Digital Reading Rulers

Evaluating Inclusively Designed Rulers for Readers With Dyslexia and Without

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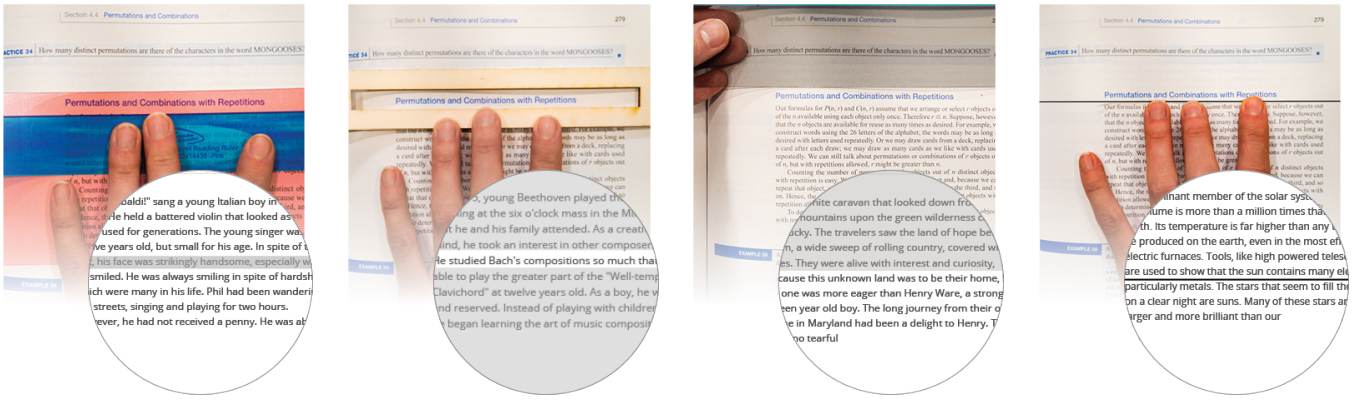

(a) Physical: Color Overlay (inset) Digital: Grey Bar

(b) Physical: Dyslexia Ruler (inset) Digital: Lightbox

(c) Physical: Color Overlay (inset) Digital: Shade

(d) Physical: Metal Ruler Piece (inset) Digital: Underline

Figure 1: Motivated by existing physical reading rulers (see the photos of the color overlay in (a) and (c), dyslexia ruler in (b), and metal ruler piece in (d)), here we present a set of four digital reading ruler designs (circular insets) that emerged from a series of focus groups including readers with dyslexia and without.

ABSTRACT

Physical reading rulers are simple yet effective interventions that help readers with dyslexia. Digital reading rulers may offer similar benefits. Given their potential value, we provide the following contributions: (1) We host focus group sessions including people with dyslexia to build upon their lived experiences, (2) We provide evidence for designs that are effective and preferred, (3) We measure reading gains of rulers for readers with and without dyslexia. Using inclusive design principles, we arrive at four digital ruler designs - Grey Bar, Lightbox, Shade, and Underline. For the first time, we offer a comprehensive evaluation of digital ruler effectiveness on 91 crowdsourced readers with dyslexia and 86 without. Considering reading speed, comprehension, and preference, many readers benefit from these rulers, with the largest gains among readers with dyslexia. Rulers designed by readers with dyslexia increased the reading speeds of readers with dyslexia, supporting the need for inclusive design practices.

KEYWORDS

Dyslexia, ADHD, Accessibility, Reading Ruler, Readability, Highlighting, Color Overlay, Human-Computer Interaction, Inclusive Design, User Sensitive Inclusive Design, Ability-Based Design.

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1 INTRODUCTION

Readers with dyslexia often experience losing their place in a text, subsequently rereading or skipping lines [44, 45], making the experience of reading confusing or demotivating. A **reading ruler** is a low-tech tool used to help children who exhibit signs of dyslexia.

One ruler design tailored to readers with dyslexia is a **color overlay**, a tinted piece of transparent plastic of various sizes that restricts attention to a block of text at a time (Fig. 1a,c). Color overlays have been shown to help readers with dyslexia increase their reading speed and comprehension, and reduce eye strain and fatigue [18, 46]. Another design features a cut-out window in the middle of the ruler (Fig. 1b). Other designs involve multiple colors or varying levels of transparency, or even simple alternatives such as an ordinary wooden ruler, bookmark, or metal strip used to underline the current line of text being read (Fig. 1d).

Digital reading comes with similar challenges. Digital reading platforms and interfaces offer digital reading rulers through tools such as *Claro Software* [15], *Immersive Reader* [26], *ReadingLine* [34], *ReaderMode* [19], and those designed by *Avelar et al.* [5]. Though a readily implementable intervention, digital reading rulers are not widely adopted for reading, existing implementations vary significantly in design and behavior, and a common implementation standard or guideline does not exist. Furthermore, there is little research on the effectiveness of reading rulers in digital reading.

Our research hopes to close these gaps. We arrived at our ruler designs through multiple user sensitive inclusive focus groups with participants with dyslexia and without. We offer a comprehensive evaluation of different digital reading ruler designs and their effects on the reading performance of participants with dyslexia and without. Our ruler designs validate and augment existing implementations available on various platforms (*Grey Bar*, *Lightbox*, *Shade*, *Underline* visualized in Fig. 4). We implemented these reading rulers into a single reading platform to evaluate and compare them to baselines (using no ruler or using a mouse cursor to track reading). We collected reading speeds, comprehension measurements, and subjective feedback in a within-subject study with 177 crowdsourced participants performing a controlled reading task. We recruited focus group participants and crowdsourced study participants with varying degrees of dyslexia. Our studies offer the first insights into the effects of different digital reading rulers on reading performance and preference in readers both with and without dyslexia.

We provide statistical evidence that digital reading rulers, specifically those designed by participants with dyslexia, increase reading speed for participants with dyslexia, thereby further validating the need for inclusive design practices. While readers with dyslexia account for 10-20% of the general population [69], our results show that readers without dyslexia can also benefit from reading rulers. We hope our findings will encourage reading platforms to offer reading rulers in the future, making reading less confusing and more enjoyable for a sizable fraction of the population.

2 RELATED WORK

People with dyslexia commonly experience difficulty reading, writing, and understanding spoken language [31, 40, 63, 68]. Prior research has sought to improve reading outcomes for readers with dyslexia by providing innovative tooling [5, 9, 27, 48], or developing special reading interfaces with multiple customizable tools [4, 17, 27, 53, 56]. We focus on digital reading rulers based on physical alternatives that are widely used by readers with dyslexia [38].

2.1 Reading Ruler Designs

Reading rulers seek to improve reading for readers with dyslexia and coexisting conditions by helping readers focus on a portion of text through cut-out rulers or colored overlays; often restricted to one or more lines of text at a time. Digital tooling offer reading rulers in the form of browser extensions [5, 6, 19, 34] and desktop applications [15]. Table 1 includes existing reading rulers designs and the interactions they afford, and Fig. 2 shows examples of ruler interfaces. Digital reading rulers often support additional configurations, such as color, height, and opacity (Fig. 2b, c, and e). For instance, Avelar et al. provided the option to highlight key phrases and words, while BeeLine [6] uses a color gradient across lines of text (Fig. 2a).

However, we did not find evidence showing that the previous ruler designs have been supported by inclusive design practices. While designers created dyslexia rulers for readers with dyslexia, these previous designs possess shortcomings: (1) the design processes did not explicitly involve designers with dyslexia to our knowledge, (2) there is no documentation of the utility of reading rulers for participants without dyslexia, and (3) there is no direct comparison between ruler designs to arrive at design guidelines or implementation recommendations.

The ruler designs we arrived at are similar to, and provide validation for, existing implementations. Our work contrasts with prior work by explicitly involving participants with dyslexia and without in conceptualizing these rulers, informed by Ability-Based Design principles [77] and User Sensitive Inclusive Design [35, 36]. During our focus groups, we emphasized the principle of Stance from Ability-Based Design [77]; specifically *Ability and Accountability*. Ability states, "Designers will focus on ability and not *dis*ability" [77]. We apply this principle by allowing a person with dyslexia to facilitate and moderate the initial focus group (§3.1). We further iterated on the ruler designs and reading interface according to feedback from both participants with dyslexia and without (§3.2). This iterative process highlights Accountability, "Designers will respond to poor performance by changing systems, not users, leaving users as they are" [77] .

2.2 Reading Ruler Impacts on Reading Performance

We find little empirical evidence exists on digital reading rulers' effects on reading performance and preference. Avelar et al. implemented a reading ruler spanning three lines of text and reported qualitative evidence from two study participants who reported improved concentration [5]. Jang found the color overlay ruler improved students' ability to accurately identify words through the Wilkins Rate of Reading Test [27]. Two out of a total of three participants read 10-20% faster with the ruler [27]. Though encouraging, these studies do not provide enough data points for statistical significance [71]. We contacted Microsoft's Immersive Reader group about their ruler design, and they responded that at the time of implementation, they neither found prior research demonstrating effectiveness nor existing design guidelines. Likewise, other tooling listed in Table 1 did not publicly report experimental evidence supporting their design choices.

In this paper, we conducted large-scale reading studies to systematically compare four digital reading ruler designs and evaluate them against baselines: no ruler or using a mouse to track reading. Some of these rulers are similar to those available in the other tools mentioned. Our studies were conducted with remote participants performing controlled reading tasks, measuring reading speed, comprehension, and preference. Our work differs from prior research [5, 27] by comparing multiple digital reading rulers simultaneously and presents statistical evidence that digital reading rulers increase reading speed for participants with dyslexia.

Separately, several studies evaluated the effect of color on reading performances but did not reach a consensus. For instance, Denton and Meindl found that color overlay had no effect on reading fluency for readers with dyslexia [18]. On the other hand, Razuk et al. found that a green filter improved reading speed for children [46]. In this work, we focus on evaluating the effect of ruler formats on performance and leave the effect of color to future works.

3 ITERATING OVER DIGITAL READING RULER DESIGNS

Reading ruler designs are available in different physical (Fig. 1) and digital forms (Table 1), but there are no standards by which to validate particular designs or implementation choices. We iterated our ruler and reading interface designs over multiple focus group sessions documented below to address these gaps.

3.1 Initial Focus Group

The initial focus group with seven participants and a moderator was split across two video conferencing meetings that lasted 60 minutes and 80 minutes respectively, separated by five days. The first meeting familiarized the group with the problem readers with dyslexia face, while reading digitally, and the second meeting focused on ideating a set of ruler designs that may support readers with dyslexia and without (Appendix A.1.1 for meeting questions and prompts).

3.1.1 Participants & Moderator. During this phase, the project was internal, therefore we recruited participants[1] applying convenience sampling of employees from the same company with a focus on recruiting experts in accessibility tooling. **P1**: Man, architect in accessibility software with 27 years of experience; **P2**: Man, full stack software developer with 20 years of experience; **P3**: Man, product manager in accessibly software with 20 years of experience; **P4**: Woman, front end developer with 2 years of experience; **P5**: Woman, security engineer with 6 years of experience; **P6**: Man, full stack software developer with 10 years of experience; **P7**: Man, machine learning developer with 18 years of experience. **M1**: Woman, computer scientist and software developer, and the first author of this work. P1-P7 reported no dyslexia and M1 self-reported moderate to severe rapid automatized naming (RAN) dyslexia [2][2]. Participants self-selected to participate in the focus group. They had different motivations for joining, including an interest in developing accessibility tooling, and most commonly because of being acutely aware of the struggles of a friend or relative with dyslexia.

Modern inclusive design practices. M1 recruited the participants and led the focus groups as facilitator and moderator, exemplifying inclusive design techniques including Ability-Based Design [77] and User Sensitive Inclusive Design [35, 36]. M1 led the discussion to focus on readers' *ability* to read and the need to leave them as they are [77]. M1's role as facilitator was to inform participants while designing for the population she is part of, supported by lived experience with dyslexia and assistive tooling [35–37, 41, 66, 70, 79]. To ensure generalizability, we conducted another focus group with a different group of participants (§3.3) and our final evaluations are with crowdworkers with varying degrees and types of dyslexia (§4.1).

3.1.2 Data Collection & Analysis. M1 took notes during the focus group meetings and recorded a meeting transcript. After the meeting, participants could continue the discussion asynchronously in a shared document. After the focus group, M1 reviewed the materials to identify descriptive codes and grouped them into high-level themes [61], each informing a distinctive ruler design (§3.1.4).

3.1.3 Introductory Meeting. The initial meeting focused on introducing dyslexia in depth as well as presenting existing digital reading ruler solutions such as specialized rulers designed for readers with dyslexia (Fig. 1a, c), rulers known sometimes as "dyslexia rulers" with cut-out windows (Fig. 1b), and simple interventions such as measurement rulers and bookmarks (Fig. 1d). Discussion around participants' experience with rulers, if any, followed. M1 then presented participants with common digital reading rulers (Fig. 2a, b, d), and shared her experience as a reader with dyslexia (e.g., skipping and re-reading lines)., then invited participants to ask questions about her reading strategies. P5 asked what M1 sees when she reads and got the response, *"...reading for me feels like I drank too much coffee and I can't keep track of the line that I am reading"*.

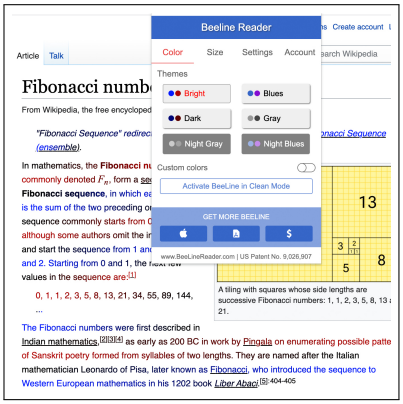
Reading ruler is relatable for readers without dyslexia. Participants P1-P7 were previously unaware of digital reading rulers but reacted positively to the concept. They also identified existing reading strategies they used that mimic reading rulers. For instance, P3 mentioned that "I'm not dyslexic, but I always . . . read using a bookmark". Other participants built on the reading ruler ideas to discuss other ways to support readers with dyslexia and without.

A variety of ruler designs and interaction patterns. Despite the novelty of reading with reading rulers, participants identified a variety of additional ruler designs and interaction patterns that may support readers. After reviewing the currently available reading rulers, participants proposed potential designs, including speed reading, "highlighting a line" with a bright color, and additional interaction patterns, such as controlling the ruler by keyboard instead of mouse and auxiliary text-to-speech feature. During the meeting, participants tried out existing ruler implementations and explored how a ruler affects their reading experience.

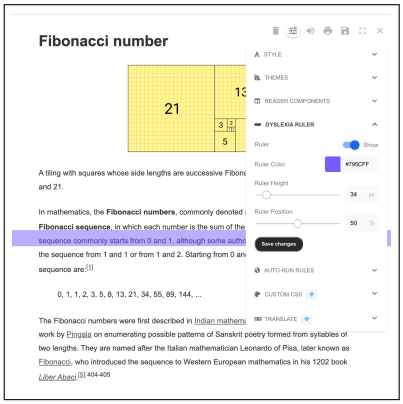
3.1.4 Exploratory Design Meeting. The second meeting took place five days after the initial meeting, to allow participants time to

[1] All study participants provided consent to join the study and have their anonymous usage data collected. IRB was not required for this industry research, but Adobe's user policy applied.

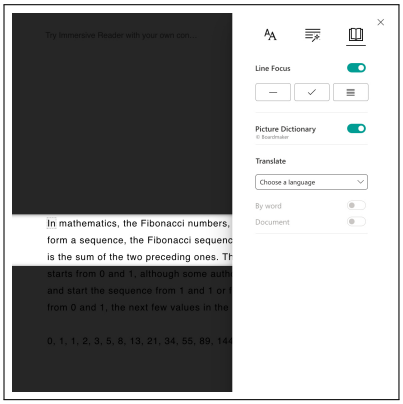
[2] Dyslexia is categorized by varying levels from mild to severe. RAN is a type of dyslexia characterized by difficulties with word retrieval.



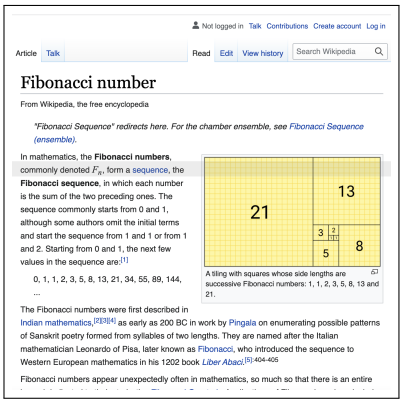
(a) BeeLine automatic text color gradient.



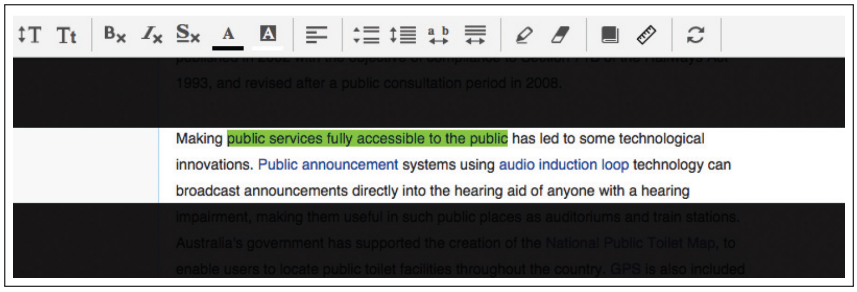
(b) ReaderMode ruler with configuration panel.



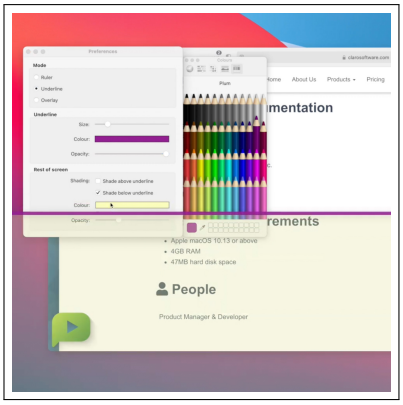
(c) Immersive Reader reading ruler tool with configuration panel.



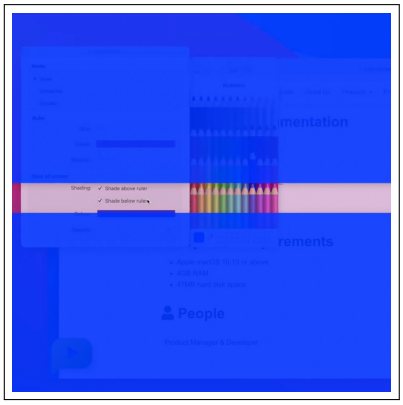
(d) ReadingLine grey bar ruler.



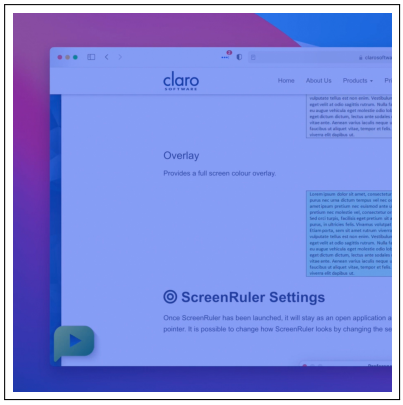
(e) Avelar et al. ruler and configuration panel.



(f) ClaroSoftware Underline ruler with shade below it.



(g) ClaroSoftware Ruler with shade above and below it.



(h) ClaroSoftware Overlay tool.

Figure 2: Reading ruler tools available commercially. (a) BeeLine applies a configurable color gradient to text rendered in the browser; (b) The ReaderMode Chrome Extension requires placing the ruler on the screen, and scrolling the text while viewing the automatically re-formatted page; (c) Microsoft's Immersive Reader snaps text to the window; (d) The ReadingLine Chrome extension follows the mouse cursor while in the browser with a non-configurable grey color applied; (e) Avelar et al.'s research-based approach to creating an interface friendly for readers with dyslexia provides a reading ruler with a configurable height. Claro Software offers 3 tools: (f) underline ruler with configurable options for shade (above and below the underline); (g) ruler with same options for shade (above and below, making the result similar to (c) and (e) except with color options); (h) simple color overlay.

Source	Platform	Format	Interaction	Price (USD)	Image (Fig. 2)
BeeLine [6]	Chrome Extension	Text color gradient	N/A	Free	a
ClaroView [15]	Claro Software	Color overlay	N/A	273 annually	h
Immersive Reader [26]	Applications & Browser	Fixed ruler	Key stroke moves text	5-10 monthly	c
ReadingLine [34]	Chrome Extension	Grey ruler	Ruler moves with cursor	Free	d
ReaderMode [19]	Chrome Extension	Ruler	Fixed ruler	0 - 30 monthly	b
ScreenRuler [15]	Claro Software	Underline, ruler	Ruler moves with cursor	248 annually	f & g
Avelar et al. [5]	Chrome Extension	Ruler	Ruler moves with cursor	Free	e
Avelar et al. [5]	Chrome Extension	Text Highlighting	User selected	Free	e

Table 1: Tools compared in this table include rulers and tools with ruler-like experiences, triggered by different interaction behaviors, and offered on different platforms and surfaces. Each tool requires configuration first in order to display the ruler, except ReadingLine, which defaults to a grey bar.

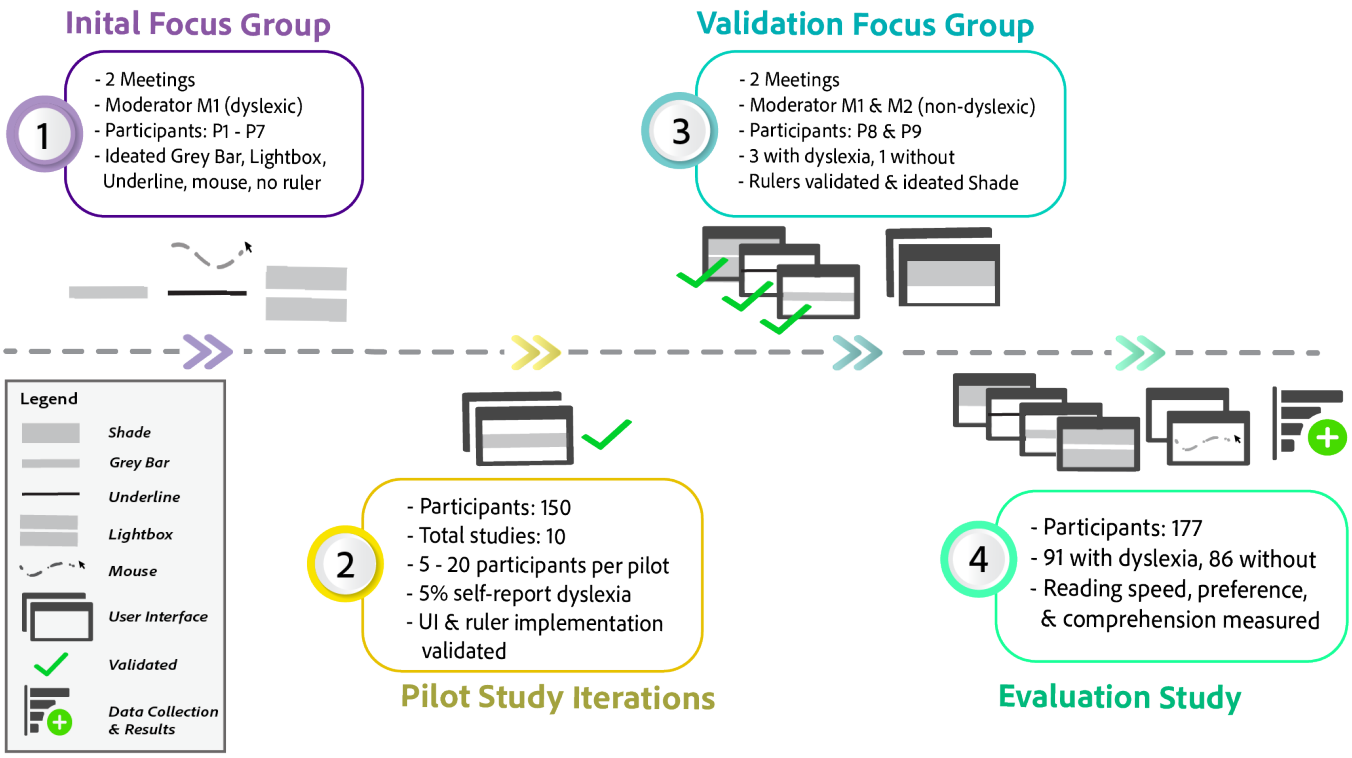


Figure 3: The iterative process of designing, validating, and evaluating digital reading rulers in this study. Initial focus group was conducted over two meetings and produced rulers Grey Bar, Lightbox, Underline, and baselines mouse and no ruler. Then ten iterative pilot studies produced the final interface, refined rulers, and promising results from reading tests. The validation focus group was conducted over two meetings which produced another ruler design, Shade, and validated the revised rulers from the pilot study. The evaluation study revealed Grey Bar, Shade, and Underline increase reading speeds for readers with dyslexia and participants preferred rulers to baselines on average.

reflect on how they read digitally, and to research available software solutions. We started by reviewing the previous meeting notes, asked participants to share their reading experiences since the last meeting, and discussed questions and clarifications as a group. Then, we ideated ruler designs for the pilot study (Appendix A.1.2 for meeting questions and prompts).

Lightbox. Multiple participants returned to the second meeting proposing a similar ruler design they referred to as "Lightbox" (P1, P2, P5, P6), where everything but a row of text is colored (Fig. 4b).

This design shares similarities with existing digital rulers in appearance and mouse-based navigation [5, 15, 26]. The Lightbox design also reminded participants of the physical dyslexia ruler with a cut-out window (Fig. 1b) introduced to them during the previous meeting.

Grey Bar. Participants also proposed "Grey Bar", an inverse of the Lightbox (Fig. 2). It includes a semi-transparent grey bar covering the current row of text (Fig. 4a). We inverted the window and background setting for the Lightbox to create an implementation for Grey Bar (Table 2), resulting in an implementation comparable to existing digital rulers [19, 26, 34].

Underline. M1 suggested a thin black underline, similar to the metal strip off of a wooden ruler (Fig. 1d), which could facilitate reading above or below it based on the reader's preference (Fig. 4d). Compared to other rulers, Underline does not cover any text, and participants recommended that it be shown in text color, commonly black, to enhance contrast (Table 2). While P1-P7 did not like this design and did not foresee it being helpful to the reader, they nevertheless agreed it was a distinct design that should be developed and tested.

Baseline reading experience. Reading without a ruler was considered a baseline (cursor attribute set to "none", Table 2). Directly using the mouse cursor to track reading is also common in web desktop settings, and was therefore identified as a second baseline.

Proposed ruler designs. In conclusion, the group converged on three rulers: *Grey Bar*, *Lightbox*, and *Underline* (Fig. 4a,b,d); and two baselines, *no ruler* and *mouse cursor*. All three ruler designs span the width of the screen, and are controlled by the mouse to mimic the interaction of a physical reading ruler. As the reader moves the mouse, the ruler follows the top of the mouse cursor pointer in real time. More details about the interaction may be found in Section 4.3 and ruler designs in Table 2.

Tool/Baseline	Color (RGB)	Opacity (%)	Height (px)	Width
Grey Bar	187, 187, 187	25	20	100%
Lightbox	187, 187, 187	25	**top:** e.pageY - 14 **bottom:** e.pageY + 14	100%
Shade	187, 187, 187	25	e.pageY - 14	100%
Underline	0, 0, 0	100	2	100%
Mouse	N/A	N/A	16 - 32	16 - 32 px
No ruler	N/A	N/A	N/A	N/A

Table 2: The attributes of each ruler and baseline as rendered in the browser. Each ruler spans from the browser's left edge, through the reading space, and ends at the browser's right edge. Should a reader resize the page, the ruler shape stays the same, shortens, but does not distort in height. Height of Lightbox and Shade are calculated based on the browser's screen, and are drawn to the Document Object Model (DOM) dynamically if the screen size changes. Mouse is enabled by using the default Cascading Style Sheets (CSS) cursor attribute. The no ruler condition disables the cursor with CSS attribute set to none.

3.2 Pilot Study Iterations

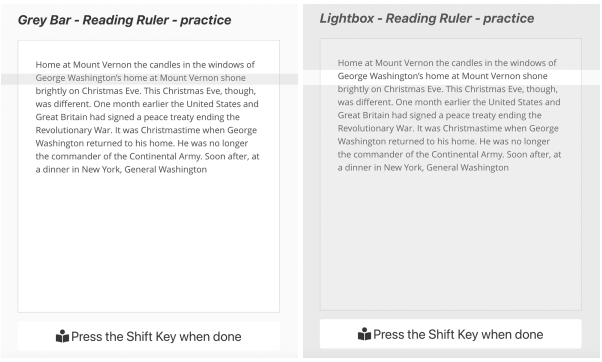
We implemented the proposed ruler designs from the initial focus group in a web application (§4.3) to gauge readers' perceptions of the rulers. We recruited paid crowdworkers from Mechanical Turk and Prolific to perform reading tasks using these rulers and baselines. We collected feedback on the ruler design and study interface to continue to iterate on both [77]. We ran ten pilot study iterations with 150 participants in total, 5–20 participants per study, as we iterated and improved our implementation after each pilot. Across all studies, the participant population consisted of 95% without dyslexia, and 5% with self-reported dyslexia. Here we include only a brief description of the pilot study and learnings; the reading interface is the same as the one described in §4.3.

3.2.1 Study Structure. The study design was adapted from prior, open-sourced readability research [71], and was composed of (1) a presurvey, (2) study instruction screen, (3) practice round, including a reading passage, comprehension and readability questions, (4) five reading rounds including a passage (split across two screens), comprehension and readability question screen (one for each of the three rulers and two baselines), (5) results page, and (6) post survey (Fig. 5). Passages and comprehension questions were randomized while pre, post, and readability questions are not. §4.2 provides additional details for each step.

3.2.2 Data Collection & Analysis. Data was collected using Google Sheets [24] for the pre/post survey data, and a SQLite database was used to store participant time, comprehension, and readability scores. Open coding was conducted on the participants' qualitative responses to identify descriptive codes describing challenges participants encountered when using rulers [61]. Similar codes were grouped together to identify high-level learnings described below (§3.2.5).

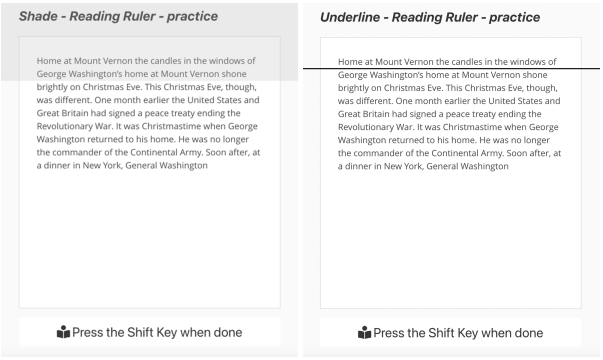
3.2.3 Reading Devices. Participants were restricted to desktop devices which we detected programmatically in our study and additionally by using the Prolific filter which requires the participant to use a desktop computer [43]. Consistent with previous remote crowdsourced reading studies, we did not control settings beyond the browser level, such as their operating system, viewing distance, screen resolution or contrast, and cursor size [11, 74].

3.2.4 Ruler Implementations. We implemented our rulers in a reading interface (§4.3). All three rulers toggled on and off automatically as a participant was taken to the reading passage and hovered on or around the reading view. Once the participant hovered above the reading view or below it (e.g. to click the next button) the ruler turned off again. For each reading passage, participants used a single ruler or baseline. One ruler or baseline was selected randomly per passage without replacement.



(a) Grey Bar

(b) Lightbox



(c) Shade*

(d) Underline

Figure 4: Digital reading ruler designs that emerged from focus group sessions. Designs Grey Bar, Lightbox, and Underline were developed during the initial focus group (§3.1). We mark Shade* with an asterisk since it was developed later, during the validation focus group (§3.3). All rulers are controlled by the reader's mouse, moving with the cursor as if the reading ruler were the cursor itself (Table 2 for more details).

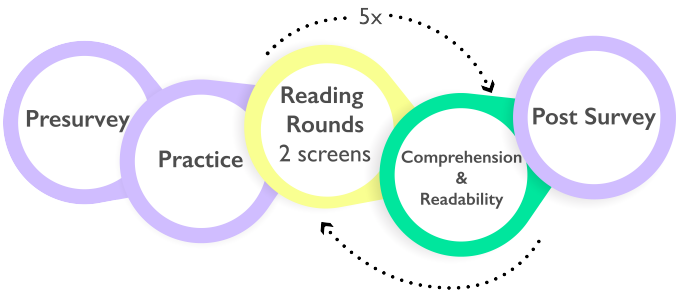


Figure 5: Pilot study design diagram. As we started our pilot studies, we start with this study design. Through 10 pilot study iterations, we take learnings and feedback from participants (§3.2.5) to create an iterative feedback loop improving the study design in preparation for the Evaluation Study (§4).

Ruler	Dyslexic %	Non-Dyslexic %
Grey Bar	24.1	28.3
Lightbox	37.0	25.0
Underline	20.4	18.3
Mouse	18.5	16.7
No Ruler	0.0	11.7

Table 3: Percent of participants with dyslexia and without in our pilot study that preferred each type of ruler or baseline for reading. Grey Bar and Lightbox were the most commonly preferred by both groups.

3.2.5 Learnings. At the end of each pilot study iteration, we asked participants to provide feedback on their experience and ruler preferences.[3] The following improvements to the study and prototype followed after data collection and coding:

- Our rulers previously spanned the entire height of the screen, making it cumbersome to interact with UI controls outside the reading area. We adjusted the design to only display a ruler when hovering over the reading area.
- Participants were initially confused about how to use rulers. Participants typically had no prior experience using digital reading rulers and did not understand what the function of the ruler was while reading; we added a 29-second instructional video showing each ruler which includes the ruler name and a subtext on how the ruler may be positioned on the screen while reading.
- Initially, the mouse cursor was always enabled, creating a "double-ruler" effect when it was used alongside another ruler. We later disable the cursor for all conditions except mouse baseline, to avoid confounds.
- Participants rated their preference for each ruler in the post survey after a results screen showed their reading speed per condition, possibly leading to a bias. We moved the preference questions earlier, to a new screen which combined readability and preference and occurred directly after participants read with each ruler.

At the end of each passage, participants were asked to indicate whether they preferred the reading ruler they just used. Summary of the preference statistics shows that overall, our participants responded positively to the reading rulers (Table 3). Lightbox was the most popular reading ruler among the participants with dyslexia; no participant from this group preferred reading without a ruler. The most popular ruler among the participants without dyslexia was Grey Bar, and 11.7% of the participants preferred reading without any ruler, making it the least preferred experience. Participants preferred different rulers, regardless of dyslexia. Thus, there was no single ruler that all participants preferred. With few participants per pilot study as well as changes to study design and implementation, reading speed, and comprehension measurements could not be statistically compared.

[3]We asked participants *"If you had a magic wand, what your ideal reading ruler look like, and how would it behave?" (§4.5)* and *"Do you have any feedback or comments on the study, reading rulers, or anything we can improve?"* to better understand their preferences and any feedback on their experiences.

3.3 Validation Focus Group

Our pilot study showed promising results for readers with dyslexia and without. We conducted a validation focus group to learn the experience of readers with dyslexia, validate the improved ruler designs after the pilot study iterations, and ideate additional designs involving participants with dyslexia (Appendix A.2 for questions and prompts).

3.3.1 Participants & Moderators. This focus group included more participants with dyslexia, varying in type and severity, based on User Sensitive Inclusive Design [35, 36]. Participants were recruited using convenience sampling and compensated with a $50 Amazon gift card each. **P8**: Man, front end developer with two years of experience, reports clinically diagnosed and treated visual dyslexia [4]; **P9**: Woman, esthetician with four years of experience, self-reports with untreated moderate surface dyslexia[5]. And two moderators, **M1** from the initial focus group (§3.1); **M2**: Man, another author of this work, with no dyslexia[6].

Modern inclusive design practices. Reading rulers Grey Bar, Lightbox, and Underline were ideated by software and accessibility tooling experts in the initial focus group (§3.1). We applied User Sensitive Inclusive Design [35, 36] by recruiting diverse dyslexic participants and focusing their lived experiences in the validation focus group introductory meeting (Appendix A.2.1). Then, while ideating new ruler designs, we highlighted data collected in the introductory meeting (Appendix A.2.2) to keep the focus on common themes during the validation design meeting. M1 and M2 both facilitated the session and M2 played the active role of prompting the group during this session, similar to M1's role in the initial focus group (§3.1); while M1 contributed by sharing experiences to prompt the P8, and P9 accordingly [37, 41, 66, 70, 79].

3.3.2 Data Collection & Analysis. Two authors both took notes during the meeting and recorded the meeting transcript. After the meeting, the authors reviewed the notes and transcripts to come up with descriptive codes jointly and summarized them into high-level themes [61] (Appendix A.2.1).

3.3.3 Introductory Meeting. The validation focus group was similar in format to the initial focus group. We split the focus group across two video conferencing meetings of 50-60 minutes each (Fig. 3), five days apart. The first meeting was aimed at learning about the reading experiences of the group of diverse dyslexic readers.

Digital reading comes with similar challenges for readers with diverse dyslexia. P8, P9, and M1 reported similar reading experiences despite variations in their background and types of dyslexia. P8, P9, and M1 also started reading later than usual, at ages around 7 – 9 and used physical reading rulers (as in Fig. 1) as students. They reported skipping lines, misreading the text, and poor spelling when reading. Additionally, they all avoided reading long-form text, and generally preferred podcasts and audiobooks to reading.

Need for focus when reading. Participants cited the need to read with focus and found images and additional text distracting. Despite their previous experience reading with physical rulers, P8 and P9 did not know about digital reading rulers but thought it would be helpful to facilitate concentration. All participants reported this session as their first experience sharing their reading experiences with other adults with dyslexia.

3.3.4 Validation Design Meeting. Participants and moderators met five days later, to ideate new ruler designs and iterate existing ruler designs where necessary. M1 and M2 reviewed themes found in the introductory meeting, opened up for questions or clarifications, then invited participants to share observations or findings during the time apart (Appendix A.2.2). We analyzed and summarized the learnings from the second meeting to inform and validate the ruler designs, using an approach similar to the first meeting.

Underline was more popular among participants with dyslexia. Participants agreed that the digital reading rulers would likely achieve similar results as the physical rulers and benefit readers with dyslexia. P8 and P9 favored Underline (previously proposed by M1) because it has high contrast and takes up less space on the screen. Other rulers, such as Lightbox, take up a larger portion of the screen and make reading challenging on websites with multi-column layouts of pictures, tables, and text. They agreed it would work well on mobile surfaces, such as in "Reader" on iOS[7].

Shade as a new reading ruler design. Participants all reported using a strategy to cover the text they have already read. When reading on their phone, P8 and M1 would scroll to hide the text as they read, using the top screen bezel to keep their focus on the current line. P8: "I look at the top line and scroll the text to it, so I don't have to move my eyes down." P9 described using a bookmark to cover the text already read either on Kindle or in physical texts.

From this discussion, P8, P9, and M1 converged on a new ruler design — *Shade*: a design identical to the top half of Lightbox (Fig. 4c). P8, P9, and M1 agreed this design should behave as if one was pulling down an overlay from the top of the screen. This design mirrored P9's use of a bookmark, and P8 and M1's use of the screen bezel to cover the text read.

Optional visual features for the rulers. A discussion around Lightbox's popularity in the previous focus group (§3.1) triggered a subsequent discussion around improving it for the needs of participants with dyslexia. M2 suggested blurring out the text instead of using color, an idea appealing to P8, P9, and M1. However, considering applications in the browser, the group concluded blurring would make it difficult to rediscover one's place in text should they lose it.

Color and opacity of Grey Bar and Lightbox rulers were discussed in the context of UI configurations. P8, P9, and M1 expressed that while reading, the need to configure the ruler felt cumbersome. They simply wanted to switch the ruler on and start reading. Black

[4]Visual dyslexia affects one's ability to learn and recognize letters and groups of letters, and subsequently words [78]

[5]Surface dyslexia is best characterized by one's ability to recognize words with irregular spelling (e.g. archive, colleague, piece) and therefore leads to phonologically plausible errors [67]

[6]M2 focused on note-taking during the study and did not participate in discussions around reading experiences.

[7]Apple's Safari/IOS Reader converts webpages into plain text and allows the user to select format presets [1]

and grey were preferred, and highlighter colors were expressed to be too bright for regular use by P8 and P9.

3.3.5 Final Ruler Designs. The two rounds of focus groups converged on Grey Bar, Lightbox, Shade, and Underline rulers (Fig. 4 for visuals and Table 2 for ruler attributes). Similar to the initial focus group and pilot study, as a reader moves their mouse over the text area, the ruler automatically appears and follows the mouse cursor.

4 EVALUATING READING PERFORMANCE WITH DIGITAL READING RULERS

In this section, we evaluate the reading ruler designs that emerged from the focus groups. Our evaluation consisted of a within-subjects remote reading test, where crowdsourced participants read with each reading ruler and baseline. The web application recorded their reading speeds, comprehension scores, and preferences. Our full study consisted of a dyslexia screener [16], presurvey, practice round, main study, and post survey (Fig. 6), which took participants between 20 and 50 minutes to complete, and we compensated participants $10.75 per hour (for comparison, the base pay rate on the platform at the time was $8.50 per hour).

4.1 Study Participants

We recruited 313 participants from Amazon's Mechanical Turk (38% of participants) and Prolific (62%), with ages 18–74. We used Prolific's learning disabilities filter to recruit participants with dyslexia. We then calculated each participant's dyslexia score using the Revised Adult Dyslexia Organisation screening [16] as explained below. Readers with dyslexia were rarer on the crowdsourcing platform. To recruit enough participants with dyslexia, we set up a separate study with a screener for dyslexia [16]. Participants who did not self-report having dyslexia and/or coexisting conditions, or those who scored less than 13 points on the screener did not continue to the main study but were paid 20-50 cents for the time spent on the 1-2 minute screener.

We removed individual reading speed measurements (per condition and per screen) below 50 or above 650 words-per-minute (WPM), similar to prior work [12, 13, 71, 73, 74]. We used 50 WPM as the lower bound since prior work finds readers with dyslexia read slower than readers without dyslexia [29]. We also removed a participant's data if they met one of the exclusion criteria: (1) did not submit a pre or post survey, (2) self-reported not being "very comfortable" reading in English, (3) self-reported being under the influence of any medications, drugs, or alcohol, (4) reported cognitive disabilities outside of known dyslexia coexisting conditions [39], (5) their reading comprehension scores were outside the normal distribution (computed using the interquartile range method), and (6) if there were missing reading speed measurements for any condition.

After the previous filtering steps, our final analysis was based on 177 crowdworkers' data: 86 without dyslexia and 91 categorized as "dyslexic": participants who both (1) reported a prior diagnosis of dyslexia or coexisting conditions in the presurvey, and (2) scored 13 or higher on the dyslexia screener [8].

[8]According to [16], scores of 13 are categorized as 1 in 7 chance of dyslexia, considered to be high likelihood for dyslexia.

It is well established in the dyslexic community to choose assessment with a clinical specialist over screening for dyslexia [20, 42, 60]. While assessment is preferred, screening is acceptable with the knowledge of its limitations [3, 30]. Prior research recognizes the coexistence of ADHD and Autism within the dyslexic population [20, 22, 39]. Our work differs from prior research, which solely recruits participants with clinically diagnosed dyslexia. Since clinical diagnosis and government definitions of dyslexia have changed over time, and our study tests adult readers, we recruited self-reported readers with dyslexia [65] and did not filter out participants with coexisting conditions. We then screened participants using an adult screen for dyslexia which consists of 12 polar questions [16]. We chose this screener because of its simple questions and output probability of dyslexia (instead of a binary result: dyslexic or not).

4.2 Study design

Presurvey & instructional video. Participants first completed the dyslexia screener and presurvey. The pre-survey asked about demographic information, current reading environment, reading frequency (how often they read for work or leisure), and diagnosis for dyslexia or other cognitive or learning disabilities. Participants then watched a 29-second tutorial video that introduced the study interface and how to utilize each ruler. We added the instructional video after pilot study feedback from participants.

Practice reading round. During initial untimed reading rounds, participants practiced using each ruler. Participants then performed a full-length practice round with breaks and an initial instructional screen. We recorded the practice round reading speeds and comprehension, but these scores did not contribute to their overall performance.

Main study. In the main study, participants completed a series of steps for each ruler and baseline: (1) read a randomized passage, split evenly across two consecutive screens; (2) answered comprehension questions with three multiple-choice questions; (3) answered three readability/preference questions (Fig. 6). Participants were encouraged to take breaks after these questions. Once a participant clicked into the next reading round, we started the timer. We stopped the timer once the participant completed each reading screen and pressed a key to continue. After they completed the reading rounds, we displayed their results which showed each ruler and their score in words-per-minute (WPM). WPM was averaged across the measurements taken from both reading screens, similar to other readability research [71].

We used eleven eighth-grade (13-14 years old) English reading passages with multiple choice comprehension questions curated by a reading specialist [71] (Lexile range[9]:800–1200, Flesch score[10]: 60.5-79.8). Comprehension questions corresponded to both halves of the passage, ensuring participants read both screens of the passage carefully to answer questions correctly. Participants answered one readability question on a 5-point Likert scale (not at all to extremely), *"How familiar are you with the previous passage?"*, and two preference questions on a 5-point Likert scale (strongly disagree to strongly

[9]https://hub.lexile.com/analyzer
[10]http://www.readabilityformulas.com/free-readability-formula-tests.php

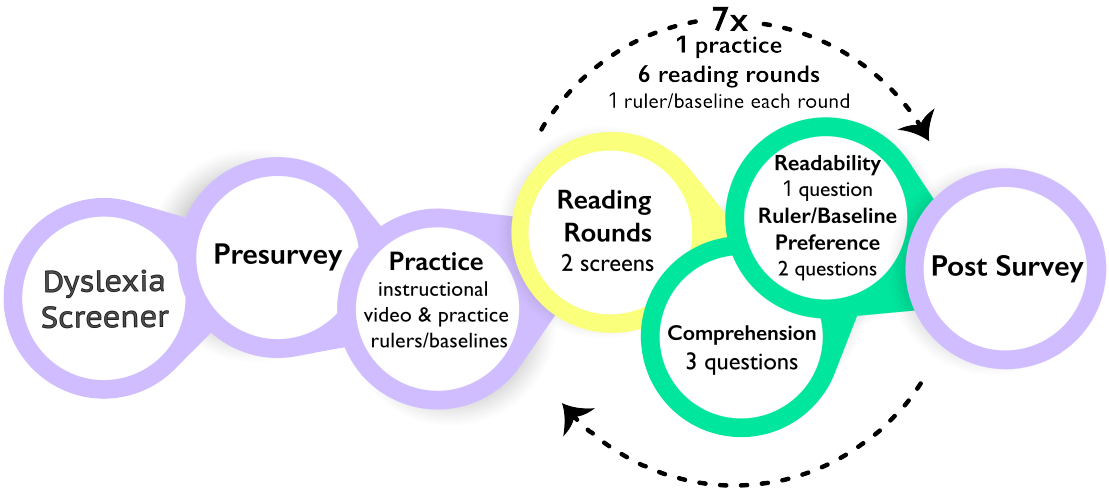


Figure 6: Reading ruler evaluation study design. Each participant completed a dyslexia screener, presurvey, then a practice round of reading prior to the main study. They then read each passage followed by three comprehension questions and three readability/preference questions. This was repeated seven times, with each of the rulers and baselines. Participants were then shown their reading score before completing a post survey.

agree), *"The reading ruler (or lack thereof) helped to understand the passage better."* and *"The reading ruler (or lack thereof) was helpful to read faster with."*.

Post survey. At the end of the study, we asked participants preference and feedback questions. Including what their favorite ruler was (if any), how they would design their ruler, how they used the rulers, their experience level with using a reading ruler, and whether they would take 2-3 minutes to install a digital reading ruler if one were available.

4.3 Reading Interface

We implemented a single-page web application in JavaScript, CSS, and HTML. Rulers and baseline conditions (mouse and no ruler) were randomized during practice and reading rounds and automatically appeared on the page once a participant hovered over the reading area (or to the left or right of the reading area boundaries, Fig. 4). One ruler was displayed per reading passage.

Ruler & baseline implementation. Our ruler implementation differs from previous approaches in two ways: (1) no configuration is necessary to use or apply the ruler, (2) our ruler designs were selected in focus groups with participants with dyslexia and without. Because of the lack of standardization for which colors are best for readers with dyslexia [46] and the discussions that emerged in our second focus group, we evaluated the effect of rulers without color.

A ruler is rendered in real time while the cursor hovers over or outside the reading area. The ruler disappears once a cursor moves below or above the reading area, and the mouse cursor with the pointer attribute reappears. When a ruler is active, the mouse cursor is not visible. We included the mouse and no ruler conditions to simulate everyday reading experiences in the browser. Mouse has the cursor pointer attribute enabled. In the no ruler condition, the mouse cursor is shown everywhere except in the reading area. In our pilot study, we removed the cursor left and right of the reading area, leaving participants disoriented. The solution to only remove the cursor in the reading screen reduced confusion. Double-clicking and highlighting or selecting text is disabled for all conditions to evaluate the reading rulers in isolation of additional actions and visual cues.

User interface. The reading area included black text on white background, intended to match typical web design. The reading area was a fixed 500px height by 480px width. Font was 16px (12pt) normal, the standard font size in Chrome and Firefox. Open Sans is a Sans Serif font and was chosen since it is the second most commonly viewed font on the web [23]. Sans Serif fonts with 16px size have been found to be good fonts for readers with dyslexia [50, 58]. Character and word spacing was set to 0, while line spacing was set to 1.5, reflecting recommendations between 0.8-1.8 as beneficial for readability and comprehension [58].

Following feedback from our pilot study, we improved the usability of the reading interface. Instead of navigating to a "Next" button, readers proceeded to the next reading screen by pressing the shift key. We implemented a two-second timer on each screen to prevent accidentally skipping reading screens. These methods allowed for the system to record more accurate reading speed measurements.

The web application fixed a reader's browser zoom level to 100% and disabled participants from changing it during the study. This ensured all participants viewed the interface in the same aspect ratio. The name of the reading ruler or baseline was displayed at the top of the screen, outside the reading area, to help participants associate the ruler with a name for post survey preference questions.

Ruler 1	Ruler 2	N	t	Corrected p	Cohen's d
Grey Bar	No Ruler	91	3.06	<0.01	0.23
Grey Bar	Lightbox	91	3.74	<0.01	0.27
Grey Bar	Mouse	91	3.76	<0.05	0.30
Shade	Mouse	91	2.60	<0.05	0.26
Shade	Lightbox	91	2.95	<0.05	0.23
Underline	Mouse	91	2.59	<0.05	0.22
Underline	Lightbox	91	2.69	<0.05	0.18

Table 4: The effect of reading rulers on reading speed across participants with dyslexia. Only ruler pairs that resulted in statistically different WPM are shown in this table. We used the Benjamini-Hochberg procedure to control for false discovery rate. Grey Bar when compared to no ruler, Lightbox, or mouse increased reading speeds, which was our most significant finding on reading speed gains. All three rulers (Grey Bar, Shade, and Underline) when compared to mouse or Lightbox increased reading speeds for readers with dyslexia.

4.4 Results: Ruler Effectiveness for Digital Reading

We compared the reading speed, comprehension, and preference measurements across the reading ruler designs (Fig. 7). For participants with dyslexia, rulers had a significant effect on reading speeds based on the one-way ANOVA test ($F = 4.70, p < 0.01$). We used paired t-tests to evaluate differences in reading speeds between pairs of rulers used by each participant. After using the Benjamini-Hochberg procedure to correct for false discovery rate [7], we found statistically significant increases to reading speeds for Grey Bar when compared to Lightbox, mouse, and no ruler (Table 4). We also observed that Underline and Shade helped participants read faster when compared to both Lightbox and mouse. For participants with dyslexia, reading with Grey Bar, Shade, and Underline led to speed increases of 19, 16, and 12 WPM on average when compared to no ruler. Rulers did not have a significant effect on comprehension for participants with dyslexia, nor did they significantly affect reading speed or comprehension for participants without dyslexia [71] (Fig. 7a, b).

When evaluating helpfulness, we asked participants to respond to "the reading ruler (or lack thereof) was helpful to read faster with" using a 5-point Likert scale from strongly disagree (0) to strongly agree (4). We compared their ratings to their answer when no ruler was used to obtain the numerical scores in Fig. 7c. Participants with dyslexia found Lightbox particularly helpful, even though a larger speed gain may be possible with Grey Bar.

Participants were also asked which ruler they preferred most in the post survey. We compared this response to our reading speed and comprehension measurements. Less than a third of the participants (52/177, or 29.4%) read fastest using the ruler they preferred (Fig. 8). Lightbox was preferred over all other rulers, similar to the observations from our pilot study (Table 3). Interestingly, not using a reading ruler was among the fastest conditions for reading, but was also the least preferred by readers with dyslexia and without, alike.

4.5 "If you had a magic wand..."

What would your ideal reading ruler look like, and how would it behave? We asked this question of participants at the end of the pilot study and evaluation study, to help us understand opportunities for improving ruler designs and interaction. To maximize the amount of qualitative data, we adopted a different data filtering approach from the quantitative results above by manually filtering out only nonsensical and empty responses, resulting in 341 answers to this question. Participants' discussions generally focused on their most preferred reading ruler. In addition to using the ruler names from the study, they often used the word "highlight" or "background color". Among the rulers discussed, the mouse received discussion from 8 participants, Shade from 27, Lightbox from 41, Underline from 43, and Grey Bar from 94. We conducted structural coding [75] on participants' feedback focusing on ruler designs, reasons supporting ruler preferences, and suggestions for interaction patterns. Below are our findings grouped by high-level themes identified.

4.5.1 Rulers Improved Focus. The most cited reason for choosing a ruler was to "keep my place" and "focus", similar to the qualitative finding from Avelar et al. [5]. We highlight this feedback since we evaluated both participants with dyslexia and coexisting conditions, namely ADHD; groups that may need the ruler tool for different reasons. Nine participants cited "focus" as the main reason for choosing Grey Bar, seven for Lightbox, and one for Shade. One participant chose Lightbox for better comprehension, saying that "I know I read fast with others [rulers], but I felt like I comprehended the text better with it".

4.5.2 More Color. Color was an important consideration for many participants. However, color choice differed by rulers. Six participants discussing Shade voiced a need for darker colors. Most specified their ideal format to be "a little darker" while keeping text "visible". For Underline, two participants wished for a blue or grey, in place of the black color used for the study. Another participant suggested having an underline in a distinct color for each line of text. On the other hand, participants often preferred "soft" or "light" colors to be used with Grey Bar. One participant similarly wished to highlight each line in a distinct color, stating that "it helps distinguish them as multiple entries in my head."

4.5.3 Ruler Navigation. Participants suggested using the keyboard for navigation, e.g., "I'd like it if I could control the grey bar ruler with the keyboard, perhaps the up and down arrow keys." An additional 24 participants suggested using eye tracking as an alternative. One mentioned that ideally, the ruler "would follow where my eyes were going, like an eye tracker or something, then I wouldn't have to use my hand on a mouse."

4.5.4 Composite Rulers. Participants also voiced the need for rulers that combine several of the current designs. For instance, one participant said they preferred "a black underline with what I've read and the rest [of the text] shaded", and another hoped for a ruler that "underline[s] the words and block[s] out the next line." Those preferring Shade proposed adding other rulers to further block out distractions.

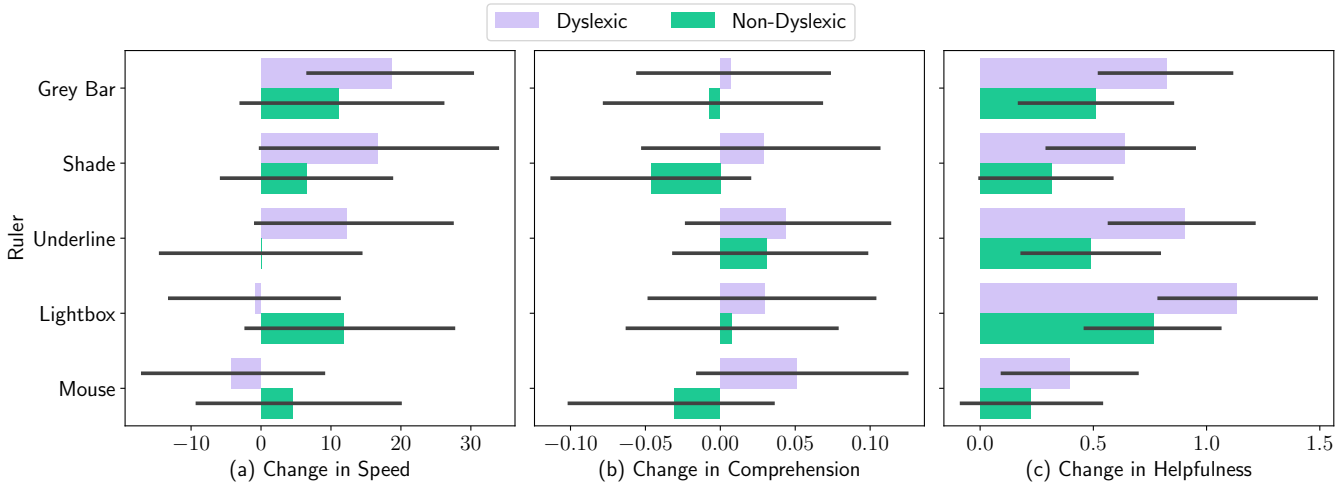


Figure 7: The relative change to each participant's performance when compared to no ruler. Speed was measured in words per minute (WPM); comprehension was a fraction of questions answered correctly (1 was a perfect score when all three questions were answered correctly); helpfulness was based on a 5-point Likert scale. These graphs together show that Grey Bar and Shade led to largest gains in reading speed for readers with dyslexia. The most helpful rulers were (in order): Lightbox, Underline, Grey Bar, and Shade.

Underline is cited as an effective add-on to other rulers, and Grey Bar and Underline form the most popular combination. Participants suggested adding it to Grey Bar, Lightbox, Shade, and mouse. For instance, one mentioned, "I'd have a black underline with a highlight box above it." Another wished to use it with the mouse to "underline each word as I read it." One participant suggested staggering Underline and Grey Bar, resulting in a ruler that "would highlight each sentence clause and underline the next clause".

4.5.5 Ruler Granularity. While the rulers used in this study helped participants focus line by line, 60 participants expressed the need for word-level focus with the rulers, citing their preference to focus on words rather than phrases or sentences when reading. For instance, one participant mentioned that "[their ideal ruler] would probably move word by word rather than line by line. My reading pattern doesn't seem to track the end of the line the way these rulers do." The emphasis on words is prevalent among participants who preferred to use the Grey Bar. Among them, 28 of 60 preferred highlighting texts by word instead, citing that it would help them better "keep their place" when reading.

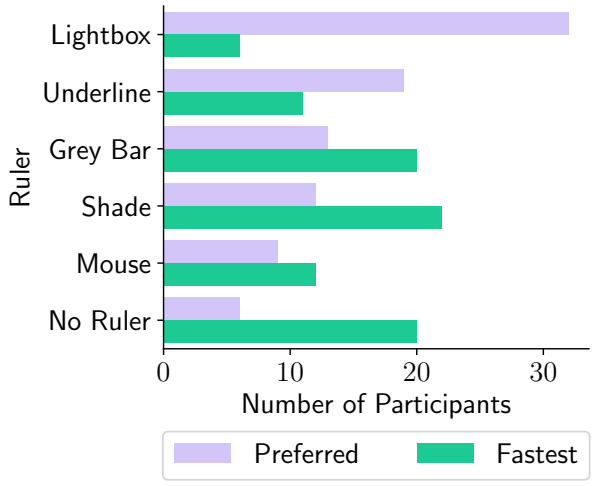
Some preferred phrase-level highlighting. For instance, one participant mentioned their need for "highlighting a few words of text on a line at a time to focus attention on a particular part of the sentence." On the other hand, 15 participants mentioned the need for sentence-level focus with reading rulers. Among this group, six requested the use of the Grey Bar to "highlight the sentence they are currently reading." No participant expressed the need for paragraph or character-level highlighting.

5 DISCUSSION

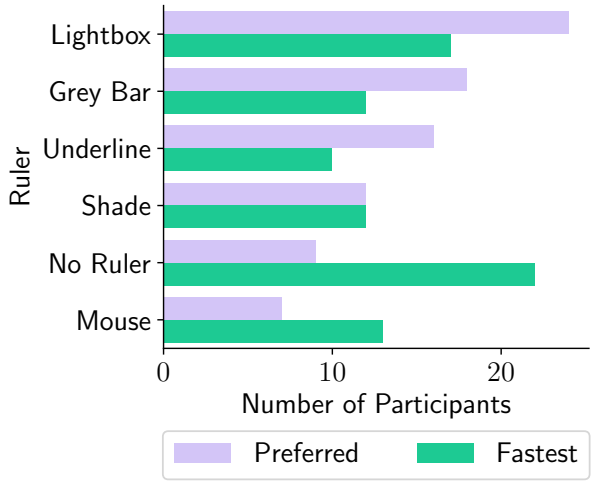
Multiple iterations of focus groups based on inclusive design principles led us to evaluate four reading ruler designs: Grey Bar, Lightbox, Shade, and Underline. Participants with dyslexia and without designed these rulers which were then evaluated on crowdsourced participants with dyslexia and without. This process allowed participants with dyslexia to voice designs they may find helpful. Including participants without dyslexia in the initial focus group (§3.1) opened up the possibility of testing reading rulers on readers without dyslexia, which we did not find prior research on. To quantify the benefits of different reading ruler designs and compare them to baselines (i.e., either not using a ruler or using a mouse cursor for tracking, a common browser reading experience), we evaluated participants' reading speeds, comprehension, and subjective evaluations. After reading with each ruler or baseline, we asked participants whether it was "helpful to read faster with". In the post survey, we asked participants to report their favorite ruler.

5.1 Inclusive Design

It is important to circle back to User Sensitive Inclusive Design and Ability-Based Design [35, 36, 64]. Our results show participants with dyslexia can create tools that work for them. Grey Bar was proposed by participants in the initial focus group, based on the tool M1 uses regularly, a simple grey bar from ReadingLine Chrome Extension (§3.1). Underline was proposed as a distinct design in the initial focus group by M1 (§3.1), then validated during the validation focus group with participants with diverse types of dyslexia (§3.3). Shade was created inclusively among P8, P9, and M1 in the validation design meeting after recognizing similar reading behaviors across the group (§3.3.4). All three designs subsequently showed improved reading speeds for readers with dyslexia. While our initial focus group included a single participant with dyslexia, we exemplified User Sensitive Inclusive Design principles by "an attitude of mind than simply mechanistically applying a design for all guidelines" while recognizing "the difficulty in finding and recruiting



(a) Dyslexic participants.



(b) Non-dyslexic participants.

Figure 8: Preferred versus fastest ruler across participants. A reader's preferred ruler is not necessarily their fastest. Note that multiple rulers may be the fastest for any given participant.

representative users" [36]. Echoing these principles, working to validate designs with diverse readers with dyslexia was an important piece of our work (§3.3). This inclusive approach can provide mutually beneficial outcomes for individuals with and without specific reading differences, and echos the need to design inclusively with, instead of for, populations with different abilities [8].

5.2 Comparison with Previous Ruler Designs

Our approach helped us validate the design of the previous reading rulers using inclusive design practices. Consistent with previous rulers, our ruler designs also include a mouse-controlled ruler that moves through the reading passage, and the rulers similarly facilitate concentration by highlighting a portion of the passage [5, 15]. Our Lightbox ruler resembles the ruler designed in Avelar et al. and ScreenRuler from Claro Software [5, 15]. The ruler in Avelar et al. completely hides text above and below the ruler, while Lightbox in our study and ScreenRuler both showed transparent overlay instead. Compared to the ruler from Avelar et al., the Lightbox design spans only one row of text instead of three. Our Underline is similar to ScreenRuler's underline option and Grey Bar is similar to ReaderMode's ruler, ReadingLine's grey bar, and Immersive Reader's ruler. Conversely, we did not identify an existing design that is similar to Shade. In this work, all four of our proposed designs were evaluated in the same reading interface using a common interaction, allowing us to compare and contrast these distinct design options.

5.3 Different Rulers Perform Best According to Different Metrics

Lightbox was the favorite ruler among both participants with dyslexia and without alike, and reading without a ruler or with a mouse cursor were the least preferred options amongst both groups of participants. When comparing reading speed, we found that readers with dyslexia read fastest using Grey Bar, while readers without dyslexia read fastest without a ruler on average. We did not find any significant effects of reading with or without rulers on comprehension. Previous research has shown that performant options may not be the most preferred [11, 71], and common reading performance objectives, such as speed and comprehension are challenging to optimize simultaneously [21, 32, 47, 72]. Despite the variation in reader demographics, preference, and reading objectives, our finding shows that both readers with and without dyslexia may find reading rulers helpful when reading digitally. Our work offers the most comprehensive evaluation to date of reading rulers, consistent in population size with recent readability studies [11, 29, 52, 71]. In comparison, prior work [5, 27] provided evaluations with 2-3 participants (§2.2).

5.4 Availability & Discoverability

In our second focus group session (Section 3.3), 2/3 participants with dyslexia had no prior experience with digital reading rulers. Indeed, other work [25, 33] has also reported that the average reader experiencing dyslexia or other reading difficulties doesn't make use of accessibility software. In our study, we considered participants with dyslexia and coexisting conditions. Prior work has found people with coexisting conditions were sometimes left undiagnosed or misdiagnosed [22, 39]. One potential reason for low uptake of similar tooling may be a lack of awareness, combined with the categorization of such tooling to be "accessible" tools not offered by default. Claro Software makes its tools available at the operating system level, as specialized software at a fee (Table 1), and may not be discoverable by the average reader. In Section 3.3 we discussed Chrome Extensions available for free for participants with dyslexia. We found this option worked for most browser webpages, but not PDFs rendered in the browser. Participants argued this was one of the most important use cases. Tooling available through Adobe Acrobat which renders PDFs, and includes some accessibility options, contains no ruler or color overlay options today.

5.5 Limitations

Remote readability studies trade internal validity, often found in eye-tracking studies, with applied validity by studying readers in their natural reading environments. While this research provides promising results on digital reading rulers, our conclusions are based on a population of 177 paid crowdworkers. Future remote work may consider using tools such as a virtual chinrest to add more control or explore using eye-tracking in a remote environment [28, 29, 57, 71]. Additional limitations include:

- Participants in our focus groups, pilot, and evaluation studies all had English as their first language, so we only considered English-speaking readers with dyslexia.
- We do not have user session recordings to determine whether participants used other assistive technology with the reading rulers. Past research showed that multi-modal reading, such as the combination of screen reader and text, may help readers with dyslexia [5, 54].
- We focused on a low-tech intervention, reading ruler; we recognize there are sophisticated tools [49, 51, 59] and modern programs [10, 62] to help mitigate the effects of dyslexia for students.
- We studied the effect of digital rulers on adult readers; future research may apply a similar study design framework with younger populations, using the rulers suggested in our study.
- We fixed the height and width of the reading screen, so scrolling was not required in our study. Therefore, more research is needed to understand the interaction between scrolling, and/or keystrokes.

6 CONCLUSION AND FUTURE WORK

In this work, we designed digital reading rulers inclusively, tested and improved ruler and reading interface designs, then conducted a validation focus group with participants with diverse experiences of dyslexia. Our ruler designs were ideated, implemented, then evaluated.

Our results show Grey Bar, Shade, and Underline rulers increased reading speeds for readers with dyslexia. While we did not find an increase in comprehension for dyslexic readers in our study, more research is needed to understand populations of dyslexia and associated coexisting conditions better, and how tooling affects these readers.

Although readers without dyslexia did not show increased reading speeds on average, they preferred reading with a ruler compared to the mouse or no ruler conditions. Lightbox ruler was a favorite among all readers but did not significantly increase reading speed in either population. More research may explore the trade-off between reading gains such as reading speed and/or comprehension to preference, motivation, or stamina while reading.

Prior research and tooling using color overlays showed that colors can allow dyslexic readers to read faster and with less eye strain [27, 76]. However, there may be a correlation with the width of the color overlay, underline, and subsequent text beneath it. This may be similar to having a background page color, which has shown to be beneficial for readers with dyslexia [55]. We used Grey Bar, Shade, and Underline as separate patterns and controlled the effect of each ruler (on top of white background and black text). Unsurprisingly but delightfully, we found that Grey Bar, Shade, and Underline rulers individually positively affected reading speeds for dyslexic readers without any other text augmentation applied. Our results agree with the findings for physical color overlays [18, 46], and digital representations of color overlays [27]. More research is needed to explore the effects of composite ruler types in a remote setting.

We used a typical webpage reading environment in our study to determine if the average reader can be aided by tools readily available on the web (Table 1). Future work can layer rulers with webpage and text augmentations found to benefit readers with dyslexia to determine which interventions are most effective and comfortable to readers [14, 17, 25, 28, 33, 52, 56]. This may aid government agencies and schools, as well as provide designers with guidelines for making reading more equitable for readers with dyslexia and coexistent conditions.

Future work can further explore in-person eye-tracking studies on readers with dyslexia and associated coexistent conditions using the digital reading rulers we developed. This may provide additional insights into how digital rulers affect the reading patterns of readers with dyslexia.

We believe that the lack of availability and design guidelines, as well as low awareness are currently the main deterrents to the widespread discoverability and use of rulers. This work demonstrates that digital reading rulers can be an effective tool for many readers. Indeed, additional external validation for this work came after we shared some of the research on digital reading rulers with an external audience (Appendix B). The unprompted feedback reinforced some of our designs (including Shade acting like the top/bottom of a screen; and physical versions of Line using a pencil to track lines), the struggles faced by readers with dyslexia, and the need for such tooling to be more broadly available. We hope our work lays the groundwork for a future where inclusive design is the norm which guides the next generation of readability, usability, and accessibility tools.

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A FOCUS GROUP QUESTIONS AND PROMPTS

A.1 Initial Focus Group

A.1.1 Introductory Meeting.

- Introduction round table
- Outline the goal of the focus groups: Information gathering on various reading rulers in production & what tool might be implemented for the pilot study for testing effectiveness
- When you learned to read, do you remember using a hand, finger, or bookmark to follow a line of text?
- Define dyslexia & some reading experiences readers encounter while reading
  - Dyslexia definition(s)
  - Dyslexia range (mild, moderate, severe)
  - Ailments: Re-reading lines/rows of text, kipping lines, low comprehension, slow reading
- Has anyone heard of a reading ruler? And/or used one before (or know someone with dyslexia who has)?
  - Follow-up question: what tool was it? How did it behave? What was the experience like? Did the person prefer the experience?
- Do you know what a digital reading ruler is?
  - Show reading rulers/alternative tools ReadingLine, BeeLine, readermode.io
  - Explain ways to utilize ruler tools
- How can we simulate/mimic the experience of reading with a reading ruler or color overlay on digital surfaces?
- Open up for questions

A.1.2 Exploratory Design Meeting.

- Review the previous meeting
  - Open up for questions or clarification
  - Review shared document and prototype contributions
    - Each person is to present their findings, prototypes, and/or ideas
- Outline the goal of the session: Narrow down the designs to be implemented in the pilot study
  - What is the surface and interaction?
  - How many distinct designs should be tested?
- Which surfaces (mobile, tablet, phone, desktop) afford the most flexibility?
- Mobile
  - Should the ruler interaction be the same in the browser as in mobile?
  - Is a reading ruler needed or helpful on mobile surfaces?
- Color
  - Should we use color? If yes, how do we choose the color the participant first sees?
  - Should the participant be able to change the color of the tool during the study?
- Discoverability & Enablement
  - How does the participant learn how to turn on the ruler?
- Dark mode (stretch topic)
  - How does the ruler behave in dark mode?

A.2 Validation Focus Group

A.2.1 Introductory Meeting.

- Introduction round table
- Outline the goal of the session: Learn the experiences of participants and introduce rulers Grey Bar, Lightbox, and Underline (already developed for the pilot study)
- What has been your experience with reading? (Entry point to talking about reading differences)
  - If you feel comfortable with it, could you share how dyslexia affects your reading? I'll (M1) go ahead and share first...
- Reading as a person with dyslexia
  - How often do you read?
  - What applications or reading environments do you prefer to read in?
  - What makes for a bad reading environment?
  - Do you prefer to read on digital or physical surfaces (or neither - audio)?
- Did you use a reading ruler while learning to read?
  - If so, what did it look like and can you describe it?
  - When was it introduced (before or after you knew you had dyslexia)?
- Do you use a digital reading ruler?
  - If so, which do you prefer?
  - If not, show reading rulers/alternative tools ReadingLine, BeeLine, readermode.io

A.2.2 Validation Design Meeting.

- Review of previous meeting
  - Review themes found in previous meeting, namely reading experiences shared by the group
  - Open up for questions/clarification
- Outline the goal of the session: Ideate new ruler designs and iterate existing ruler designs (as necessary)
- Did you notice anything new about the way you read after our previous meeting?
  - If so, did anything surprise you?
- Did you find any helpful digital aids?
  - If so, which ones?
- Present reading rulers developed (Grey Bar, Lightbox, and Underline)
  - Would you change anything about the interaction or design?
  - Which do you prefer (if any)?
  - How would you utilize the ruler/does it make sense for your preferred reading environment?
- What types of ruler designs should we consider adding to the validation study?
  - Should Underline be kept as a distinct design helpful to readers with dyslexia?
  - How should the ruler designs behave?
  - What surfaces would existing ruler designs be most appropriate for?

B EXTERNAL FEEDBACK

We presented some of our research about digital reading rulers to an external audience at Adobe MAX, a conference for creative professionals[11]. The feedback we received was overwhelmingly positive and provided additional unprompted validation for some of our designs. Some of the audience comments (A1-A7) are reproduced here verbatim:

- "This is why I prefer reading on a smaller screen and using the bottom of the screen as the 'ruler' when scrolling through each line" (A1)
- "Same with the top of the screen!" (A2)
- "I'm so glad these tools are emerging" (A3)
- "I just showed my dyslexic son the reading ruler and he lit up" (A4)
- "I use the top of the screen as well! I had no idea others did this" (A5)
- "In elementary school I was not allowed a ruler, so I made do with a pencil" (A6)
- "I won't even lie - I'm a bit emotional reading this. I'm in my mid-30s and have struggled through dyslexia my whole life. Tools like this can be a game changer not just for me but so many kids that hopefully won't have to struggle half as much." (A7)

[11] Adobe MAX presentation: https://www.adobe.com/max/2022/sessions/na-new-directions-in-readability-and-accessibilit-s200.html