Reconciling print-size and display-size constraints on reading

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Two fundamental constraints limit the number of characters in text that can be displayed at one time—print size and display size. These dual constraints conflict in two important situations—when people with normal vision read text on small digital displays, and when people with low vision read magnified text. Here, we describe a unified framework for evaluating the joint impact of these constraints on reading performance. We measured reading speed as a function of print size for three digital formats (laptop, tablet, and cellphone) for 30 normally sighted and 10 low-vision participants. Our results showed that a minimum number of characters per line is required to achieve a criterion of 80% of maximum reading speed: 13 characters for normally sighted and eight characters for low-vision readers. This critical number of characters is nearly constant across font and display format. Possible reasons for this required number of characters are discussed. Combining these character count constraints with the requirements for adequate print size reveals that an individual's use of a small digital display or the need for magnified print can shrink or entirely eliminate the range of print size necessary for achieving maximum reading speed.

reading | low vision | visual perception | visual displays

Two fundamental constraints limit the number of characters that can be displayed in text at one time—print size and display format. The print size must be legible for the reader, and the size of the display (or page) limits the amount of text that can be rendered at this print size. As the print size gets larger, the amount of displayable text (number of characters per line and number of lines per page or screen) shrinks. These dual constraints conflict in two important situations—when magnification is required for people with low vision, and when people with normal vision read text on small digital displays. In this paper, we provide a unified analysis of the joint impact of these constraints. We also present empirical evidence showing how these constraints limit reading performance in cases of reduced acuity and small displays.

A widely used measure of text legibility is reading speed, measured in words per minute (1–3). Reading speed is straightforward to measure, is sensitive to changes in both eye condition and text properties, and is functionally significant to readers (4). The relationship between print size and reading speed has been studied in detail, reviewed by Legge and Bigelow (5). Numerous studies have shown that as angular print size (i.e., the visual angle subtended by text letters) increases from the reader's acuity limit, reading speed increases until a critical print size (CPS) is reached and, then, levels off at a maximum reading speed (MRS) for print sizes larger than the CPS. An example of reading speed as a function of print size is shown in Fig. 1*A*. This typical reading speed curve has been verified by various studies, and the idea of CPS is widely used by researchers and clinicians. For normally sighted readers, the CPS is ∼0.2°, and reading speed remains maximum for a factor of 10 in print size from 0.2° to 2° (5).

Early studies by Tinker and Paterson showed that when print size is fixed, the length of text lines, measured in picas (1 pica = 0.167 in), affects reading speed, indicating physical line length is an important factor to be considered when deciding on typographical layout (6). Several later studies examined the effect on reading speed of "window size" or "field of view" of magnifiers (7, 8) and provided estimates of the minimum field size in terms of the number of characters visible in the magnifier's field of view. These prior findings are suggestive of the impact of display format on reading speed but do not show how print size and display size jointly constrain reading performance for continuous text. In the current study, we first examined the hypothesis that, for an individual to achieve maximum reading speed, lines of text must include, at least, a critical number of characters. We term this hypothetical number the critical character count (CCC). Our hypothetical curve of reading speed as a function of character count per line is shown in Fig. 1*B*: The reading speed stays at its maximum for large character counts but drops for character counts below the CCC. We hypothesize that the CCC (green vertical line) determines the minimum size of displays for effective reading.

Why would the number of characters per line affect reading speed? Some property of the text, unrelated to the reader's vision status, might impose a constraint. For example, the distribution of word lengths might be crucial; reading speed may be unaffected as long as the line length can accommodate most or all of the words in the text, but may slow down when some individual words occupy more than one line. If an intrinsic text property is the limiting factor, we might expect similar CCC values for participants with both normal and low vision. Alternatively, the character count impact on reading speed might be

Significance

Accessibility of digital text is essential in modern society. The growing use of small mobile displays forces attention to the competing requirements for adequate print size and adequate screen real estate. As print size gets larger, the number of characters per line and the number of lines per screen shrinks, ultimately affecting reading performance. This is particularly challenging for older people who may require larger print and for the growing population with low vision. We developed a unified framework for measuring the impact of print size and display size on the readability of text. We show how these constraints reduce the range of print size, and for some display formats, prevent some readers from maximizing their reading performance.

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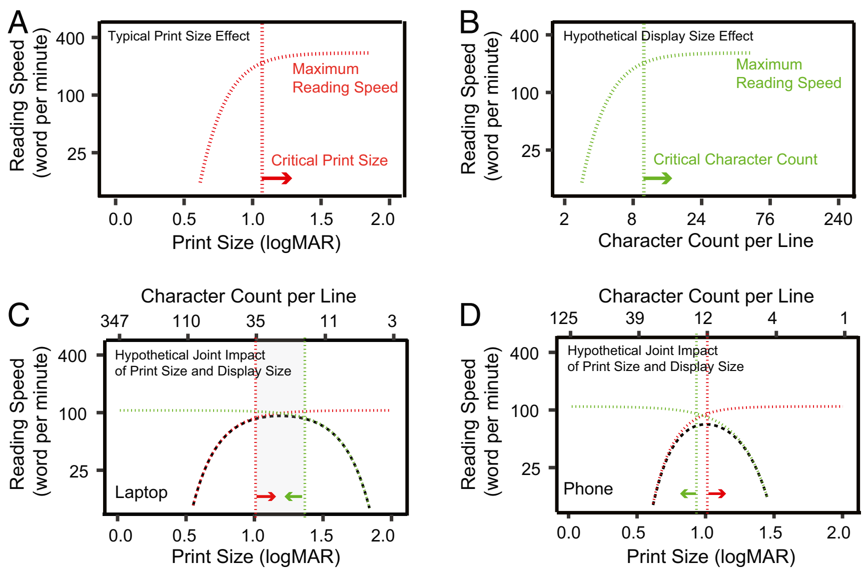

Fig. 1. Illustration of the impact of print size and display size on reading speed. (*A*) A typical reading curve illustrating the impact of character print size on reading speed (3,4, and 22). (*B*) A hypothetical reading curve illustrating the impact of display format on reading speed. (*C* and *D*) The hypothesized reading curves showing the joint impact of print size and display format (*C*: laptop, *D*: phone) on reading speed. The number of characters per line is now expressed in terms of angular print size. The conversion is described in *SI Appendix*, Appendix 2. The CPS and the print size corresponding to the CCC determine the lower and upper bounds of the range of recommended print size that allows near-MRS. In the examples shown in *C*, a recommended print size range exists in the laptop format as indicated by the gray zone. However, as shown in *D*, near-maximum reading is not possible for the phone format because the CPS exceeds the CCC.

determined by the perceptual span. McConkie and Rayner defined the perceptual span as the region around fixation in which printed information facilitates reading behavior (9). They introduced a "moving window" method to measure the perceptual span in which gaze-contingent eye tracking was used to distort text at varying distances from the point of fixation. Studies have shown that the perceptual span in normal vision includes three or four characters to the left of fixation and 14 to 15 characters to the right of fixation (see citations 10, 11). It is measured in terms of character spaces because it is independent of angular print size over a wide range (12–14) and is not font dependent (15). Recent studies have shown that the perceptual spans of low-vision participants with macular degeneration are substantially smaller than in normal vision (see citations 16–18). It is plausible that, if lines of text have fewer characters than the extent of a reader's perceptual span, reading would slow down because less information is available on each eye fixation. Moreover, if the size of the perceptual span determines the critical character count, we would expect the CCC to be lower in low vision than in normal vision.

Interest in the text capacity of small displays emerged with the advent of digital displays on microwave ovens and other appliances, and then with mobile devices such as cellphones and smart watches. Similar concerns exist with traffic displays and other electronic message signs viewed at a distance. For a given print size, the screen size determines the number of characters per line and the number of lines on the display and, therefore, the total text capacity for the display. When the display capacity is small, many pages will be required to render lengthy texts with associated time costs in line and page switching.

The tradeoff between print size and screen size becomes particularly acute for people with low vision who require large print to read. By a recent estimate, there are 5.7 million Americans with impaired vision with the number expected to increase to 9.6 million by the year 2050 as the population ages (19). Most people with impaired vision are not blind but have low vision. They continue to read visually but require substantial magnification of print. There is an important need for enhancing accessibility of websites and other digital displays for low-vision users by providing customizable text formats in terms of the number of characters per line and lines per screen. The flexibility of digital displays for customizing print size, page layout, and other properties of text has substantial advantages for people with low vision (20, 21). However, digital displays on small mobile devices pose challenges for people with low vision. For example, suppose a small display can fit 10 lines of 60 characters per line at the CPS of a normally sighted reader. The same display might only accommodate one line of six characters for a person with 20/200 acuity.

The major goal of the research presented in this paper was to establish how display format interacts with the need for adequate print size in constraining reading performance for people with both normal and low vision. Our hypothesized unified framework for evaluating the joint impact of these constraints is shown in Fig. 1 *C* and *D*. Critically, for a given display format and font, the angular print size (lower axis) determines the character count per line (top axis); as the print size increases, the character count decreases. This reciprocal relationship enables the independent constraints on reading speed of print size (red curve from Fig. 1*A*) and character count (green curve from Fig. 1*B*) to be represented in a unified framework (Fig. 1 *C* and *D*). The black curves show the impact of the joint constraints, indicating that reading speed is expected to fall on or below the red and green curves. The CPS (red vertical line) determines the smallest print, the CCC (green vertical line) determines the largest print, and the gray zone in between represents the range of print sizes for achieving near-maximum reading speed (Fig. 1*C*). When a large CPS is required on a small display, the gray zone will shrink, and entirely disappear if the CPS exceeds the print size associated with the CCC (Fig. 1*D*). In this case, readers cannot achieve their maximum reading speed.

To examine this unified framework, we measured reading speed as a function of print size for participants with both normal and low vision. They were tested with eight print sizes and three display configurations simulating typical sizes for cellphones, tablets, and laptops. The eight print sizes were selected to approximately match the character counts across the three display formats (see Fig. 2 and *Methods*). Participants were instructed to read silently as quickly and accurately as possible while retaining good comprehension. Reading speed was calculated as the total number of words read within a 1-min time period. We compared how the joint impact of print size and character count on reading speed changes with vision status, display format, and font.

Results

Reading with Normal Vision. We examined the impact of the number of characters per line on reading speed and evaluated the existence of a CCC in normal vision. Thirty normally sighted participants read different stories from *Grimms' Fairy Tales* in 24 conditions defined by eight print sizes and three display formats. Fourteen of the participants read with the Times New Roman font and 16 read with Courier. The group reading curves for each combination of display format and font are shown in the panels of Fig. 3*A*. Individual reading curves are provided in *SI Appendix*, Appendix 1 Figs. S1 and S2.

The reading curves isolated the impact of character count on reading speed because all of the tested print sizes were larger than the CPS for normally sighted participants (5). As shown in Fig. 3*A* and *SI Appendix*, Fig. S1, the reading speed remained constant for large character counts and dropped at smaller character counts, following the expected pattern. We modeled the reading curves as a function of character count (Eq. **2**, see *Methods*). Two reading indices were obtained from the fitted curves: MRS and CCC, defined as the smallest character count for near-maximum reading speed of 80% of the MRS. The estimated values are provided in Table 1.

Our primary question was whether the CCC changes with font and display format. Font (Times or Courier) did not significantly affect the CCC ($F[1,28] = 3.74$, $P = 0.06$). The only significant display difference was between tablet and laptop when reading with Courier (mean difference [MD] = 3.1, $P = 0.005$, 95% confidence interval [CI] = [0.7, 5.4]). The average CCC per line across fonts and displays was 12.8 characters.

The MRS ranged from 300 to 306 words per minute (wpm) for Times New Roman, and ranged from 285 to 298 wpm for Courier. Although this difference was not significant ($F[1,28] = 1.26$, $P = 0.27$), the slightly faster MRS in Times New Roman for normally sighted participants is consistent with previous findings (22).

Reading with Artificially Reduced Acuity. We next examined the joint impact of print size and character count on reading speed. We asked the same normally sighted participants to read another 24 stories while wearing goggles covered with diffusing films, which artificially reduced their acuity to an equivalent letter acuity of 0.83 logarithm of the minimum angle of resolution (logMAR) (Snellen equivalent 20/135). The group reading curves are shown in Fig. 3*B*. Individual reading curves are provided in *SI Appendix*, Appendix 1 and Figs. S1 and S2.

Reduced acuity necessitated larger print size for maximum reading, requiring attention to both print size and display format constraints. These joint constraints can be observed in Fig. 3*B*, consistent with our expected pattern (Fig. 1 *C* and *D*). Accordingly, the reading speed was modeled as a function of both print size and character count (Eq. **3**, see *Methods*).

The mean MRS values were 260 and 227 wpm for Times New Roman and Courier, slower than the no-blur condition ($F[1,140] = 42.3$, $P < 0.001$). The CCC was similar for laptop and tablet, averaging 9.2 characters, which was significantly smaller than the no-blur condition (laptop: $P < 0.001$, MD = 4.1, 95% CI = [−6.1, −2.2]; tablet: $P = 0.003$, MD = 3.0, 95% CI = [−5.0, −1.1]). The CCC for phone averaged 16.4 characters, which was significantly larger than the no-blur condition ($P < 0.001$, MD = 3.8, 95% CI = [1.9, 5.8]). The larger CCC of the phone display might have been an artifact of the simulation as we did not observe this effect with low-vision participants as shown in the low-vision results below. In our joint model, we considered CCC and CPS as two independent constraints (Eq. **3**). Consistent with this hypothesis, there was no significant correlation between CCC and CPS for any font or display (all $P > 0.05$).

There exists a range of print sizes that allows the participants to read at a reading speed of at least 80% of their MRS. This range is shown in gray in Fig. 3*B*. The range averages 0.29 logMAR for laptop (nearly a factor of 2 in print size) and 0.20 logMAR for tablet (about a factor of 1.6 in print size). For our testing conditions, there is no print size enabling 80% of MRS for the cellphone display because the print size required to achieve the CCC is smaller than the CPS.

Fig. 2. Two sets of sample stimuli. The upper panel shows a story excerpt with equal character count per page across three display formats. The lower panel shows excerpts with similar print size across the three display formats. Display formats and print sizes in the figure are scaled in size to fit journal requirements. Here, the same story was used across the displays for demonstration purposes. In the actual experiment, no story was presented more than once to a given subject.

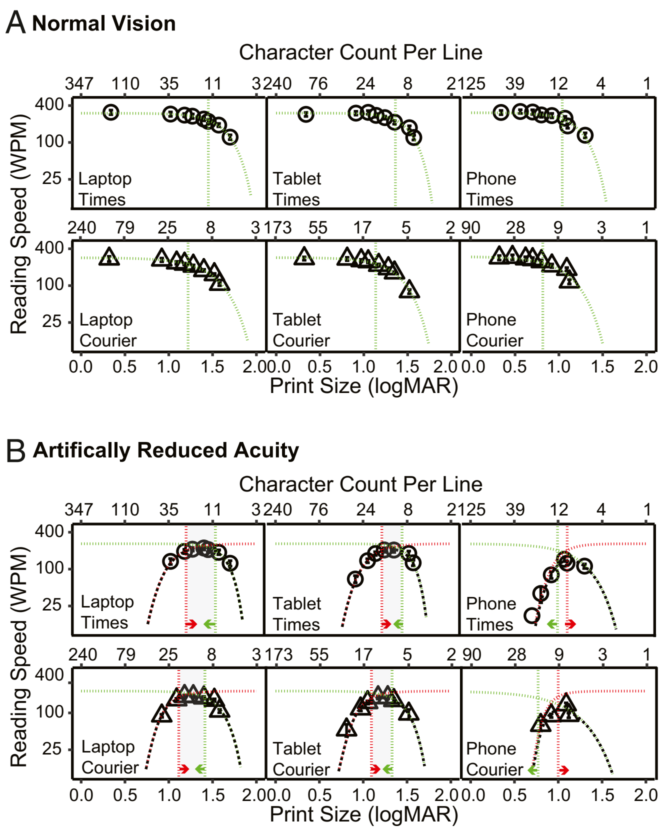

Fig. 3. The group average reading curves of the normally sighted participants in the normal viewing (*A*) and artificially reduced acuity (*B*) conditions. The reading speeds are represented by circles for Times New Roman and by triangles for Courier. The red and green dashed curves (fitted by Eq. **1** and Eq. **2**) illustrate the impact of print size and character count on reading speed, respectively. The black dashed curve is the actual reading curve jointly affected by print size and character count (fitted by Eq. **3**). The red and green vertical lines represent the CPS and CCC corresponding to 80% of the MRS, and the gray area between them is the range of print size for near-MRS (at 80% of the MRS), which we term the recommended print size range. In the normal viewing condition (*A*), all print sizes were larger than the CPS for normally sighted participants (5), therefore, only the green curves are plotted representing the character count effect. Note that in some situations (e.g., reading with the phone format in the artificially reduced acuity condition), a recommended print size range does not exist, that is, there is no range of print sizes for which the subject can achieve at least 80% of MRS.

We refer to the highest reading speed achievable, given print size and display format constraints, as the constrained MRS. Here, the mean constrained-MRS values were significantly lower than the MRS for all three displays. For laptop and tablet formats, the constrained MRS was slower than the MRS by 15.9% ($P < 0.001$, MD = 38.5 wpm, 95% CI = [32.6, 44.4]) and 20.1% ($P < 0.001$, 95%, MD = 48.7 wpm, CI = [44.7, 56.8]), respectively, indicating that, although reading speed exceeded the criterion value (80% or more of the MRS), the joint constraints of print size and character count prevented participants from reaching their MRS.

For the phone format, the constrained MRS was slower by 47.5% ($P < 0.001$, MD = 115.2 wpm, 95% CI = [103.8, 126.6]).

Reading with Low Vision. How do the joint constraints of print size and character count affect the reading speed of people with low vision? Ten low-vision participants with various vision diagnosis and binocular visual acuities (listed in Table 2) participated in our study. These participants were chosen because they continue to read visually on a regular basis in their daily lives. They performed the story reading task with the Times New Roman font only. The individual reading curves are shown in Fig. 4. Reading speed was modeled as a function of both print size and character count (Eq. **3**, see *Methods*), and individual reading indices are listed in Table 2.

The MRS varied widely across the low-vision participants, ranging from 30 to 398 wpm. CPS also had a wide distribution, ranging from 0.47 to 1.84 logMAR. These wide individual differences are not surprising, given the heterogeneity of the low-vision sample. Despite these substantial differences in overall reading ability, the CCC was similar across display formats, averaging 8.4 characters. There was a slightly smaller value in the tablet format, which was 1.8 characters smaller than the laptop ($P < 0.001$, 95% CI = [1.0,2.6]), and 1.5 characters smaller than the phone ($P < 0.001$, 95% CI = [0.6,2.4]). Again, there was no significant correlation between CCC and CPS for any of the displays (all $P > 0.05$).

For some low-vision participants and display formats, the CPS was larger than the print size corresponding to the CCC, meaning that there was no print size to achieve the criterion of 80% of MRS. For example, subject LV10 had similar CPS values of ∼1.4 logMAR across the three display formats, but for the phone format, there was no print size above this critical size that allowed eight characters to be fit on each line (Fig. 4).

The constrained-MRS values were smaller than the MRS for all three displays by 7.6% for laptop ($P = 0.022$, MD = 12.9 wpm, and 95% CI = [2.4, 23.4]) and 6.2% for tablet ($P = 0.032$, MD = 10.6 wpm, and 95% CI = [1.2, 20.0]). The phone display showed the largest reduction of 20.7% ($P = 0.005$, MD = 37.2 wpm, and 95% CI = [14.3, 60.0]).

Discussion

We have defined the concept of CCC representing the minimum number of characters per line to achieve a criterion of 80% of an individual's MRS. We have shown how the CPS required for this near-MRS interacts with the CCC to constrain reading performance. Our findings are relevant to the usefulness of small displays for people with normal vision and the requirements of display format for people with reduced acuity.

Three major findings emerge from the results: 1) The CCC is constant across fonts and display formats. On average, it is 13 characters for normally sighted participants and 8 characters for low-vision participants. 2) The range of print sizes to achieve the near-MRS has a lower bound determined by the CPS and an upper bound determined by the CCC. When the CPS is greater than the print size associated with the CCC, no print size will support the near-MRS. 3) Even within the range of print sizes limited by the lower and upper bounds, the highest achievable reading speed (constrained MRS) will often be less than the unconstrained MRS.

Earlier studies have investigated the impact of window size on reading, in the context of magnifiers for low vision [summarized by Legge, Chapter 4 (4)]. Window size is the number of characters visible on a line of text in a magnifier's field of view, which decreases when the power of the magnifier increases. There are two major differences between our current investigation on CCC and the earlier studies on critical window size. First, in the current study, the constraints on visible text were imposed by the display format rather than by the field of view of a magnifier. Second, we allowed the print size and character count to covary as they would for any fixed-size display rather than controlling one factor and varying the other. This approach allowed us to investigate the joint effects of print size and display format on reading in a more realistic context.

The current study has identified a critical value for the number of characters per line (CCC) as a fundamental limitation on reading speed. What accounts for the critical value? The CCC value of 13 for normal vision is consistent with the possibility as

Table 1. Summary of the reading indices in the normal vision and low-vision groups (mean [95% CI])

	Display, Font	MRS, wpm	Constrained-MRS wpm	CPS logMAR	CCC	CCC (logMAR)	Range* (logMAR)
No blur	Laptop, T	300 [261,339]	–	–	12.8 [10.5,15.0]	1.42 [1.37,1.47]	–
	Tablet, T	301 [264,339]	–	–	10.7 [8.5,13.0]	1.34 [1.30,1.37]	–
	Phone, T	306 [267,345]	–	–	11.5 [9.3,13.7]	1.02 [0.97,1.07]	–
	Laptop, C	285 [247,323]	–	–	15.4 [13.3,17.5]	1.21 [1.16,1.27]	–
	Tablet, C	287 [252,321]	–	–	12.3 [10.2,14.4]	1.14 [1.09,1.19]	–
	Phone, C	298 [253,342]	–	–	13.6 [11.5,15.7]	0.81 [0.76,0.87]	–
Blur	Laptop, T	260 [232,287]	221 [194,249]	1.22 [1.18,1.25]	10.1 [7.8,12.3]	1.52 [1.49,1.55]	0.30 [0.25,0.35]
	Tablet, T	260 [232,287]	210 [184,237]	1.22 [1.19,1.26]	8.5 [6.3,10.7]	1.43 [1.40,1.46]	0.21 [0.16,0.26]
	Phone, T	260 [232,287]	142 [120,163]	1.11 [1.07,1.14]	13.9 [11.7,16.2]	0.95 [0.89,1.02]	−0.15 † [-0.23,-0.08]
	Laptop, C	227 [213,241]	188 [175,202]	1.12 [1.08,1.15]	9.8 [7.7,11.9]	1.39 [1.35,1.43]	0.27 [0.22,0.33]
	Tablet, C	227 [213,241]	179 [162,195]	1.11 [1.06,1.16]	8.4 [6.3,10.5]	1.30 [1.25,1.34]	0.19 [0.12,0.25]
	Phone, C	227 [213,241]	114 [99,130]	0.99 [0.95,1.02]	18.9 [16.8,21]	0.71 [0.62,0.80]	−0.28 [-0.38,-0.17]
Low vision	Laptop, T	170 [114,226]	157 [102,212]	1.07 [0.83,1.31]	9.1 [8.3,9.9]	1.73 ‡ [1.70,1.77]	0.66 [0.44,0.89]
	Tablet, T	169 [111,227]	159 [102,217]	1.06 [0.83,1.29]	7.3 [7.0,7.6]	1.67 [1.64,1.69]	0.61 [0.39,0.83]
	Phone, T	180 [115,245]	143 [83,203]	1.03 [0.80,1.26]	8.8 [7.8,9.8]	1.31 [1.26,1.35]	0.28 [0.07,0.49]

The reading indices include: MRS, constrained MRS, CPS, CCC, its corresponding logMAR value, and the range of recommended print size (range).
*The range is the difference between the CPS and the logMAR value of CCC.
†The negative value indicates that the CPS is smaller than the logMAR value of CCC, therefore, the range for near-MRS does not exist.
‡For a fixed CCC, the corresponding logMAR sizes were ~0.18 log units larger at the 40-cm viewing distance (used by the low-vision participants) than the 60-cm viewing distance (used by the normal vision participants).

outlined in the Introduction of a line-length limitation due to perceptual span. Estimates of the size of the perceptual span to the right of fixation in normal vision of 10–15 characters are consistent with this possibility (11). Lending additional support, previous findings showing that the perceptual span is smaller in low vision (16–18) are consistent with our finding that the CCC is lower in low vision. It has also been shown that the perceptual span appears to be constant across fonts (15).

The difference in CCC between normal and low vision might also be related to the time required for the eyes to retrace from the end of one line to the beginning of the next line (23, 24). When the number of characters per line decreases, the number

Table 2. The individual diagnosis, visual acuity, and reading indices of the low-vision participants

ID	Diagnosis	Visual acuity	Display	MRS wpm	Constrained-MRS wpm	CPS logMAR	CCC	CCC logMAR	Range logMAR
01	Left eye glaucoma, no sight right eye	0.48	Laptop	182	182	0.49	11	1.64	1.15
			Tablet	204	204	0.49	8	1.61	1.12
			Phone	240	234	0.47	11	1.20	0.73
02	Retinal detachment	0.54	Laptop	263	257	0.80	11	1.65	0.85
			Tablet	269	269	0.82	8	1.62	0.80
			Phone	275	257	0.74	11	1.22	0.48
03	Septo-optic dysplasia	0.68	Laptop	102	100	0.90	9	1.75	0.84
			Tablet	95	95	0.90	7	1.68	0.78
			Phone	105	95	0.87	8	1.32	0.45
04	Glaucoma	0.68	Laptop	32	32	0.65	8	1.79	1.14
			Tablet	31	31	0.65	7	1.70	1.05
			Phone	30	30	0.62	7	1.38	0.75
05	Macular hole	0.74	Laptop	355	331	1.07	11	1.65	0.58
			Tablet	355	339	1.08	8	1.62	0.54
			Phone	398	316	1.01	11	1.22	0.20
06	Diabetic retinopathy	0.84	Laptop	178	170	1.06	8	1.77	0.71
			Tablet	162	158	1.07	7	1.69	0.62
			Phone	162	145	1.01	8	1.35	0.34
07	Aniridia	1.08	Laptop	204	186	1.33	8	1.77	0.44
			Tablet	195	182	1.31	7	1.69	0.37
			Phone	209	138	1.32	8	1.34	0.02
08	Aniridia	1.12	Laptop	117	115	1.16	8	1.76	0.61
			Tablet	117	112	1.14	7	1.68	0.54
			Phone	117	95	1.14	8	1.34	0.20
09	Age-related macular degeneration	1.14	Laptop	123	74	1.84	8	1.78	−0.06
			Tablet	115	72	1.74	7	1.69	−0.05
			Phone	120	44	1.63	8	1.36	−0.28
10	Diabetic retinopathy, Glaucoma	1.16	Laptop	148	129	1.39	9	1.76	0.37
			Tablet	145	126	1.38	7	1.68	0.30
			Phone	141	76	1.44	8	1.34	−0.10

The reading indices include: MRS, constrained MRS, CPS, CCC, and the range of recommended print size (range).

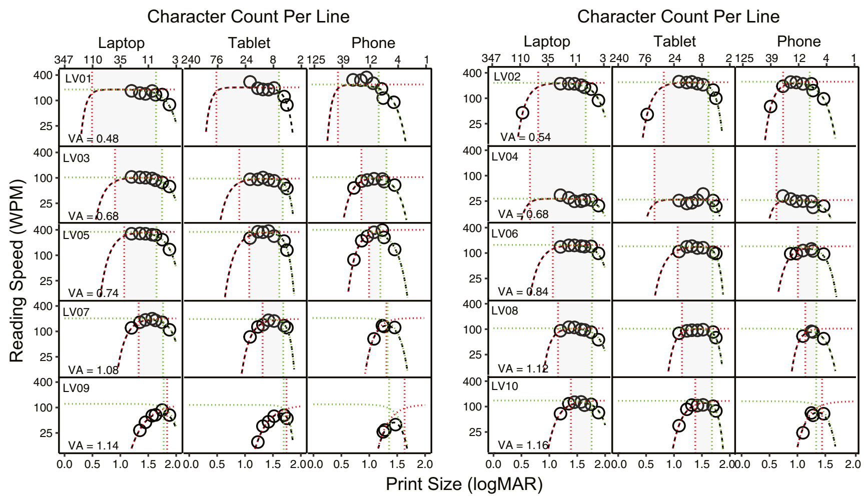

Fig. 4. The reading curves of low-vision participants. The measured reading speeds are represented by circles. The red and green dashed curves (fitted by Eq. **1** and Eq. **2**) illustrate the impact of print size and character count on reading speed, respectively. The black dashed curve is the actual reading curve jointly affected by print size and character count (fitted by Eq. **3**). The red and green vertical lines represent the CPS and CCC corresponding to 80% of the MRS, and the gray area between them is the range of print size for near-MRS (at 80% of the MRS). Note that for some combinations of severe vision loss and display format (e.g., all three displays for subject 9 and phone format for subject 10), there is no recommended print size range.

of these return sweeps (and number of lines to be read) increases, taking up proportionately more time in reading. The impact on reading speed would be greater for fast readers with normal vision (as the associated time cost would be proportionally larger) than slower readers with low vision. This difference might contribute to a larger CCC in normal vision.

We also considered the possibility that the CCC is related to the distribution of word lengths in text. About 80% of English words in text are nine or fewer letters (computed from the frequency distribution of word lengths in the Corpus of Contemporary American English, 2020, ref. 25), thus, a CCC of eight or nine letters could avoid most word splitting across lines. This observation seems consistent with the CCC of eight we found for low vision but not the higher value of 13 for normal vision. Taken together, our findings are most compatible with the perceptual span as the primary determiner of the CCC.

What are the real-life implications of our findings? The CPS for people with normal vision is ∼0.2° (equivalent to 0.38 logMAR) (5). If text is presented on a smart watch at a viewing distance of 40 cm for a normally sighted user, the minimum display width would need to be about 1.7 cm in order to include 13 characters per line at the required print size.

For reading with low vision, our findings have implications for two groups: eye-care clinicians and display designers. Clinicians may wish to recommend digital displays for their patients. How large should the display be? An individual's CPS can be measured directly from a test, such as MNREAD (26) or estimated from a measure of letter acuity (27). Our findings establish the relationship between the CPS and the minimum display size required for the critical number of characters per line. Fig. 5 plots minimum display width as a function of letter acuity (lower axis) or CPS (upper axis). The blue line represents a standard reading distance of 40 cm, and the red line represents a reading distance of 15 cm. Low-vision readers often adopt shorter than normal viewing distances for reading but rarely less than 15 cm (28) because of difficulties of posture or accommodation. The equation generating the red and blue lines is provided in *SI Appendix*, Appendix 2. These lines show the results for Times New Roman, while the surrounding gray bands represent the corresponding values for 18 fonts (see *SI Appendix*, Appendix 4 for details). The variation across most fonts is tiny. This is because of a fortuitous tradeoff: fonts with wider character spacing, such as Courier, take up more horizontal space but have a smaller CPS (29). This means that Fig. 5 provides guidance for display selection and is appropriate for a wide range of fonts that may be encountered by the low-vision reader. The intersection of the vertical dashed lines and the blue and red lines show the minimum display widths for low-vision readers with three levels of acuity. For a low-vision reader with visual acuity of 1.0 logMAR (the boundary for legal blindness in the United States), the minimum display width for near-maximum reading is 11.0 cm at 40-cm viewing distance (intersection with the blue line), which excludes use of a smart phone with a width of 10 cm (landscape layout). However, if the person is comfortable reading at 15 cm (intersection with the red line), this smart phone now meets the minimum display width of 4.2 cm.

Display designers can use Fig. 5 to estimate the inclusiveness of their devices for users with low vision. For a display of a given width, the intersection of a horizontal line at this display width with the blue and red lines in Fig. 5 show the required acuities to achieve the critical number of characters per line for viewing at 40 cm (blue line) or 15 cm (red line.) The larger the logMAR acuities required, the more inclusive the device for low vision. Table 3 shows the acuity requirements for the five display sizes listed on the right of Fig. 5. For example, a smart phone with a landscape width of 10 cm can accommodate users with visual acuities up to 0.97 logMAR at 40-cm viewing distance and 1.41 logMAR at 15-cm viewing distance. (The corresponding Snellen fractions are close to 20/200 and 20/500).

In this article, we have provided a unified framework for understanding the interacting effects of print size and display format on reading speed. Not only must characters exceed a critical size for near-maximum reading, there must also be more than a critical number of characters per line (CCC). Our analysis reveals a requirement of about 13 characters for normally sighted readers and about eight characters for people with low vision. Our findings have implications for the design of small text displays for people with normal vision and the prescription of appropriate reading aids for people with low vision.

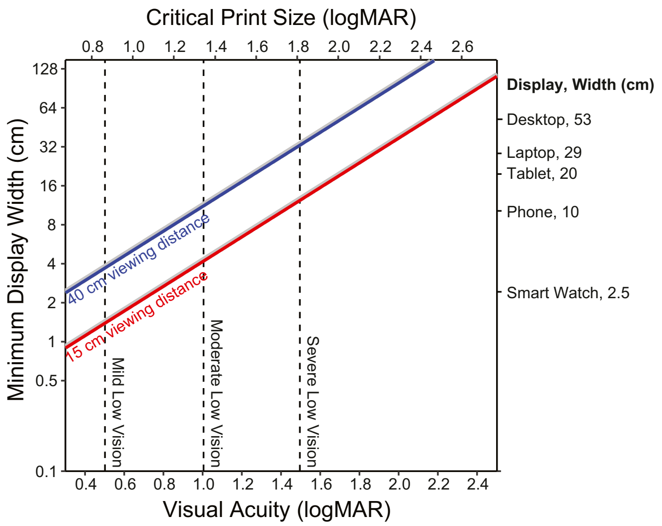

Fig. 5. Minimum display width for low-vision individuals. The minimum display widths are presented as a function of visual acuity (VA, bottom *x* axis) for two viewing distances (40 cm, blue line: $y = 1.22*10^{0.96VA}$ and 15 cm, red line: $y = 0.46*10^{0.96VA}$), where *y* is the minimum display width in centimeters and VA is visual acuity (logMAR). The derivation of the equations for the red and blue lines are provided in *SI Appendix*, Appendix 2. These equations use a liberal CCC value of nine characters, rounding up to the nearest integer value from the average value of 8.4 found in our experiment for low vision. The CPS corresponding to each VA are shown on the top *x* axis. The relationship between VA and CPS was obtained from 87 low-vision participants (29–31, a scatter plot is provided in *SI Appendix*, Appendix 3). Eighteen fonts were included in the analyses (*SI Appendix*, Appendix 4) with the colored lines showing results for Times New Roman and the gray ribbons representing the results across all fonts*. Dashed vertical lines show examples for mild, moderate, and severe low vision with corresponding acuities of 0.5, 1.0, and 1.5 logMAR. The intersections of these vertical lines with the blue and red diagonal lines represent the minimum display widths for these acuities and reading distances. The display widths of five common digital displays (smart watch, phone, tablet, laptop, and desktop computer) are shown on the right *y* axis.

Materials and Methods

Participants. Thirty normally sighted students (mean age = 21.6 y) participated through the University of Minnesota Research Experience Program. They had normal or corrected to normal vision with no history of reading impairments. The participants were separated into two groups (n = 14 and n = 16) to read with different fonts (see below). The sample size was determined based on our primary interest in the impact of display formats on the critical number of characters per line for near-maximum reading. From previously published data, we estimated the distribution of the number of characters per line at the preferred print size and viewing distance for a group of normally sighted participants (28). Using the "SIMR" package, we obtained the minimum sample size yielding a significant difference in display format at 80% power, based on 1,000 simulations of each sample size (32, 33). The result showed that to achieve 80% power at $P = 0.05$ with an effect size of Cohen's $d = 1.15$, a sample size of at least 10 is needed.

Ten low-vision (mean age = 58.3 y) participants were recruited from the Minnesota Laboratory for Low-vision Research roster. These participants had heterogeneous diagnoses and levels of visual impairment. They were selected because of their ability and interest in reading large print regardless of diagnosis. The diagnosis and binocular distance visual acuity for the low-vision participants are provided in Table 2. They were all native-English speakers and had no history of dyslexia or other reading disabilities. All participants gave written informed consent. The study was approved by the University of Minnesota Institutional Review Board (IRB).

*The eighteen fonts include five common fonts (Times, Courier, Helvetica, Arial, and Calibri) and their italic and bold variations and three new fonts developed for patients with macular degeneration (36, 37). Font details are provided in *SI Appendix*, Appendix 4.

Materials.

Stimuli. Forty-eight short stories from *Grimms' Fairy Tales* (34) were used in this study. The stories were screened to avoid offensive content and were selected from the full set of stories in the book. The 48 stories have similar levels of complexity in vocabulary, content, and style. The average Flesch–Kincaid grade score of the stories is seventh grade (calculated with text readability consensus calculator).

The stories were rendered in either the Times New Roman or the Courier font. Normally sighted participants were randomly assigned to one of the two font conditions, resulting in 14 participants in the Times New Roman and 16 in the Courier conditions. All of the low-vision participants were tested with the Times New Roman font.

Participants read different stories in 24 conditions defined by eight print sizes and three display formats as described below. While all of the participants read two stories for each condition, normally sighted participants were tested with artificial acuity reduction (blur) for the second set of 24 stories. Blur was produced with customized diffusing goggles. Specifically, three layers of polyethylene films were added in front of a pair of safety goggles. The diffusing film layers were carefully flattened and tightly stretched to avoid optical distortion. These goggles artificially reduce acuity to an average of 0.83 logMAR (Snellen 20/135), measured with the Lighthouse distance visual acuity chart, and reduce Pelli-Robson contrast sensitivity to an average of 1.0 log unit. LogMAR is a unit of angular print size, which refers to the retinal-image size and depends on both the physical size of the print and the subject's viewing distance. The LogMAR value can be calculated from the angular print size (in degrees) by the following equation: LogMAR = $\log_{10}$(angular print size/0.083).

No story was presented in more than one condition for any subject. The pairings of story and presentation condition were randomly selected for each subject. The order of the conditions was counterbalanced across participants.

Display. All of the stories were presented on a 27-in Apple Cinema Display (2,560 × 1,440 pixels, pixel density:109 ppi, refresh rate:60 Hz). The stories were displayed with black text (0.42 cd/m^2) on a white background (432 cd/m^2).

In separate conditions, text was confined to portions of the monitor simulating the size of commonly used digital displays—a laptop (6.6 × 11.4 in, matching a 13-in MacBook Pro), a tablet (5.9 × 7.9 in, matching an iPad), and a cellphone (2.3 × 4.1 in, matching an iPhone 6).

Each story was presented in one of the eight print sizes and one of the three display formats. For a given print size, the number of characters per display (the display character count) varied with the size of the display. We selected a different set of eight print sizes for each display format. For each format, the smallest print size was 12 pt. The remaining print sizes were chosen to approximately match the sets of character counts. All three display formats were presented in landscape layout. This layout allowed us to minimize the possible effect of word splitting. Word splitting was only observed in the largest print size condition in cellphone and tablet displays. For words longer than six characters (~10% of the words in our reading material), the first five to six characters were displayed on one page, and the following characters appeared on the next page, no hyphens were used.

Fig. 2 shows two sets of sample stimuli, one set demonstrates stories with equal character counts per page across the three display formats, while the other set demonstrates stories with similar print sizes across the display formats. The specific ranges for print sizes (in units of points and logMAR) and character counts per page for each display and font are provided in *SI Appendix*, Appendix 5.

Procedure. Participants were tested with the Lighthouse near letter acuity chart before the main experiment. Participants were seated at a specified viewing distance from the display (normally sighted participants at 60 cm, low-vision participants at 40 cm).

At the beginning of the study, participants were told that their comprehension would be evaluated, and they were instructed to silently read the story presented on the screen for 1 min as fast and accurately as possible, switching pages when necessary. They pressed the spacebar to change the page. There was no noticeable delay associated with page switching. After 1 min, a sound indicated the end of the trial, and the subject reported the last word read. The experimenter recorded the ending word. This information was used later to calculate the reading speed (see *Analysis* section). For several randomly selected stories, participants were asked comprehension questions to confirm they were understanding the stories. Each subject was asked 15 comprehension questions across 48 stories. No subject made more than three mistakes in the comprehension questions.

Prior to the main experiment, each subject was tested with a practice trial taken from "*The Catcher in the Rye*," presented in Times New Roman on the tablet display format with the fourth largest print size of the display

Table 3. Acuity requirements for five digital displays viewed from 40 or 15 cm

Display	Width (cm)	Required acuity at 15-cm distance mean [Min, Max] (logMAR)	Required acuity at 40-cm distance mean [Min, Max] (logMAR)
Desktop	53	2.16 [2.14, 2.17]	1.71 [1.70, 1.72]
Laptop	29	1.88 [1.87, 1.89]	1.43 [1.42, 1.44]
Tablet	20	1.71 [1.70, 1.72]	1.27 [1.25, 1.28]
Phone	10	1.41 [1.40, 1.42]	0.97 [0.95, 0.98]
Smart watch	2.5	1.27 [1.25, 1.28]	0.76 [0.75, 0.77]

The acuity requirement is determined by the angular size of letters when there is an average of nine characters per display width.

(1.24 logMAR, 35 characters per page). The comprehension test was not included in the practice trial.

After the practice trial, participants started the main experiment with one of the three display formats. Each display format included eight print sizes and within each display format, the stories were presented either from largest to smallest print size or vice versa. This pattern was repeated six times (two times for each of the three display formats). Normally sighted participants either started with the blur goggles on and took them off after the first three display conditions (total of 24 stories) or started without the blur goggles and put them on after the first half. All of the participants were encouraged to take breaks between the stories.

Analysis.

Reading speed. Reading speed (wpm) was calculated based on the last word read by participants when the 1-min time limit ended. Specifically, the experimenter calculated how many characters (including spaces) were read in each 1-min trial using the character count feature in Microsoft Word. The character count was divided by six to estimate the number of "standard-length words" read (2). Reading speeds were obtained at each of the eight print sizes tested in each condition (i.e., three display formats × two blur/no-blur conditions for normally sighted participants, and three display formats for low-vision participants).

Reading model. We modeled the joint impact of print size and display format on reading speed by incorporating the existing model for print size and our hypothetical model for character count.

It is well known from the reading literature that reading speed drops with print size in an exponential manner (3, 4, 22). Specifically, the reading speed stays at its maximum (MRS) for large print sizes but drops rapidly for small print sizes (Fig. 1*A*). We implemented the exponential function in our model to describe the independent impact of print size on reading speed in cases where display size is sufficiently large so that its impact is negligible (Eq. **1**),

$$rs = \mathrm{MRS}\left(1 - e^{-e^{lrc_{ps}(\mathrm{PS}-xint_{ps})}}\right), \quad [1]$$

where rs is the reading speed in log wpm, lrc_{ps} is the rate of change in reading speed with print size (in logMAR), and $xint_{ps}$ is the print size at which reading speed is 0 log unit.

The impact of character count on reading speed, however, is not well established. We hypothesized that character count affects reading speed in a similar way as print size: The reading speed stays at its maximum for large character counts but drops for small character counts. We used a similar exponential function to describe the independent impact of character count on reading speed in cases where the print size is sufficiently large so that its impact is negligible (Eq. **2**),

$$rs = \mathrm{MRS}\left(1 - e^{-e^{lrc_{cc}(\mathrm{CC}-xint_{cc})}}\right), \quad [2]$$

where again rs is the reading speed in log wpm, lrc_{cc} is the slope of the rate of change in reading speed with character count per line, and $xint_{cc}$ is the character count at which log reading speed is 0 log unit. We verified the hypothetical pattern of Eq. **2** by our empirical reading speed vs. print size data under the normal viewing condition (Fig. 3*A*).

In real-life situations, both constraints are present. We hypothesized that trade-off between the print size and the number of characters per line connects the two independent constraints and imposes a joint impact on reading speed. The hypothetical joint impact of print size and character per line on reading speed is modeled by Eq. **3**,

$$rs = \mathrm{MRS}\left(1 - e^{-e^{lrc_{ps}(\mathrm{PS}-xint_{ps})}} - e^{-e^{lrc_{cc}(\mathrm{CC}-xint_{cc})}}\right). \quad [3]$$

To express these constraints in terms of one independent variable, the number of characters per line is expressed in terms of angular print size, given specification of the display format and font. Briefly, when angular print size increases, the number of characters per line decreases; for a fixed angular print size, the number of characters per line is larger on a wider display and with a narrower font. A detailed derivation of the transformation from mean character count per line to print size in logMAR units is provided in *SI Appendix*, Appendix 2. Eq. **3** was used to fit the reading speed vs. print size data under the artificially reduced acuity (Fig. 3*B*) and low-vision (Fig. 4) conditions.

Curve fitting and key reading indices. Plots of reading speed vs. angular print size were fitted using a nonlinear mixed effects model ([NLME], "nlme" package) as described in Cheung et al. (35). The NLME model treated MRS, lrc_{ps}, lrc_{cc}, $xint_{ps}$, and $xint_{cc}$ as fixed effects and subject as the random effect. Display was included as a covariate for the fixed effects and nested within the subject in the random effect. Additionally, Font was included as a covariate for the normally sighted participants, and visual acuity was included as a covariate for the low-vision participants. The significance of the covariates in the fixed effects were examined by the F statistics (ANOVA) in the nlme package, and the significance of the random effects was examined by the likelihood test also using the ANOVA function. The nonsignificant components were excluded from the NLME model stepwise.

A display should provide a range of print sizes enabling maximum or near-MRS. We adopted a criterion of 80% of MRS as near-MRS. Five key reading indices were obtained from the optimally fitting model as summarized: 1) MRS: The fastest reading speed participants can achieve without any constraint of print size or display format. 2) Constrained MRS: The fastest reading speed participants can actually achieve when constrained by print size and display format. 3) CPS: The smallest print size for a reading speed of 80% of the MRS. 4) CCC: The smallest character count per line for reading speed of 80% of the MRS. 5) Range of recommended print sizes: print sizes between the CPS and the print size associated with the CCC.

LME was then performed to clarify the contributions of font and display format on each of the reading indices, and significant main effects and interactions were followed by pairwise comparisons with Bonferroni adjustment. Note that the reading indices in the no-blur and artificial blur conditions were analyzed in a single LME model to reduce type-I errors.

Data Availability. Human subjects reading data have been deposited in the Data Repository for the University of Minnesota, https://conservancy.umn.edu/handle/11299/212120 (38).

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