yes	No	No	No	0	Yes	No	No	No	1
3	Yes	No	No	No	1	Yes	No	No	Yes	1	Yes	No	No	No	1
4	Yes	No	No	No	1	Yes	No	No	Yes	1	Yes	No	No	No	1
5	Yes	No	No	No	1	Yes	No	No	Yes	1	Yes	No	No	No	1
6	Yes	No	No	No	1	Yes	No	No	Yes	1	Yes	No	No	No	1
7	Yes	No	No	No	1	Yes	No	No	Yes	1	Yes	No	No	No	1
8	Yes	No	No	No	1	Yes	No	No	Yes	1	Yes	No	No	No	1
9	Yes	No	No	No	1	Yes	No	No	Yes	1	Yes	No	No	No	1
10	Yes	No	No	No	1	Yes	No	No	Yes	1	Yes	No	No	No	1
11	Yes	No	No	No	1	Yes	No	No	Yes	1	Yes	No	No	No	1
12	Yes	No	No	No	1	Yes	No	No	Yes	1	Yes	No	No	No	1
13	Yes	No	No	No	1	Yes	No	No	Yes	1	Yes	No	No	No	1
14	Yes	No	No	No	1	Yes	No	No	Yes	1	Yes	No	No	No	1
15	Yes	No	No	No	1	Yes	No	No	Yes	1	Yes	No	No	No	1
16	Yes	No	No	No	1	Yes	No	No	Yes	1	Yes	No	No	No	1
17	Yes	No	No	No	1	Yes	No	No	Yes	1	Yes	No	No	No	1
18	Yes	No	No	No	1	Yes	No	No	Yes	1	Yes	No	No	No	1
19	Yes	No	No	No	1	Yes	No	No	Yes	1	Yes	No	No	No	1
20	Yes	No	No	No	1	Yes	No	No	Yes	1	Yes	No	No	No	1
21	Yes	No	No	No	1	Yes	No	No	Yes	1	Yes	No	No	No	1
22	Yes	No	No	No	1	Yes	No	No	Yes	1	Yes	No	No	No	1
23	Yes	No	No	No	1	Yes	No	No	Yes	1	Yes	No	No	No	1
24	Yes	No	No	No	1	Yes	Yes	No	Yes	0	Yes	No	No	No	1
25	Yes	No	No	No	1	Yes	No	No	Yes	1	Yes	No	No	No	1
26	Yes	No	No	No	1	Yes	No	No	Yes	1	Yes	No	No	No	1
27	Yes	No	No	No	1	Yes	No	No	Yes	1	Yes	No	No	No	1
correct	Yes	No	No	No		Yes	No	No	Yes		Yes	No	No	No	
count					27					25					27

Survey results - Task 3, phone screen

Survey results

Task 3, time statistics

	Time in seconds				
	computer		phone		
	109 ppi	217 ppi	202 ppi	403 ppi	806 ppi
1	48.07	45.79	39.34	42.64	41.85
2	36.78	33.4	50.92	55.02	97.76
3	47.6	51.99	41.79	47.15	42.26
4	42.43	53.32	39.61	41.61	39.79
5	35.78	37.71	38.54	40.7	47.73
6	49.09	43.93	50.43	57.24	53.01
7	40.31	44.33	43.81	44.01	43.21
8	44.91	38.66	48.32	48.69	54.21
9	60.56	51.13	57.96	59.29	52.52
10	43.89	42.6	49.83	53.31	53.76
11	45.45	46.48	37.1	39.75	51.04
12	64.85	46.79	42.58	44.01	41.36
13	58.06	56.97	44.32	37.87	45.03
14	35.96	36.35	44.74	38.58	42.42
15	51.96	54.46	45.69	41.63	39.64
16	59.59	60.7	66.46	60.21	68.49
17	58.63	61.55	42.19	41.5	45.25
18	31.49	47.99	41.06	45.77	50.37
19	59.2	71.51	55.45	53.36	54.33
20	37.24	44.27	40.88	41.95	43.87
21	69.01	63.9	63.39	69.98	63.41
22	52.78	57.44	51.47	50.99	58.28
23	143.02	123.29	126.15	115.61	86.23
24	85.18	83.75	106.94	109.29	105.03
25	59.21	65.91	54.51	51.28	54.23
26	75.93	67.56	42.24	41.7	44.92
27	59.08	43.16	41.94	41.61	55.06
Minimum	31.5	33.4	37.1	37.87	39.64
Maximum	143.0	123.3	126.2	115.6	105.0
Average	55.4	54.6	52.1	52.4	54.6