Influence of Pixel Density on the Image Quality of Smartphone Displays

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Abstract

We investigated the influence of pixel density on the image quality of the characters displayed on smartphone screens. The image quality of characters increased steadily as the pixel density increased up to around 700 pixels per inch (ppi), and the perception of jagged edges for aliased artifacts was not saturated at 800 ppi.

Author Keywords

Smartphone display; Pixel density; Image quality; Visual acuity; Resolution

1. Introduction

The pixel density of smartphone screens has been increasing every year. As of February 2015, commercially available smartphone displays have reached up to 564 pixels per inch (ppi). The requirements of pixel density for displays have been determined by user's visual acuity and viewing distance.

However, it is difficult to assume a certain display viewing distance. In addition, some visual acuity measures, such as Vernier acuity [1] depend on the characteristics of target objects and tend to show higher values than other measures. Therefore, it is required that empirical research should be conducted using displays with various pixel densities.

In existing studies [2], [3] on the requirements of pixel density for smartphone displays, a viewing distance of 25–30 cm was assumed. In authors' previous study, the viewing distances of 32 university students were measured using smartphones [4]. The results showed that the average viewing distance was 23.7 cm, 5 percent of which was 15 cm—a very short viewing distance—specifically when using smartphones in recumbent position. Therefore, it is necessary to conduct empirical research using shorter viewing distances than those assumed in the existing studies. As for the display character size, it was observed that a character size of approximately 1.5 mm was often used.

In this study, 5 types of LCDs were used, developed for the next-generation smartphones with pixel densities of 403, 533, 588, 706, and 806 ppi, and Japanese texts were displayed on these smartphones. Then, using a paired comparison method, 30 university students evaluated the image quality of Japanese characters displayed on five LCDs. Each student chose his own viewing distance at which he/she could most easily recognize the difference in image quality, and the viewing distance of each student was measured.

2. Experimental method

For the experiments in this paper, characters approximately 1.5 mm in height were used, and the Japanese texts (see Figure 1) were displayed on five LCDs with different pixel densities, as shown in Table 1. Japanese characters in four font types were employed, regarded as one of the most complex characters like Chinese, Korean and Russian. The image quality of the displayed characters was evaluated through blind test, using the Scheffe's method of paired comparison with Nakaya's variation [5]. LCDs used in the experiments had the display luminance of 230 cd/m^2, and the luminance contrast ratio was set at 500:1 or higher in a dark room. The horizontal illuminance in the laboratory was 400 lx and the screen illuminance was 300 lx. A total of 30 university students (8 females and 22 males) participated in the experiments. All participants had normal vision, wearing their own usual correction lenses, if needed. Participants were not screened due to their visual acuity.

Figure 2 shows the experimental scene. Each participant was given a pair of LCDs, randomly selected from five LCDs with different pixel densities, then evaluated the given pair at the viewing distance he/she chose and indicated either of LCDs, of a higher image quality by the following scales; 0: the same, 1: slightly better, 2: better, and 3: much better.

源ノ角ゴシック　標準
①曇り空に白鷺と鷹が舞う。
②三鷹市では雹が降り豪雨が襲った。
③劇場の音響環境に驚愕した。
④綺麗な蘭と薔薇の花が薫る。
⑤超高精細パネル視認性実験中。
⑥Ultra-High Resolution Display

Figure 1. Evaluated text image. Character size was approximately 1.5 mm in height. As an example of one of four font types used in the experiment, Gennokaku Gothic-Standard is shown.

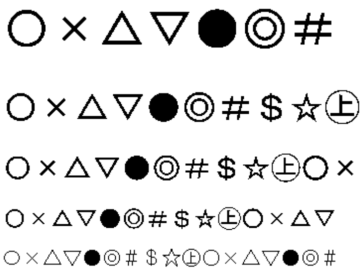
Table 1. Specifications of evaluated LCDs and displayed characters.

Pixel density (ppi)	Pixel pitch (mm)	Character format	Character height (mm)	LCD panel format	Display area format *	Display area size (mm) *
403	0.0630	24×24	1.51	1440×2560	1440×2560 (Scaled factor 2)	45.36×80.64
538	0.0472	32×32	1.51	1440×2560	960×1707	45.36×80.66
588	0.0432	34×34	1.47	1440×2560	1050×1867	45.36×80.65
706	0.0360	43×43	1.55	1440×2560	1260×2240	45.36×80.64
806	0.0315	49×49	1.54	1440×2560	1440×2560	45.36×80.64

* Outer display area was filled with black

Figure 2. Experimental situation. Participants were free to choose their own viewing distance.

Each participant, who was asked under blind conditions compared 10 pairs of pixel densities (${}_5C_2$) for each of four font types. Using a stopwatch, time was measured from when a participant was given a pair of LCDs to when the participant indicated the LCD of better image quality. The viewing distance was also measured for each participant.



Symbol sizes were 1.2 mm to 3.2 mm.

Figure 3. Aliased symbols to evaluate the perception of jagged edges.

After the paired comparison experiments on the image quality, each participant viewed symbols in aliased font on each of five LCDs with different pixel densities. Each participant evaluated his/her perception of the jagged edges of the symbols by the rating scale method. Figure 3 shows the aliased (bi-leveled) symbols to evaluate the perception of the jagged edges. Each participant chose his/her own viewing distance at which he/she most easily recognized the jaggedness of the symbols.

3. Results and Discussion

Figure 4 shows the result of the paired comparisons between different pixel densities, where the average of 30 participants is given for each of four font types. Furthermore, Figure 5 shows the distribution of viewing distances in the paired comparisons of the participants.

According to Figure 4, subjective image quality improves as the pixel density increases. Further, when the pixel density increases from 706 ppi to 806 ppi, the ratio of the image quality improvement is almost saturated. Table 2 summarizes the statistical difference in the subjective image quality over the pixel densities. With three of four font types, there is no significant difference in the subjective image quality between the 706 ppi and 806 ppi pixel densities.

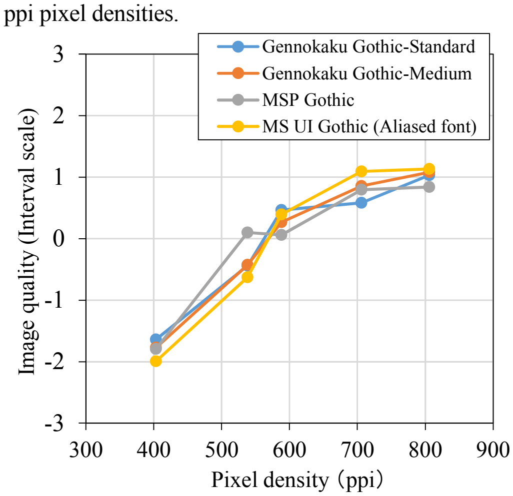


Figure 4. Subjective image quality as a function of pixel density for each font. It does not readily allow direct comparison among different font types.

Furthermore, compared with other font types, the pixel density significantly impacted on the subjective image quality when viewing MS UI Gothic, one of aliased fonts. In interviews after the experiments, many participants stated that when reading MS UI Gothic, it was easier to determine the difference in image quality resulting from the difference in pixel densities.

In the experiments, time was measured from when a participant was given a pair of LCDs to when the participant indicated the LCD of better image quality. For each font type, Figure 6 plots the time required to evaluate the image quality and the difference in image quality scores of 10 possible pairs of the pixel densities. It was observed that the greater the difference

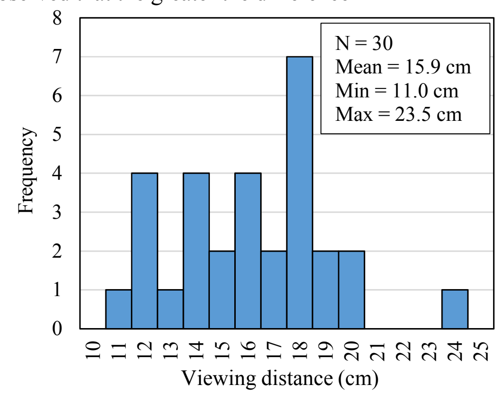


Figure 5. Distribution of participant's viewing distance during the paired comparison experiment.

Table 2. Statistical significance of the confidence interval between two adjacent pairs

Display font	Pair of comparison			
	403ppi vs 538ppi	538ppi vs 588ppi	588ppi vs 706ppi	706ppi vs 806ppi
Gennokaku Gothic-Std	**	**	n.s.	**
Gennokaku Gothic-Medium	**	**	**	n.s.
MSP Gothic	**	n.s.	**	n.s.
MS UI Gothic (Aliased)	**	**	**	n.s.

*: p<0.05, **: p<0.01, n.s.: Not significant

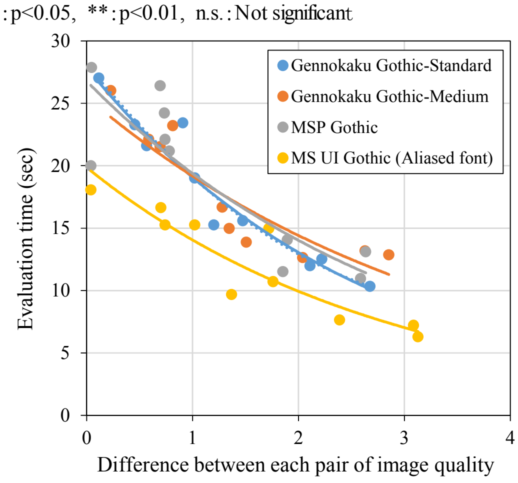


Figure 6. Evaluation time and subjective quality difference between LCDs with different pixel densities.

in image quality scores becomes, the shorter the evaluation time takes. It was also observed that the evaluation time for MS UI Gothic was significantly shorter than that of other font types. The short evaluation time of MS UI Gothic is consistent with the interviews of participants. This is because MS UI Gothic was the only aliased font used in the experiments and that it was easier to detect the difference in the pixel density with aliased fonts than with anti-aliased fonts.

Figure 7 shows the evaluation results of the jagged edges for aliased fonts using the rating scale method. Note that the participants actually perceived the jagged edges even at 806 ppi. In other words, this result indicates that much higher pixel density is required for aliased font types so that the jagged edges would not be perceived in the displayed images.

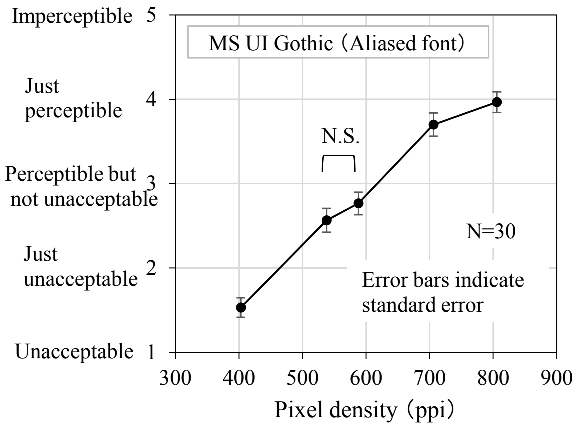


Figure 7. Perception of the jagged edges of the symbols as a function of the pixel density of LCDs.

Considering the diversity of smartphone users, it is necessary to examine how the visual acuity of participants impacted on the experimental results. Figure 8 plots the relationship between the percentage of accurate evaluation of the image quality and the Landaulet visual acuity at 30 cm for each participant in the paired comparison experiments. The percentage of accurate evaluation is defined as the percentage of the participants' evaluation where they indicated the higher image quality for the LCD with the higher pixel density out of a total of 40 pairs (= ${}_5C_2$ number of pixel density pairs × four font types). Spearman's rank correlation coefficient ρ was calculated, and a statistically significant correlation was observed when $\rho = -0.539$ and $p < 0.01$. In other words, a participant with better visual acuity tends to achieve higher evaluation accuracy in the paired comparison experiments.

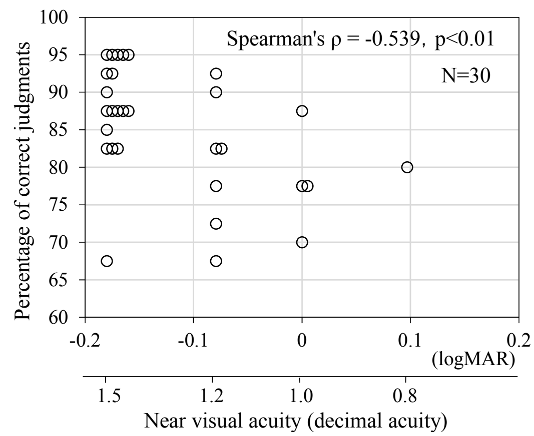


Figure 8. Visual acuity measured at 30 cm and the percentages of correct judgment of the paired comparison test.

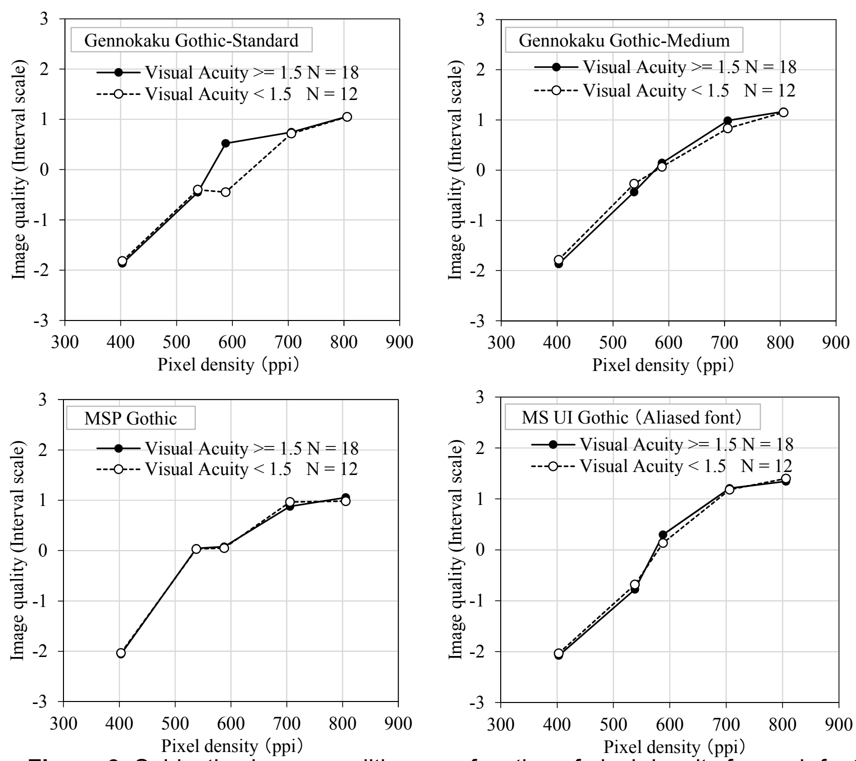


Figure 9. Subjective image qualities as a function of pixel density for each font. Comparison between the higher and lower visual acuity groups

Given the observations mentioned above, Figures 9 group the participants into two categories, those with a visual acuity higher than or equal to 1.5 and those lower than 1.5, and plot the same evaluation measures as those used in Figure 4 for each font type. Figures 9 show almost no difference between the participants with higher visual acuity and those with lower visual acuity. Note that, as shown in Figure 10, the participants with visual acuity higher than or equal to 1.5 tend to perceive the jagged edges better than those with visual acuity lower than 1.5 do.

Comparing both the results in Figures 9 and Figure 10, it could not be found, if the visual acuity affected image quality, in Figures 9. However, in Figure 10, the visual acuity affected the perception of jagged edges. For these results, two reasons can be considered: First, while the assessments of image quality depend on general Landolt acuity, the perception of jagged edges depends on hyper acuity, such as Vernier acuity; Second, different methods were used to assess the image quality and the perception of jagged edges. Absolute assessments by the rating scales were used for the perception of jagged edges, while relative assessments by the paired comparisons were used for image quality.

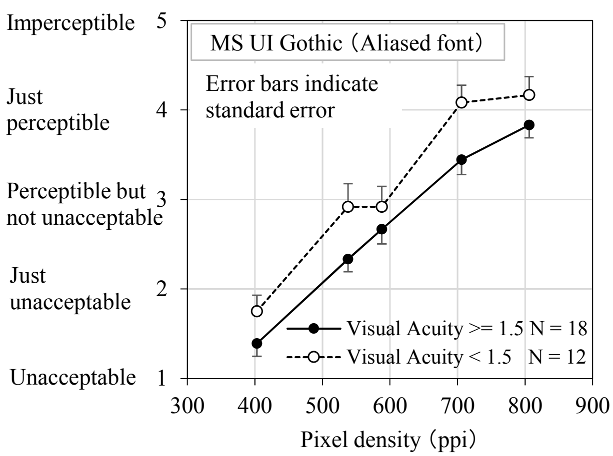


Figure 10. Perception of jagged edges of symbols as a function of the pixel density of LCDs. Comparison between the groups of higher and lower visual acuity.

4. Conclusion

This study examined how the pixel density of smartphone displays influenced the subjective image quality of the displayed Japanese characters. The main research findings are summarized as follows:

(1) The subjective image quality improved when the pixel density increased. However, with three of four font types, there was no significant difference in the subjective image quality between 706 ppi and 806 ppi pixel densities, showing the saturation in the improvement of image quality.

(2) Participants perceived jagged edges even at 806 ppi. Considering the perceived jagged edges, a higher pixel density is required when displaying aliased images.

(3) Participants were divided into those with high visual acuity and those with low visual acuity. Image quality evaluation in each group showed no visual acuity impacted on the evaluation and the observation made in (1) could apply to both groups.

(4) Participants with high visual acuity perceived jagged edges better than those with low visual acuity.

The experiments showed that the improvement in the displayed image quality of smartphones was not saturated at a pixel density of 564 ppi, the highest pixel density currently available in the market. This is the most commonly observed in the context of young users reading the displayed Japanese characters of approximately 1.5 mm in height. The experiments also showed that the improvement in the image quality started saturating when the pixel density is beyond approximately 700 ppi. They also suggested that for some font types, the higher pixel densities than 700 ppi would be necessary. Although pixel densities are required for smartphone users so as not to perceive the jaggedness in character edges, the density levels are beyond the discussion of pixel densities dealt with in the experiments of this paper.

5. Acknowledgements

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6. References

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