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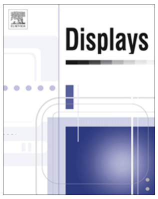

Effects of high pixel density on reading comprehension, proofreading performance, mood state, and physical discomfort

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ABSTRACT

Displays with low pixel densities that were common in the 1980s and 1990s were shown to impair visual performance. Display technology, especially pixel density, has tremendously improved in recent years and new technologies allow densities of 264 ppi and beyond. Two experiments were conducted to test whether there are any measurable benefits of high pixel density displays (264 ppi) over moderate pixel density displays (132 ppi). In Experiment 1, participants performed a reading comprehension task on a display with either high or low pixel density. In Experiment 2, participants' speed and performance in a proofreading task were compared using the same displays with high and low pixel density. There were no differences in reading comprehension and reading time (Experiment 1) as well as proofreading speed and performance (Experiment 2) between a 132 ppi and a 264 ppi display. However, subjective ratings of physical discomfort revealed significantly more complaints about headache and musculoskeletal strain in the 132 ppi condition than in the 264 ppi condition (Experiment 2). Reading comprehension, reading speed, and proofreading performance are unaffected by pixel densities above 132 ppi, but reading from high-resolution screens seems to be less exhausting at least subjectively. Thus, while large performance differences cannot be expected, displays with high pixel densities (264 ppi and above) have some advantage over displays with moderate (132 ppi or lower) pixel densities.

1. Introduction

Developments in screen technology and display design over the past years have resulted in improvements of the legibility of text presented on computer screens. This can be concluded from two facts. First, whereas studies from the 1980s and 1990s revealed clear performance detriments when reading from cathode ray tube (CRT) screens as compared with reading from paper [for comprehensive reviews of these earlier studies see e.g., 1,2] more recent studies using modern liquid crystal displays (TFT-LCDs) revealed comparable performance for screen and paper [3–9]. Second, direct comparisons between TFT-LCDs and CRTs have repeatedly revealed a superiority of TFT-LCDs over CRT screens with regard to measures such as visual search speed, search accuracy, letter identification, and eye movement parameters [10–14].

Among other variables (such as a flicker-free presentation, high background luminance and luminance contrast, and improved text presentation capabilities), increased pixel density (pixel per inch; ppi) is one factor that accounts for the improved legibility of text on modern TFT-LCDs. Even with CRTs, increases in pixel density and, hence, display sharpness have led to improved text legibility. For example, in a post hoc analysis of several previous experiments Gould et al. [15] showed that proofreading speed increases as a function of pixel density within a range of about 60–90 ppi. Ziefle [16] reported lower visual search performance and longer fixation durations in a 62 ppi condition than in a 89 ppi condition. There was no difference in proofreading performance between a 60 ppi and 120 ppi screen, but participants preferred the 120 ppi over the 60 ppi screen. Bridgeman et al. [17] reported descriptively higher reading comprehension scores with a 75 ppi display than with a 47 ppi display, but the difference missed statistical significance.

Pixel density has increased tremendously over the past 30 years: Whereas pixel densities within a range of 60–90 ppi were common in the 1980s [e.g., 15], pixel densities of up to 120 ppi were common in the late 1990s and at the beginning of the 21st century [e.g., 16]. In 2010 and 2011, Apple Inc. introduced the first and second generations of their iPad with a 9.7 in. and 132 ppi (1024 × 768 pixels) display, followed by the iPad 3 in 2012 with a 9.7 in. display with a pixel density of 264 ppi (2048 × 1536 pixels, so-called Retina display). By now, pixel densities at this

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level and higher have become available in many mobile phones and tablet computers as well as for some laptop and desktop displays. The "normal" human eye can discriminate two pixels separated by a gap of 1 arcminute.[1] The visual angle of one pixel presented at a 264 ppi display equals 1 arcminute when the viewing distance is set to approximately 33 cm. At this distance and beyond, single pixels can no longer be distinguished from another. Thus, the goal of display research "to match the information output of the display to the information capacity of the human visual system" [19, p. 315] seems to have been achieved. The question of interest here is whether these more recent increases in pixel density lead to measurable performance improvements.

Note that the levels of the pixel densities for which performance increases were reported were considerably lower (typically between 60 and 120 ppi) than the 264 ppi (and beyond) of recent high-resolution displays. Studies investigating the possibly beneficial effects of high-resolution displays with pixel densities at or even beyond the limit of the human eye's resolution capability are rare. Gujar et al. [3] compared an 85 ppi CRT, a 282 ppi LCD, and a 300 ppi print on paper. They reported no significant differences in proofreading performance and viewing distance, but participants found it subjectively easier to read from paper than from screen, and the 85 ppi CRT received the lowest ease-of-reading ratings. Gujar et al. pointed out that the lack of any performance differences between conditions may have been due to the short duration and the low complexity of their task. Wright et al. [20] compared a 102 ppi CRT display with an 83 ppi and a 157 ppi TFT-LCD. They found no differences in visual search performance, reading speed, and comprehension among the displays, but legibility in terms of visual acuity (number of words read in a word chart) increased with increasing pixel density. Further, participants preferred the 157 ppi TFT-LCD over the other displays. The 83 ppi TFT-LCD was the least preferred display and the worst in overall visual comfort. When Wright et al. positioned a CRT display at a viewing distance that resulted in the same retinal size of the pixels as in the 157 ppi TFT-LCD condition, they found no differences in preference and subjective ratings of overall visual comfort, indicating that retinal pixel size and, consequently, pixel density are determining factors in subjective evaluations of display quality. Finally, Huang et al. [21] found slower reading speed for a pixel density of 125 ppi as compared with densities of 167 ppi, 200 ppi, and 250 ppi. Visual search performance was not affected by pixel density. Unfortunately, participants read texts or conducted a visual search task on different mobile devices with various screen and font sizes such that pixel density was confounded with these variables. For instance, the largest font sizes were used in the 125 ppi condition, most probably resulting in longer reading times due to longer scrolling times.

A cautious conclusion from these findings is that an increase in pixel density up to the level of about 150 ppi seems to have positive effects [as shown by 15,16,20,21], but there is currently not much evidence for similarly positive effects of increases in pixel density beyond that level. The main purpose of the experiments presented here was thus to test whether an increase in pixel density from 132 ppi to 264 ppi would have positive effects on measures of visual performance. Specifically, we investigated possible effects of pixel density on reading comprehension (Experiment 1) and on proofreading performance (Experiment 2). In addition, we administered questionnaires to measure physical and psychological strain. This seemed necessary because participants might attempt to compensate adverse effects of a lower pixel density on visual performance by increased effort which could mask performance differences between the two pixel density conditions in the present experiments. However, increased effort should result in more symptoms of physical or psychological strain in the more adverse (lower pixel density) condition [16,22].

2. Experiment 1

We compared the effects of reading from two displays that differed in pixel density but were basically identical with respect to all crucial display variables such as display size, luminance, luminance contrast, font size, and anti-aliasing algorithms. Reading comprehension was chosen as the dependent variable because this task is often required in the daily routine as well as at work (e.g., reading news online, e-mails, safety instructions, e-learning etc.) and therefore provides a measure of high ecological validity. In addition, we collected subjective ratings of psychological and physical strain to test whether more effort was spent in the more difficult (lower pixel-density) condition than in the less difficult (higher pixel density) condition.

We also measured additional variables that may reflect participants' attempts to compensate for the negative effects of the lower pixel density display. First, we assessed reading speed because participants may read more slowly from the lower pixel density display with the goal of maintaining their preferred level of comprehension [e.g., 1,2]. This consideration is based on findings reported by Cushman [23] who found a negative correlation between reading speed and comprehension such that an effect of pixel density on reading comprehension may be reflected partially, perhaps even completely, in the time taken to read the texts. Further, participants may try to compensate for legibility deficits when reading from the lower pixel density display by increasing or decreasing their viewing distance. For instance, the lower pixel density might cause a blurred display image that participants might want to compensate by reducing their viewing distance. Alternatively, an increased viewing distance causes a smaller retinal image of the pixels and might increase the perceived image quality [20]. Such adjustments are possible in everyday tasks in which people are usually free to choose their preferred viewing distance when reading text from a screen. Restricting participants' posture (e.g., by the use of chin rests) would have resulted in a severe reduction of ecological validity. Therefore, we did not restrict the seating position of the participants. Instead we measured the chosen viewing distance as an additional indicator of perceived visual quality at the end of the experiment.

2.1. Method

2.1.1. Participants

Participants were 156 adults. One data set had to be excluded from the analyses because, by accident, the participant was given a non-corresponding combination of texts and comprehension questions. Thus, the final sample size was 155. The 132 ppi condition comprised 80 participants (14 male) who ranged in age from 18 to 40 years ($M = 22$). The 264 ppi condition comprised 75 participants (20 males) who ranged in age from 18 to 32 years ($M = 22$). The groups did not differ with regard to their familiarity with the texts (Question 1 of the final questionnaire; for details see below), $\chi^2(1) = 0.01$, $p = 1.00$, their familiarity with the task (Question 2), $\chi^2(1) = 0.21$, $p = 0.77$, and their reading time per day (Question 8), $\chi^2(5) = 9.23$, $p = 0.08$. Similarly, there were no differences between the groups regarding the use of an iPad or another tablet computer (Question 5), $\chi^2(1) = 0.03$, $p = 1.00$, the use of an iPod touch, iPhone, or another smartphone (Question 6), $\chi^2(1) = 0.22$, $p = 0.75$, or their experience with those devices (Question 7), $\chi^2(2) = 1.14$, $p = 0.60$.

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[1] Note, however, that for certain visual tasks that require to discern relative object position, visual discrimination is at least one order of magnitude more precise than normal acuity (e.g. Vernier acuity). While traditional acuity is limited by the resolving capacity of the retinal receptors, this so-called hyperacuity phenomenon is caused by complex neural processes [18].