Reading on Smart Glasses: The Effect of Text Position, Presentation Type and Walking

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ABSTRACT
Smart glasses are increasingly being used in professional contexts. Having key applications such as short messaging and newsreader, they enable continuous access to textual information. In particular, smart glasses allow reading while performing other activities as they do not occlude the user's world view. For efficient reading, it is necessary to understand how a text should be presented on them. We, therefore, conducted a study with 24 participants using a Microsoft HoloLens to investigate how to display text on smart glasses while walking and sitting. We compared text presentation in the *top-right*, *center*, and *bottom-center* positions with *Rapid Serial Visual Presentation* (*RSVP*) and line-by-line *scrolling*. We found that text displayed in the top-right of smart glasses increases subjective workload and reduces comprehension. *RSVP* yields higher comprehension while sitting. Conversely, reading with *scrolling* yields higher comprehension while walking. Insights from our study inform the design of reading interfaces for smart glasses.

ACM Classification Keywords
H.5.m. Information Interfaces and Presentation (e.g. HCI): Miscellaneous

Author Keywords
Smart Glasses; reading; RSVP; HoloLens; reading on the go.

INTRODUCTION
Smart glasses are increasingly used in various fields, including manufacturing, gaming, engineering, and research. These wearable displays provide users with information through an overlay in front of their eyes. In particular, smart glasses offer the possibility to access information without holding a device in the hand. Optical see-through smart glasses do not completely occlude the users' field of view and allow being aware of the surroundings. Therefore, using these wearable displays while being on the move does not require abrupt attention shifts between the device and the environment.

CHI 2018, April 21–26, 2018, Montreal, QC, Canada

ISBN 978-1-4503-5620-6/18/04...$15.00
DOI: https://doi.org/10.1145/3173574.3173619

Figure 1. One participant is reading with RSVP while walking during the study. In the study, we investigated the effect of different text positions and presentation types on binocular see-through smart glasses.

Presenting text is one of the functions of smart glasses. For other mobile devices, previous research shows that walking affects reading [24, 26]. However, it is not clear if this effect is also valid for reading on smart glasses. As see-through smart glasses do not completely occlude users' field of view, it is promising to use smart glasses for reading while walking. Related work shows that smart glasses enable higher awareness of the surroundings than smartphones [21]. While presenting text on smart glasses, it is important that user's visual field is not completely occluded. We need an effective solution that only occupies a part of the screen. Therefore, line-by-line scrolling and Rapid Serial Visual Presentation (RSVP) are promising presentation types for reading on smart glasses. With line-by-line scrolling, the text is split into lines which are presented one after the other. RSVP, a concept introduced by Forster [7], is a technique that presents text word by word in a rapid sequence at a fixed location. As both techniques only require display space for a single word or a short phrase, they are especially useful when the display space is limited. Since these presentation types appear only on one part of smart glasses, it is not clear how the text position affects the reading.

In this paper, we compare three text positions and two presentation types for a binocular see-through smart glasses while walking and sitting. We compared three text positions: 1) *top-right* as the Google Glass' display; 2) *center* as the most noticeable position based on the related work [4]; and 3) *bottom-center* which is the subtitle position in movies. As presentation types, we use *RSVP* and reading with line by line *scrolling*. We conducted a study with a reading application we developed for the Microsoft HoloLens (see Figure 1).

Through a study with 24 participants, we determine text comprehension, reading and walking speed, perceived workload as well as subjective preference. By comparing the text positions and presentation types on smart glasses while walking and sitting, we make following contributions:

1. We show that presenting text in the lower center or center of smart glasses increases comprehension and decreases perceived workload, both while walking and sitting.

2. We demonstrate that RSVP results in higher text comprehension while sitting whereas reading with scrolling increases comprehension while walking.

RELATED WORK

Our work is based on previous research on reading while walking, text presentation, and effects of text placement on smart glasses.

Reading On The Go

Mobile devices enable a user to access information on the go. A fundamental way of consuming information is reading. Previous work showed that walking has an effect on reading on mobile devices. Mustonen *et al.* investigated text legibility on mobile phones while walking at different speeds [18]. Their results show that increasing walking speed reduces visual performance, and that performance declines as task load increases. Similarly, Schildbach and Rukzio, compared reading while walking and standing [24]. They found that walking reduces reading performance and increases workload. Increasing the text size does not decrease adverse effects because of the need to scroll more frequently. Vadas *et al.* compared text comprehension when reading on a handheld mobile device with text to speech output while walking and sitting [26]. They show that walking causes a significantly higher perceived task load and lower comprehension compared to stationary reading. Comprehending information from an audio output led to a higher walking speed and path accuracy than reading from a visual display. Furthermore, walking speed was significantly faster with audio than reading on a smart phone.

Overall, previous work showed that walking has an adverse effect on reading using smartphones: reading text on a mobile phone and the task of navigating the environment requires sharing the attention. Reading on smart glasses might be affected by walking as well. However, the only work investigating reading on smart glasses while walking was by Lucero and Vetek [15]. In their work, an application that showed social network notifications on see-through smart glasses was studied. It was found that receiving minimalistic notifications on smart glasses while walking does not interfere with what users are seeing. However, it is not clear how walking while reading on smart glasses affects comprehension and workload. It is also not clear if reading on smart glasses while walking affects reading and walking speeds.

Text Presentation

Different screen sizes pose challenges for displaying text efficiently for reading. Previous work investigated how text presentation affects reading. Researchers considered the effect of the number of text lines, splitting of sentences, reading speed, and text length on reading. Work by Dillon *et al.* suggests that display size does not affect text comprehension whereas sentence splitting between pages results in a frequent return to the previous page to reread the text [5]. However, Duchnicky and Kolers showed that users read only 9% slower when one or two lines of text are presented at the same time compared to presenting 20 lines of text at a time [6]. Furthermore, text and background contrast variations affect text legibility [23]. It was also shown that longer text could overload users and hence result in lower comprehension [17].

Reading from small displays requires more interaction than reading on large displays [5]. Rapid Serial Visual Presentation (RSVP) for reading allows displaying text on small screens and does not require frequent interactions. RSVP presents text word-by-word in a fixed location and enables to read without large eye movements. A large body of work discussed the advantages and limitations of RSVP. Hedin and Lindgren examined text comprehension and efficiency when reading on mobile devices using RSVP and scrolling [12]. They found that despite a higher preference for reading with scrolling, comprehension was roughly equal for both presentation types. Furthermore, efficiency, computed as comprehension score multiplied by reading speed, was higher for RSVP than for scrolling. Kang and Muter found that comprehension using Times Square reading, where a text automatically scrolls from right to left, was as high as comprehension using RSVP [14]. A study by Hester *et al.* suggests that traditional reading, when all text is displayed on the screen at once, and reading with RSVP result in the same level of comprehension [13].

RSVP has recently gained more attention owing to *Spritz* [1]. It is a commercial application that enables speed reading of digital textual content using the RSVP technology. With Spritz each word is aligned on the Optimal Recognition Point, the letter most important to understand the word. In a study, Benedetto *et al.* found that reading with Spritz reduces comprehension and increases visual fatigue as well as workload [2]. Furthermore, it has been found that RSVP causes higher mental load than traditional presentation types [9]. High mental load reduces secondary task performance. Smart glasses may solve this insufficiency by allowing the reader to maintain overview of the environment while concentrating on the text without the need for scrolling or paging interaction. Furthermore, reading with RSVP is promising for smart glasses: Firstly, because of current low-resolution smart glasses presenting all text at once results in poor readability. Secondly, displaying a page of text on smart glasses occludes the surroundings and therefore might hinder navigation. Thus, smart glasses might benefit from using RSVP for presenting text. However, it is not clear how reading with this presentation type on smart glasses affects comprehension and workload.

[1] http://www.spritzinc.com (last accessed January 9, 2018)

Text Position on Smart Glasses

The position of textual information on smart glasses can affect users' ability to perceive the surroundings and simultaneously comprehend the text. Previous work provides initial insights into the effect of different text positions on smart glasses. Multiple studies focus on putting text into the environment using augmented reality (AR) smart glasses. Gabbard *et al.* investigated text readability using see-through AR glasses by comparing text drawing styles, outdoor background textures, and natural lighting [8]. They showed that a fully-saturated green drawing style enabled the highest reading performance and that participants performed the slowest when the text overlayed onto a sidewalk texture. Orlosky *et al.* proposed a dynamic text management system that maintains changes in the position of the textual information on a see-through wearable display in the user's field of view [20]. As the user moves, the system finds dark, uniform regions within the user's field of view to place the information. Furthermore, previous work suggested algorithms for placement of annotations in an AR environment using smart glasses. Bell *et al.* developed an algorithm to arrange a large number of annotations to increase visibility and avoid occlusion [1]. Makita *et al.* suggested a method for optimal location to overlay annotations of moving or non-rigid objects using wearable augmented reality system [16]. As text must be presented at a fixed position relative to the user, dynamic label placement cannot be used for longer reading sessions.

Previous works also studied text positions on smart glasses. Tanaka *et al.* investigated the viewability of information on an optical see-through smart glasses [25]. The authors divided the screen to find the ideal area for displaying information. For finding the area, the proposed method relies on the evaluation of the image of the scene behind the smart glasses by using a camera mounted on it. Chua *et al.* investigated the effect of the physical position of the display of a monocular smart glasses on performance in dual-task scenarios [4]. In a study comparing nine display positions, participants had to drive a car simulator and react to incoming notifications by clicking the button behind the steering wheel. The notifications were displayed in nine different positions. The results showed that the middle-center was the most noticeable position, whereas the participants mostly preferred the middle-right position.

Summary

In summary, previous work showed that walking has a negative effect on reading using mobile phones. In particular, attention shifting between text and environment while on the go decreased reading comprehension. Smart glasses might reduce this adverse effect by overlaying the text in front of the user's eyes. Previous work suggests that text presentation types also affect reading. RSVP and line-by-line scrolling are especially promising for reading on smart glasses since they do not completely occlude users' field of view. Furthermore, there is an effect of position on viewability of information on smart glasses. However, it is not clear how reading on smart glasses is affected by walking, presentation type, and text position.

METHOD

To gain a deeper understanding of reading on smart glasses, we conducted a study that investigated three text positions and two presentation types on smart glasses while walking and sitting. The aim was to provide an answer to the following research question: What is the most efficient combination of text presentation type and position for reading text on see-through smart glasses while walking and sitting? For the study, we chose *RSVP* and reading with line-by-line *scrolling* as text presentation types as they do not completely occlude the surroundings. Furthermore, we used three text positions: *top-right* as the Google Glass' display, *center* as the most noticeable position based on the related work [4], and *bottom-center* as a location of a subtitle in a movie.

Participants

We recruited 24 participants (8 female) through our university mailing lists. Their average age was $M = 23.5$ ($SD = 2.8$) years. Most had a background in IT and were university students. Seven wore glasses (29%), and three wore contact lenses (12.5%) while participating in the study. 75% of the participants reported their English proficiency level as *upper intermediate* and above. Six were acquainted with the RSVP reading technique (25%), and 11 had experience with smart glasses (45.8%). Except for two participants, all (91.6%) indicated that they read texts from their smartphones while walking on a regular basis. Participants received 10EUR or course credits for taking part in the study.

Study Design

We employed a mixed design with three independent variables: mobility, presentation type, and text position. Mobility (*walking, sitting*) was a between-subject factor. Presentation type (*RSVP, reading with scrolling*) and text position (*center, top-right, bottom-center*) were within-subject factors, which resulted in a total of 12 conditions. As dependent variables, we measured text comprehension, reading speed, walking speed (in *walking* conditions), subjective task load assessed by the Raw TLX (RTLX) [11], and perceived satisfaction using the "overall reactions to the software" part of the Questionnaire for User Interaction Satisfaction (QUIS) [3] after each condition. In addition, we asked participants to provide qualitative feedback for each condition.

Apparatus

To conduct the study, we developed a prototype using smart glasses that ran an application enabling a text to be presented in three text positions and two presentation types. As smart glasses, we used a Microsoft HoloLens that had see-through lenses and runs Windows 10. We used Unity 5.5.1f1 [2] to develop the application. The application displayed white text on a transparent background with the monospace font *Droid Sans Mono* [3]. The application could show text in the top-right, center, and bottom-center of smart glasses (see Figure 2). We used 6.5° elevation and azimuth angles to generate these positions. The text was placed $1.5m$ in front of the user. This

[2] https://unity3d.com (last accessed January 9, 2018)

[3] https://fonts.google.com/specimen/Droid+Sans+Mono (last accessed January 9, 2018)

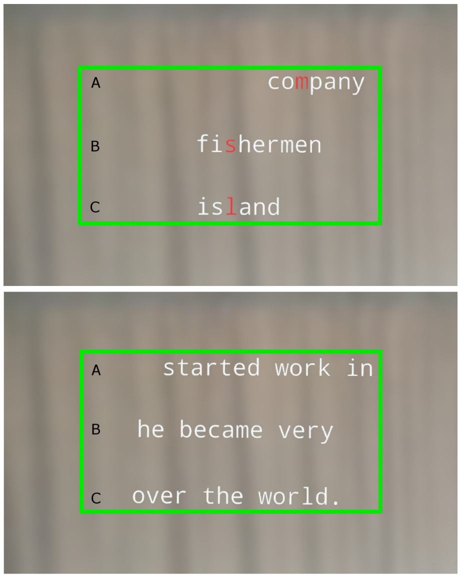

Figure 2. Reading with RSVP (top) and line-by-line scrolling (bottom). Green rectangular represents the field of view of the used smart glasses, and labels A, B, and C show top-right, center, and bottom-center positions respectively.

distance is within the close social space $(1.2 - 2.1m)$ [10] and similar to the distance of a person reading text on a poster or public display. Perceived font height was $4cm$ for an upper case H. We selected the font size through a pilot study with seven participants. In the pilot study, participants compared different font sizes from $1.5m$ distance on a HoloLens while walking. Each participant started reading a text with a font height of $1cm$ for an upper case H. We increased the font height by $1cm$ until the participant assessed the text readable and not distracting. 5 participants (71.4%) selected font height of $4cm$ for an upper case H.

We used the algorithm applied in *OpenSpritz* [4], a free speed reading bookmarklet, to create the *RSVP* presentation type. In *RSVP* reading, the application displayed text sequentially and centered around a red letter which acted as a resting point for the user's eyes while reading. Based on the used algorithm, the red letter appeared roughly after the first third of the words. Depending on word length and punctuation characters, the used algorithm displayed word for different durations. Words with more than eight characters and words followed by a comma, colon, dash, or open bracket were displayed twice as long as other words. Furthermore, after each punctuation character, the algorithm paused for the same as displaying three words in the selected reading speed. The application enabled starting, pausing and resuming the reading flow and also enabled changing the speed of the text presentation. To avoid potential effects caused by learning to use a new interaction modality, such as HoloLens's mid-air gestures, we decided to used a Bluetooth mouse to control the reading.With a click on the left mouse button, users could start or pause/resume the text presentation. The speed of the *RSVP* presentation could be adjusted by 10 WPM with the mouse's scroll wheel.

[4] https://github.com/Miserlou/Glance-Bookmarklet (last accessed January 9, 2018)

Figure 3. Participants are reading text on a HoloLens while walking (left) or sitting (right).

While reading with *scrolling*, the application displayed text line by line. To show text only in the three pre-defined positions, the application created 15-character long chunks resulting in on average three words in a line. Users could control the presentation using the scroll wheel of the mouse. As for *RSVP*, the user could not go back in the text to reread previous lines. Hence, with both presentation types, each word of a text was displayed only once.

Procedure

For the study, we assigned participants to two groups. One group's task was to read while *walking*, and the other group while *sitting* (see Figure 3).We counterbalanced the order of presentation types, text positions and the texts with a Latin-square. Furthermore, we kept the lighting condition uniform across all study conditions.

After introducing the purpose of the study, we asked participants to sign a consent form and answer questions about demographic data, general reading habits, and technology familiarity. We then introduced the Microsoft HoloLens, helped participants to wear it, and handed them the mouse. We explained its usage, the *RSVP* reading technique and how to control reading with both presentation types using the mouse.

The texts used for the study were from a collection adapted from the book *Speed Reading: A Course for Learners of English* [22]. The texts had an average of 551 words ($SD = 2.14$) and came with 10 comprehension questions per text.

Before starting the study, we accustomed participants with reading on the smart glasses. Through a training session participants read an example text trying both *RSVP* and reading with *scrolling* using a HoloLens while either *walking* or *sitting*. For the *sitting* condition, participants sat on a chair and were instructed to sit comfortably. We asked them not to stand up from the chair until they finished reading the text. They were able to control the reading speed and pause if needed using the mouse. For the reading while walking condition, we asked them to walk at their regular speed around a path. The path was approximately $35m$ long between two chairs in an ellipse

		Walking						Sitting					
		top-right		center		bottom-center		top-right		center		bottom-center	
		M	SD	M	SD	M	SD	M	SD	M	SD	M	SD
Comprehension	**RSVP**	6.33	1.92	7.58	2.07	8.50	1.73	7.33	1.23	8.08	1.98	8.00	1.65
	Scrolling	7.67	1.50	8.17	1.34	9.08	1.38	6.25	1.42	8.25	1.14	7.92	1.44
Reading speed	**RSVP**	101.2	32.53	95.55	37.15	95.85	28.23	134.45	27.98	126.85	39.37	127.25	39.23
	Scrolling	131.75	24.2	140.4	28.62	138.15	28.86	157.55	40.21	147.45	34.41	151.8	20.11
Walking speed	**RSVP**	2.40	.83	2.42	.75	2.51	.79						
	Scrolling	2.54	.75	2.55	.61	2.59	.77						
RTLX	**RSVP**	65.42	14.15	49.58	14.74	45.67	13.61	62.83	20.07	56.50	19.51	53.25	13.53
	Scrolling	59.25	12.37	46.33	12.54	46.50	15.26	57.33	15.24	47.67	15.29	51.58	12.55
QUIS	**RSVP**	32.08	7.72	40.50	8.73	46.00	9.96	34.75	10.28	37.33	10.34	39.08	6.50
	Scrolling	36.58	9.08	45.17	7.17	46.42	10.64	36.17	9.16	41.33	6.83	39.83	5.39

Table 1. Descriptive results for all conditions.

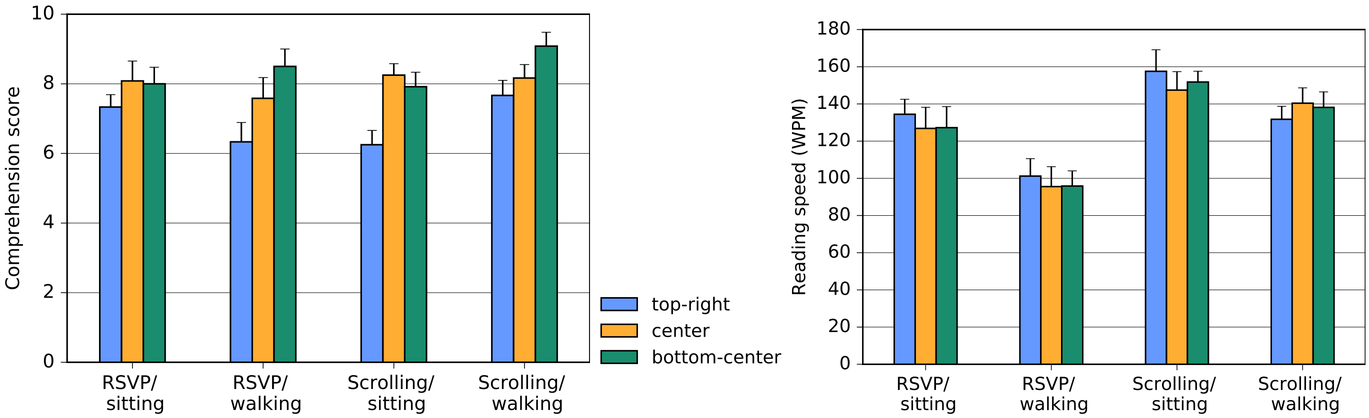

Figure 4. Average comprehension score (left) and reading speed in word per minutes (WPM) (right) for all conditions (error bars show standard error).

form. To make the distance measurement easier, we placed markers in 1-meter intervals beginning from the start position. We asked participants to continue walking along the path until they finished reading the text. Each time when a text came to its end, the application gave visual (*e.g.* an “End" sign) and audio feedback to the user.

At the beginning of the study, we informed participants about the pending comprehension tests to motivate them. We asked them to be as accurate as possible. The test contained 10 multiple choice questions with four answer options each. Following each comprehension test, we asked participants to complete an RTLX and the “overall reaction to the software" part of the QUIS questionnaire. The experimenter always asked participants to consider the last reading condition while filling the questionnaires. Then, they answered the question “What did you like or dislike in the last reading?" as a free text to give feedback about their experience with reading on smart glasses in a particular condition. Afterwards, participants continued with the remaining reading conditions. The study took about an hour and 20 minutes. At the end, participants were asked for their final feedback about the system, and the most and least preferred text positions and presentation types.

RESULTS

Each participant read six texts resulting in one text in each condition. After the study, we collected the data and analyzed it. We used a three-way mixed ANOVAs with position (*top-right*, *center*, *bottom-center*) and presentation type (*RSVP*, *scrolling*) as within-subjects factors and mobility (*walking*, *sitting*) as between-subjects factor to reveal main effects on text comprehension, reading speed, and on the subjective assessments through the RTLX and QUIS questionnaires. Furthermore, we employed a two-way ANOVA to find an interaction between text presentation type and position on walking speed. We used pairwise t-tests with Bonferroni correction for post hoc analysis. Table 1 summarizes the descriptive measurements.

Objective Results

Comparing the comprehension scores (see Figure 4 (left)) we found a main effect of position ($F(2,44) = 14.919$, $p < .001$, $\eta_p^2 = .404$) on text comprehension. Post hoc test revealed that showing text in the *center* ($M = 8.021$, $SD = 1.644$) of the smart glasses elicited a slight decrease in text comprehension with compared to *bottom-center* ($M = 8.375$, $SD = 1.579$) position, which was not significant ($p = .653$). However, presenting text in the *top-right* ($M = 6.896$, $SD = 1.614$) position resulted a significantly lower text comprehension with compared to the *center* ($p = .002$) and the *bottom-center* ($p < .001$) positions. Furthermore, there was a significant effect of interaction between presentation type and mobility on the text comprehension ($F(1,22) = 5.133$, $p < .034$, $\eta_p^2 = .189$). While *walking*, reading with *scrolling* resulted in a higher comprehension score ($M = 8.306$, $SD = 1.489$) compared to reading with *RSVP* ($M = 7.472$, $SD = 2.063$). However, participants in the *sitting* condition showed the opposite pattern (for reading via *RSVP* $M = 7.806$, $SD = 1.636$ and for reading with *scrolling* $M = 7.472$, $SD = 1.576$). The comprehension score reading of the *scrolling* condition ($M = 7.889$, $SD = 1.579$) was

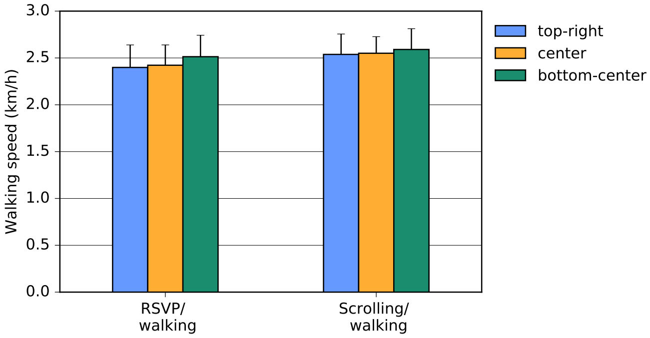

Figure 5. Average walking speed in the two presentation types and three text position (error bars show standard error).

higher compared to reading with *RSVP* reading ($M = 7.639$, $SD = 1.856$), but not significant ($p = .342$).

We measured the reading speed by dividing the number of words in a text by the time spent to read it (see Figure 4 (right)). Participants read faster ($F(1,22) = 30.860$, $p < .001$, $\eta_p^2 = .584$) with *scrolling* ($M = 144.517$, $SD = 30.327$) than with *RSVP* ($M = 113.525$, $SD = 37.014$). Furthermore, there was a significant main effect of mobility on reading speed ($F(1,22) = 5.850$, $p < .024$, $\eta_p^2 = .210$). Participants read texts faster while *sitting* ($M = 140.892$, $SD = 35.251$) compared to *walking* ($M = 117.150$, $SD = 35.332$). We found no significant main effect of text position on reading speed ($F(2,44) = .335$, $p > .05$).

Figure 5 shows average walking speed for reading with *RSVP* and *scrolling* in all three text positions. The average walking speed was slightly higher when participants read with *scrolling* ($M = 2.559$, $SD = 0.695$) than with *RSVP* technique ($M = 2.445$, $SD = 0.772$). However, the results of a two-way ANOVA showed no significant main effect of presentation type ($F(1,11) = .257$, $p > .5$), text position ($F(2,22) = .438$, $p > .5$), or interaction of presentation type and text position ($F(1,22) = .102$, $p > .5$) on walking speed.

Subjective Results

For the subjective assessment through the RTLX, we found a significant effect of text position on perceived workload ($F(2,44) = 19.928$, $p < .001$, $\eta_p^2 = .475$). Presenting text in the *top-right* resulted in a higher subjective workload ($M = 61.208$, $SD = 15.534$) than *center* ($M = 50.021$, $SD = 15.717$, $p < .001$) or *bottom-center* ($M = 49.250$, $SD = 13.719$, $p < .001$) positions. Average RTLX scores for the two presentation types are $M = 55.542$, $SD = 17.090$ for *RSVP* reading and $M = 51.444$, $SD = 14.417$ for reading with *scrolling*, but the differences are not significant (ANOVA: $p = 0.149$). The RTLX scores are presented in Figure 6 (left).

Comparing the QUIS scores (see Figure 6 (right)), we found a significant difference between the text positions ($F(2,44) = 15.445$, $p < .001$, $\eta_p^2 = .412$). Post hoc test revealed a significant difference in QUIS scores between text positions *top-right* ($M = 34.896$, $SD = 8.987$) and *center* ($M = 41.083$, $SD = 8.589$, $p = .003$), and *top-right* and *bottom-center* ($M = 42.833$, $SD = 8.839$, $p < .001$). Furthermore, there was a significant effect of interaction between text position and mobility ($F(2,44) = 3.477$, $p = .04$, $\eta_p^2 = .136$) on QUIS score. Descriptive statistics showed that participants in both mobility conditions evaluated QUIS score for text position *top-right* similarly ($M = 34.333$, $SD = 8.555$ for *walking* condition, and $M = 35.458$, $SD = 9.551$ for *sitting* condition). However, while in the *sitting* condition, QUIS scores for *center* ($M = 39.333$, $SD = 8.810$) and *bottom-center* ($M = 39.458$, $SD = 5.853$) text positions were similarly evaluated, participants assessed these higher for *bottom-center* ($M = 46.208$, $SD = 10.082$) text position than *center* ($M = 42.833$, $SD = 8.170$) position in the *walking* condition. The average QUIS scores for reading via *RSVP* ($M = 38.292$, $SD = 9.781$) and reading with *scrolling* ($M = 40.917$, $SD = 8.854$) are not significant ($p = .074$).

Qualitative Feedback

After each reading session, participants gave feedback on their experience with reading on smart glasses using the particular text position and presentation type. Furthermore, at the end of the study, each participant gave general feedback on reading texts on a HoloLens. Although for some participants reading with RSVP was a new experience (*e.g.* *"...words come out one by one, it is different from the reading experience that I am used to."* (P13)), after using the presentation type for some time, they quickly got used to it: *"Initially I needed some practice, but once I came to know it, it was a comfortable experience."* (P7) *"First tasks felt insecure, and then quickly got better."* (P16)

Participants of both *walking* and *sitting* conditions preferred the *bottom-center* position: *"The [bottom-center] position was much better than center and top-right. Even if the difference in position is not that big from center to bottom-center mode, it felt better. In this mode, I even increased the speed, because I felt more secure that I was not distracted."* (P2) *"I liked the subtitle text position as it was the easiest of the three positions to read the text. This text position was least stressful for the eyes. I could see the floor in the background, and therefore was less prone to hit something."* (P7) *"...I felt like I was reading at the normal level that I would read a book or something on a computer."* (P17) Participants in the sitting condition favored the *center* text position similarly to the *bottom-center* position. However, they mentioned that in a multitasking scenario, reading text on the *center* position may have been challenging: *"The fact that the text was in the very center of my vision and demanded my full attention means [that] it would not be good for multitasking or receiving passive information."* (P23)

As reported in the post-study questionnaire, *top-right* was the least favored text position while *sitting* and *walking*. However participants saw the possibility to use this text position for short reading sessions or navigation tasks: *"On this text position, one has more freedom concerning the view of the environment, but the reading is quite impaired. I had the feeling all along that I had to look up, which after some time I found exhausting."* (P4) and *"[It is] very hard to focus on the top. The position is rather good for navigation or really short texts, but not for longer texts."* (P19)

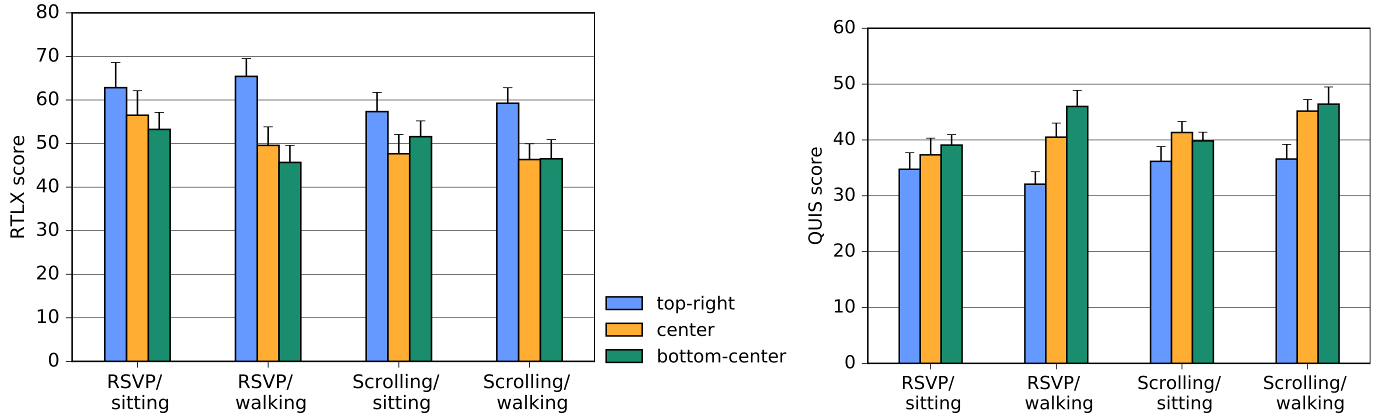

Figure 6. Average Raw TLX (left) and "overall reactions to the software" part of QUIS (right) scores for all conditions (error bars show standard error).

Participants in the *walking* condition preferred presentation type that did not constantly require attention and allowed more eye movements to observe the surroundings: *"As single words were displayed, the person must always be ready and pay attention to the next word. If the pace is reduced, it makes reading uninteresting and hence, requires more attention."* (P5) *"I liked that I could control the scrolling of text using my finger. It was better/easier than just being able to play/pause or just controlling the speed. I do not have to focus on a single word. Thus, I can also easily observe my way while walking."* (P7) However, while *sitting*, participants did not feel the need for many eye movements and found it tiring: *"While reading with scrolling my eyes had to move a lot to read the text."* (P21) *"RSVP takes some time to know how to use it. It is totally different but helps to reduce the eye movements. It is useful for reading while sitting since I just need to look at the same location."* (P14)

Participants also mentioned the limitations of the HoloLens: *"I like the whole task, but I found it a little bit difficult to wear the HoloLens for an hour and read continuously. It sometimes hurts my eyes."* (P10) *"The HoloLens is a bit heavy and to keep it on the head for a long time is irritating."* (P6) However, in general, participants described their reading experiences on a HoloLens as *"...easy multitasking and entertained during a boring walk."* (P1), *"...efficient way of reading as no need to carry a book."* (P8), and to enable *"...reading while keeping the awareness of the surroundings."* (P13).

DISCUSSION AND LIMITATIONS

The study showed that, while walking, showing text in the *bottom-center* results in the highest comprehension followed by the *center* and the *top-right* position. The qualitative feedback revealed that when text is displayed in the *bottom-center*, it is easier to observe the walking path compared to the *top-right* position. Consequently, the perceived workload was highest when the text was displayed in the *top-right* position which also resulted in the lowest QUIS score.

While *sitting*, the *top-right* position also resulted in the lowest comprehension. In contrast, comprehension, when text is presented in the *center*, was slightly higher than when text is shown in the *bottom-center*. From the qualitative feedback, we learned that reading from the *center* or *bottom-center* position on smart glasses resembles reading from a computer screen or a book. However, continuously reading in the *top-right* position of the smart glasses resulted in eye strain.

While *walking*, *reading* with *scrolling* led to higher comprehension than reading with *RSVP*. This effect can be explained by the need to focus on the text with *RSVP* continuously. While reading with *scrolling*, participants could observe the walking path more easily as they could pause anytime since no explicit action to pause the text presentation was required. However, while *sitting*, *reading* with *RSVP* resulted in higher comprehension than reading with *scrolling*. As supported by the qualitative feedback, while *sitting*, observing the surroundings is less important, and too many eye movements while reading might be tiring.

In line with previous work on reading with smartphones, we found that walking affects reading speed [24]. We also found that reading speed decreases while walking. Since there is the need to share cognitive resources between navigation and reading, participants decreased their reading speed. Furthermore, similarly to previous work [19], reading speed was higher while reading with scrolling than with *RSVP*. Since reading with *RSVP* required more attention to avoid missing words, participants reduced the reading speed.

We recognize that our approach has limitations. We conducted the study in rooms in which wall colors and light condition do not interfere with the visibility of the text. Furthermore, we selected the walking path and sitting position in a way that the text would not be behind walls or obstacles. There was always at least $1.5m$ space between participants and walls. In real life situations, both cases might happen. Future work should investigate the effects of these limitations. Moreover, in our study, we used a HoloLens as smart glasses which has limitations. Despite its limited field of view and resolution, we found a significant effect of text position on comprehension and subjective workload. Repeating this experiment using smart glasses with wider field of view, positions further towards top-right or bottom would likely amplify this effect. However, future research is needed to determine this effect. Another limitation was the use of a calm environment for the study. In a real-world setting, participants might pause reading more frequently because of the environmental noise. This could bring further advantage for reading with scrolling since it does not require an explicit command to pause the reading. However, future research is needed to confirm this.

CONCLUSION

We investigated three text positions (*top-right*, *center*, *bottom-center*) and two presentation types (*RSVP*, *line-by-line scrolling*) on a binocular see-through smart glasses while *walking* and *sitting*. We studied how walking, text position, and presentation type affect comprehension, reading and walking speed, and workload. We supported our investigation with quantitative objective and subjective data, and qualitative feedback. We found that presenting text in the *top-right* of a smart glasses results a significantly lower text comprehension and higher workload with compared to the *center* and the *bottom-center* positions while both *walking* and *sitting*. *RSVP* results in higher comprehension while *sitting* and reading with *scrolling* results in higher comprehension while *walking*. Furthermore, we found that mobility affects reading speed: reading while *walking* was slower than while *sitting*. The findings can be used as design recommendations for implementing reading-based applications on smart glasses. As in our study, we did not use secondary task while *sitting* or obstacles while *walking*, we suggest future work to investigate these effects on reading on smart glasses. As we did our study in an indoor environment, we plan to carry out of these studies in outdoor settings.

ACKNOWLEDGMENTS

We thank the participants of our study. We further acknowledge the financial support from the JST (CREST, Presto), Grant No: JP-MJPR16D4, and by the graduate program Digital Media of the Universities of Stuttgart and Tübingen, and the Stuttgart Media University. This research was partly supported by the German Federal Ministry of Education and Research as part of the project KoBeLU (grant no. 16SV7599K).

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