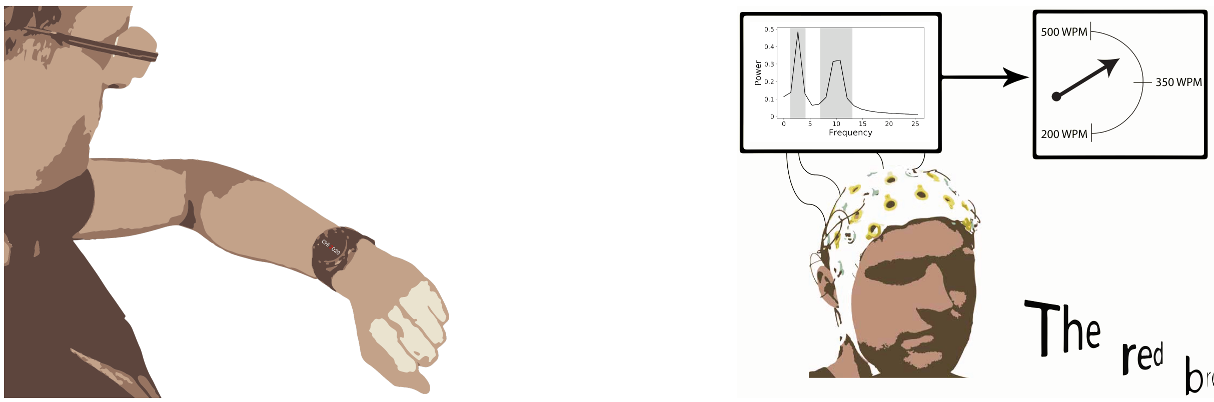
One does not Simply RSVP: Mental Workload to Select Speed Reading Parameters using Electroencephalography

Thomas Kosch, Albrecht Schmidt, Simon Thanheiser, Lewis L. Chuang
LMU Munich, Munich, Germany, {firstname.lastname}@ifi.lmu.de



(a) (b)

Figure 1. (a): User reading on a device with small screen space. (b): Electroencephalography determines the current level of cognitive workload for different *Text Alignments* and *Presentation Speeds*.

ABSTRACT
Rapid Serial Visual Presentation (RSVP) has gained popularity as a method for presenting text on wearable devices with limited screen space. Nonetheless, it remains unclear how to calibrate RSVP display parameters, such as spatial alignments or presentation rates, to suit the reader's information processing ability at high presentation speeds. Existing methods rely on comprehension and subjective workload scores, which are influenced by the user's knowledge base and subjective perception. Here, we use electroencephalography (EEG) to directly determine how individual information processing varies with changes in RSVP display parameters. Eighteen participants read text excerpts with RSVP in a repeated-measures design that manipulated the *Text Alignment* and *Presentation Speed* of text representation. We evaluated how predictive EEG metrics were of gains in reading speed, subjective workload, and text comprehension. We found significant correlations between EEG and increasing *Presentation Speeds* and propose how EEG can be used for dynamic selection of RSVP parameters.

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CCS Concepts
•**Human-centered computing** → **HCI theory, concepts and models;** *User studies; Usability testing;* User models;

INTRODUCTION
In recent years, the mass adoption of wearable mobile computing has created a pressing challenge and demand for effective text presentation on displays with limited screen space. A popular solution has been Rapid Serial Visual Presentation (RSVP). Instead of requiring readers to move their eyes to fixate individual words whilst reading, readers would fixate the display center while the words of the targeted text would be presented one after another at a chosen frequency [18]. Doing so enables full text to be accurately presented on smartphones [20, 46], smartwatches [14, 15], or smart glasses [54], in spite of the available display area (see Figure 1a) [24]. Furthermore, removing the need to move one's eyes and the ability to raise the rate of word presentation above one's normal reading speed allows for clear time-savings which provides the opportunity to increase the presentation rate for faster text processing. The primary display parameters of most RSVP applications are *Text Alignment* and *Presentation Speed* [53]. This is either fixed or adjustable to user preferences. Past research has shown that these two parameters influence perceived workload and text comprehension [3, 7, 52].

Recent concepts of *Text Alignment* incorporate visual markers inside words to direct the attention at relevant spots of words [28]. The overall aim is to gain more reading speed by aligning the readers' eye fixation around an Optimal Recognition Point (ORP). Commercial applications, such as *Spritz*, adopted the concept of ORPs where users can adjust various settings. This can reduce cognitive load and result in better comprehension [35, 47], which is highly disputed in the community [3]. *Presentation Speed* determines the rate of the presented words. Previous research found that *Presentation Speed* is an individual factor that has to be adjusted according to reading ability, text content, and individual preference [10]. Choosing unsuitable *Presentation Speeds* may have negative effects on the overall reading efficiency [9, 53]. For example, setting a high *Presentation Speed* may result in lower text comprehension and text retention since less time is available to process the presented text. In contrast, setting *Presentation Speeds* below the regular reading speed results in a loss of time. Since reading speed is an individual factor, it is difficult for novice users to estimate their optimal *Presentation Speed*. While users can modify the *Presentation Speed* during RSVP to estimate their preferred speed, the adjustment itself places additional workload on users which might compromise their assessment. Hence, the selected *Presentation Speed* remains static during the reading session. Given individual differences and variable user states for and throughout an RSVP reading session of even a single user, it is worthwhile to investigate the viability of developing a real-time measurement that could determine appropriate *Text Alignments* or *Presentation Speeds*.

In this work, we investigate the use of electroencephalography (EEG) as a direct metric for information processing whilst reading with RSVP with different *Text Alignments* and *Presentation Speeds* (see Figure 1b). EEG allows for real-time measurements of a user's brain activity with high temporal resolution across different scalp locations [42]. This multi-channel recording can be decomposed into specific frequency bands to indicate the engagement of different cognitive mechanisms, such as working memory [23, 34, 36]. While text comprehension and subjectively perceived workload have previously been assessed with *post hoc* questionnaires for evaluating RSVP applications [16, 54], we propose that EEG could serve as a direct, implicit, and real-time measurement of cognitive workload during RSVP reading. This overcomes many of the limitations of questionnaires, which includes the need for an explicit measurement phase as well as the mitigating influence of the user's subjective self-evaluation (e.g., perceived workload) or their prior knowledge of the read content (e.g., text comprehension). Here, we evaluate if EEG could feasibly be used to predict the individual current gain in reading speed, text comprehension, and subjectively perceived workload.

Our findings show that RSVP can increase the reading speed for specific *Presentation Speeds* while maintaining text comprehension, subjective workload, and cognitive workload comparable to regular full-text reading. We contrast EEG measures of regular reading with RSVP and find significant correlations between cortical activity and *Presentation Speeds* as well as subjective workload assessments. However, different *Text Alignments* did not contribute to significant changes in cognitive workload, indicating that *Presentation Speed* is a critical factor that should be prioritized first for future novel RSVP designs. A regression analysis shows that EEG frequency bands are predictive towards the gain in reading speed. Based on these findings, we discuss how our work indicates the feasibility of dynamic or manual RSVP parameter selection by cognitive workload assessments through EEG.

CONTRIBUTION STATEMENT

This paper makes three key contributions: (1) We report a user study that measures cognitive workload which is raised by the two RSVP parameters *Text Alignment* and *Presentation Speed* using EEG and complement this with traditional subjective workload assessments and text comprehension tests. (2) We evaluate EEG as a direct physiological measure to anticipate the current individual gain in reading speed, subjectively perceived workload, and text comprehension using predictive models from regression analyses. Finally, we (3) discuss how our results contribute to the evaluation of future novel RSVP designs and how our findings can be used to select individual RSVP parameters based on cognitive workload.

RELATED WORK

We surveyed related research that investigated the impact of RSVP on the reading experience, performance, working memory, and engagement. We summarize the results in the following.

Reading using RSVP

Past researchers investigated how RSVP can be used to increase, control, or manipulate the overall reading speed. While reading with RSVP, words are displayed word-by-word on a fixed space. This is achieved by updating the currently displayed word with a fixed frequency in a single-word-at-a-time notion [18, 59].

Using RSVP to read text is believed to increase the overall reading speed. Words are constantly presented in the same visual field of view and thus neglect eye movements, that require time, to jump from word to word [27, 50]. For example, Rubin and Turano [52] compared the reading speed and comprehension between the regular reading of a single page letter and previously calibrated RSVP speeds. Their findings show that RSVP speeds up the reading process while maintaining a text comprehension similar to regular reading. However, the presented approach relies on a calibration method that requires users to read the text aloud. Based on the incorrect or correct reading, the RSVP speed was adjusted manually by the experimenter.

Since RSVP presents a word at a time, it reduces display-related space restrictions that enable the representation of longer texts on devices with small screen space. For example, RSVP has been successfully employed on mobile phones [46], smartwatches [14], and mobile augmented reality devices [54]. Since the requirements and context for RSVP designs differentiate between devices, the requirements for RSVP may be different depending on the used device as well as on the user requirements [29]. For example, users may prefer slower word representation speeds in a mobile scenario than in a static context. In the following, we present related research that investigated relevant RSVP designs and their parameters to provide suitable reading experiences.

Design of RSVP Parameters

RSVP reading operates by presenting single words or short phrases one after another. In contrast to regular text reading, it removes the need for eye movements and controls the rate at which text information is accessed by the reader. Past research was concerned with factors that optimize the overall reading performance.

The centering of text and the rate of its presentation henceforth referred to as *Text Alignment* and *Presentation Speed* respectively, can be argued to critical design parameters. A faster *Presentation Speed* reduces the time it takes to read a document. Meanwhile, effective *Text Alignment* ensures that the presented word or phrase is appropriately fixated by the reader upon presentation without the need for eye movements. Thus, a factor for effective *Text Alignment* is the fixation location of a word or sentence, where a large number of neighboring letters are visible to recognize the word in a short amount of time [5]. Some commercial RSVP implementations (e.g., Spritz Inc.[1]) adopt an appropriate fixation location, also known as an Optimal Recognition Position (ORP), to eliminate unnecessary saccades and minimize eye movements. For instance, highlighting and centering words around their ORP can reduce the overall word processing time. However, reading with ORPs over longer periods suppresses parafoveal processing, increases subjectively perceived workload, and elicits a higher number of eye blinks which is an indicator for visual fatigue [3, 8]. Thus, Dingler et al. [16] explored how alternative ORP representation, such as underlining ORPs instead of coloring them, affect subjectively perceived workload and text comprehension. Although no significant results in subjective workload and text comprehension were found between underlined and colored ORPs, participants elaborated that they adjusted more quickly to colored ORPs instead to underlined ORPs. An alternative approach that utilizes colors in text representations is BeeLine Reader[2]. BeeLine Reader integrates color gradients within text lines to save time during return sweeps. Beyond that, Russel and Chaparro [53] investigated how different font sizes affected RSVP reading compared to regular reading. They find that font sizes did not significantly influence text comprehension. However, participants stated a preference for font sizes that were readable and did not strain their eyes.

Presentation Speed yields another critical RSVP design parameter. An effective *Presentation Speed* has the potential to speed up reading times by accelerating the frequency of displayed words. However, as *Presentation Speed* increases, less time is available to cognitively process words. Previous studies found significant differences in text comprehension, whereas text comprehension and *Presentation Speed* are correlated negatively [53]. In fact, previous studies have confirmed that the preferred reading speed is a factor that depends on individual preferences and text type [35].

[1] www.spritzinc.com - last access 2020-01-08

[2] www.beelinereader.com - last access 2020-01-08

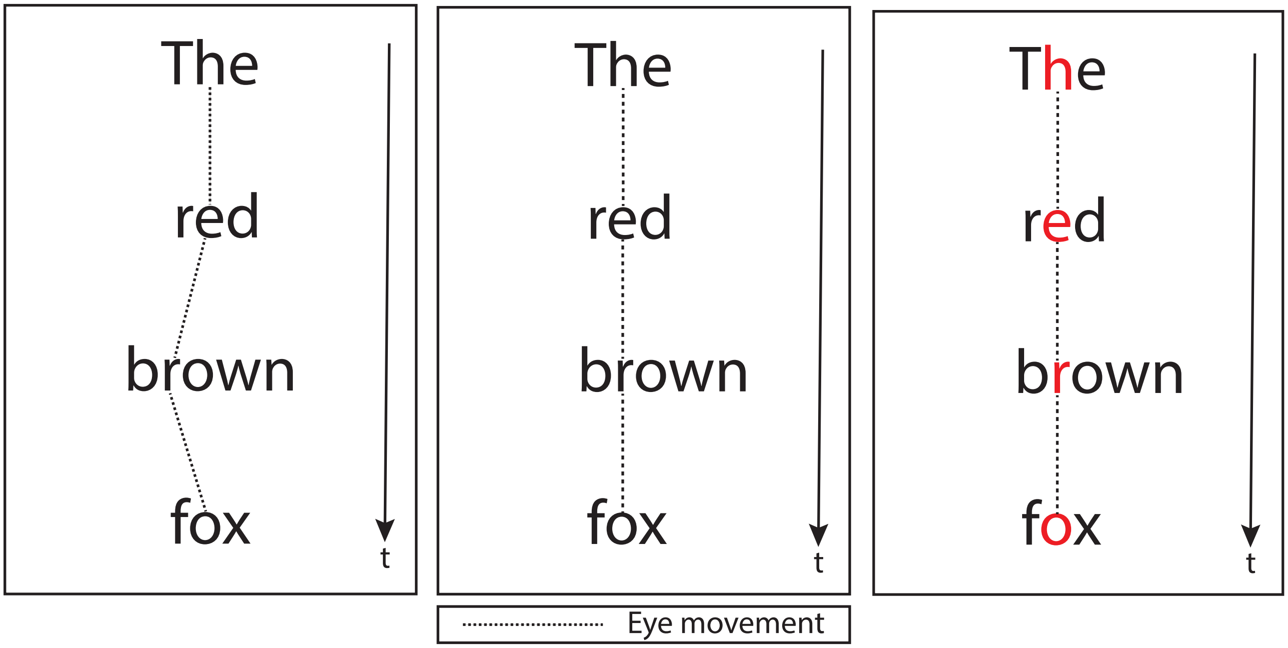
Cognitive Processing during Reading

Reading elicits different strains of working memory regarding information retention. Daneman and Carpenter [13] revealed that reading performance and comprehension is individual among users. A reader with poor processing and storage functions may retain information for a shorter time compared to more experienced readers. However, at the cost of time, readers that take more time to process information are able to increase their overall text comprehension [38].

Various researchers presented approaches to quantify the exert of working memory for different RSVP design parameters that mainly include *Text Alignment* and *Presentation Speed*. The awareness about the workload placed on readers enables to compare RSVP design parameters in terms of time-savings and information retention. For example, Dingler et al. [16] presented the use of the NASA-TLX questionnaire [25, 26] to measure several facets of experienced workload when reading with different RSVP design parameters. Further subjective measures, such as the Continuous Subjective Workload Assessment Technique (C-SWAT) [39], have been employed to measure the placed cognitive workload for various RSVP parameters [19]. However, the aforementioned measures are susceptible to subjective biases. When comparing RSVP design parameters in a study, participants might suggest a better reading performance due to previous knowledge about the presented text or lack of recall regarding their performance during the self-assessment itself.

To overcome the previous gaps from subjective assessments, physiological measurements have been proposed as an alternative to evaluating the suitability of RSVP design parameters regarding reading and information retention performance. Oliveira et al. present how EEG has been used to detect reading activity [43, 44, 45]. They incorporate several frequency bands for each electrode to train a k-nearest neighbor classifier. However, they apply their approach for regular text reading only and do not evaluate reading activity during different RSVP design parameters. A similar approach was taken by Yuan et al. [60], where reading comprehension was evaluated instead of reading activity during regular reading. Finally, Lees et al. [37] provide a literature review about RSVP and EEG. In their review, they present past work that utilized an event-related potential-based brain-computer interface paradigm during the RSVP of images and words for analysis or input. The aforementioned research investigates frequency bands as an indicator of reading activity and comprehension. In fact, specific EEG bandwidths, such as the frontal theta bandwidth (4 Hz to 8 Hz) or alpha bandwidth (8 Hz to 12 Hz), are correlated with executive cognitive functions and brain resting states that whether synchronize (i.e., theta power increases) or desynchronize (i.e., alpha power decreases) when cognitive workload is raised [31].

Cognitive functions correlate with changes in the power of theta and alpha frequency bands of EEG measurements. In particular, high alpha power is associated with the default mode of a resting brain, which is exemplified by synchronized neural activity in the alpha bandwidth [40]. Hence, cortical processing of perceived stimuli disrupts this default mode,



(a) (b) (c)

Figure 2. Word position alignment for each text representation. (a): Centered word positioning. (b): ORP-centered word without color. (c): ORP-centered word with color.

resulting in alpha-desynchronization that manifests as reduced alpha power. For instance, inter-individual differences in alpha power have shown to reflect memory performance at the occipital lobe [33]. In line with this, reading and text comprehension elicits lower alpha power as reading requires cognitive resources to memorize recently read propositions, text coherence, and information to put sentences into their context [12, 22]. The theta frequency bandwidth, on the other hand, is related to executive functions and correlates negatively with the default mode of a resting state [55]. An increase in theta power is indicative of focus or higher task engagement [4] across vigilance, learning, and memory tasks. In the context of the current work, high theta power is also prominent during the effective semantic processing of language [2]. Thus, theta power is expected to rise with increasing language processing activity.

Some researchers also adopt the theta-alpha ratio [31] as a hybrid metric for cortical activity that normalizes frontal theta power relative to alpha power. This entangles previous findings of frequency bands on brain resting states (i.e., alpha) and semantic processing (i.e., theta) into a metric that expresses cognitive processing or engagement during reading. Thus, a small theta-alpha quotient could correlate with low reading effort or no engagement in reading at all while a large theta-alpha quotient can indicate high reading engagement or increased cognitive demand.

Summary

Past research investigated how different settings of RSVP influence individual information processing, working memory, and engagement. However, previous work did not address how RSVP parameters can be implicitly evaluated without the need for individual user adjustments or reading interruptions, hence utilizing fixed RSVP reading parameters that do not take the mental demand into account. We close this gap by presenting a study that investigates the impact on EEG measures from three different *Text Alignments* and *Presentation Speeds*. We compare the alpha and theta bandwidth, subjective workload, and text comprehension of different RSVP parameter settings to regular reading and examine the placed cognitive workload. Finally, we evaluate alpha and theta bandwidths as a predictive metric for the current gain in speed relative to regular reading, subjectively experienced workload, and text comprehension.

STUDY

We designed and conducted a controlled user study to evaluate the influence of the two RSVP parameters *Text Alignment* and *Presentation Speed* on text comprehension, subjective workload, and measured cortical activity. The experiment consisted of a repeated-measures design comprising two factors with three levels each. They were *Text Alignment* (*centered*, *ORP*, *ORP* with colored letter) and *Presentation Speed* in words per minute (WPM) (200 WPM, 350 WPM, and 500 WPM). Text comprehension, subjective workload, and cortical activity (i.e., power in the theta and alpha frequency band) served as the primary measures in our study. Comparisons are drawn to the baseline of normal non-RSVP reading from a PDF document and across the test conditions. We describe the independent variables in the following.

Text Alignment

RSVP can vary in terms of the alignment of presented words, relative to the display and each other. A *centered* condition

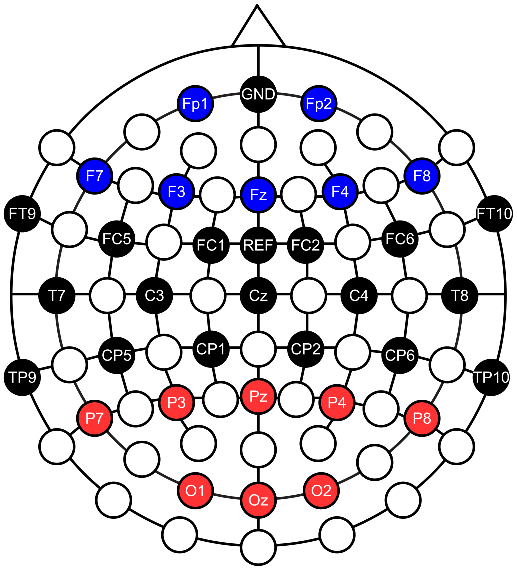


Figure 3. 32 electrode layout used in the experiment. The ground electrode was placed on *Fpz* and the reference electrode on *FCz*. The red marked electrodes were used to analyze alpha frequencies while the blue electrodes were used to analyze theta frequencies.

presented words within a bounding box that is *centered* in the display (see Figure 2a). An *ORP* condition centered each word around the *ORP* (see Figure 2b). An *ORP* with colored letter condition colored the *ORP* red in addition (see Figure 2c). This approach is similar to the algorithm employed by Spritz Inc. [3].

Presentation Speed

RSVP can vary in terms of how quickly they are presented measured in words per minute (WPM). Three *Presentation Speeds* were chosen with equal intervals, namely 200, 350, and 500 WPM. Previous work suggests that readers can understand RSVP content well at 200 WPM [9]. The conditions of 350 WPM and 500 WPM were chosen to investigate the influence of higher *Presentation Speeds* on cortical activity, subjective workload, and cortical activity [6, 56]. Hence, we hypothesized workload to increase with higher *Presentation Speeds*, albeit not necessarily at the cost of reading comprehension.

Participants

We recruited 18 participants (7 females, 11 males; age $M = 27$, $SD = 3.7$). All participants had a normal or corrected-to-normal vision and none of them reported a history of neurological disorders. Two participants have used RSVP once before. Participants were recruited through university mailing-lists. They received 15 Euro or lecture study points for their participation. We removed one participant from our analysis due to technical difficulties during the experiment.

Apparatus and Stimuli

The study was conducted in a self-contained room with constant luminance throughout experimentation. The room was divided into two areas, a test area for the participant and a control area for the experimenter. The experiment was controlled remotely with a laptop while participants were presented with

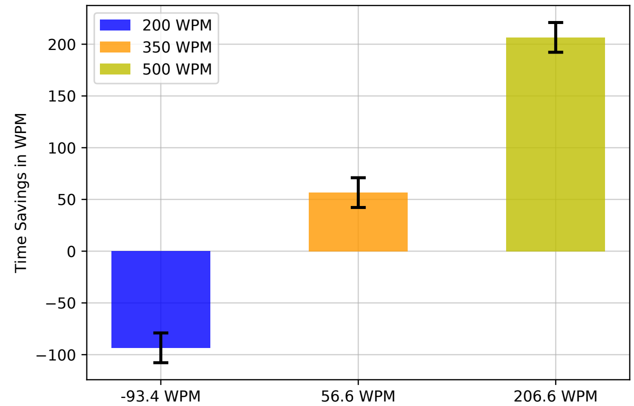


Figure 4. Time difference of using RSVP compared to reading a PDF. Using 200 WPM slowed participants down, while 350 WPM and 500 WPM accelerated the reading times. Hence, 200 WPM did not provide effect time-savings compared to 350 WPM and 500 WPM. The error bars depict the standard error.

stimuli via an LCD monitor (Dell U2715H; 27 inches diagonal; 2560 × 1440 pixel resolution; 60 Hertz refresh rate). The reading distance approximated 50 cm from the participants' head to the display. As suggested by previous research, words were displayed with a font size that did not strain the participants' eyes to avoid confounding measures during the experiment [53]. These were consistently 20 points during the PDF trial and 55 points during the RSVP trials. The font size was adjusted to match a similar size relative to the screen resolution. EEG data was collected using a 32 active gel electrodes wireless system (BrainVision LiveAmp[3], BrainProducts GmbH; bandpass: 0.1-1000 Hz, no notch filter). Electrodes were placed in accordance to the International 10-20 layout (ground electrode: *Fpz*, reference electrode: *FCz*; see Figure 3). Before testing, the impedance of all electrodes was kept to less than 10 $k\Omega$. EEG data was collected at the occipital and frontal lobe. Changes in alpha power at the occipital lobe are associated with respective changes in brain resting states, where high alpha power is associated with a distinct resting state. Respectively, low alpha power is associated with low brain resting states [21]. Theta power is an indicator of task engagement [30] when measured at the frontal lobe. Thereby, high theta power corresponds to high task engagement whereas low theta power suggests the opposite. EEG data were annotated with unique triggers for the start and end of the experiment as well as for each word presentation according to the relevant test condition. We adopted a set of ten short excerpts from the book *Speed Reading: A Course for Learners of English* [49, 54]. The presented excerpts had a mean average of $M = 547.9$ words ($SD = 3.7$) and were accompanied by a unique set of ten comprehension questions.

Procedure

Before testing, participants were required to perform some tasks to establish baseline measures. First, we derived the individual alpha frequency (IAF) by recording one minute of

[3] www.brainproducts.com/productdetails.php?id=63 - last access 2020-01-08

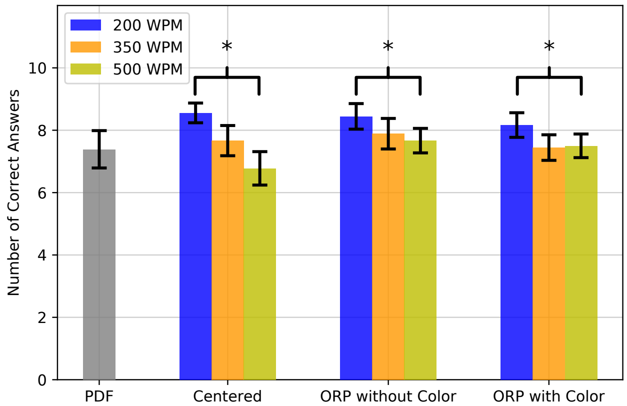


Figure 5. Mean comprehension scores for the showed questionnaires. Increasing the *Presentation Speed* reduces the number of correct answers and may impact the overall comprehension. The error bars depict the standard error. Brackets indicate significant differences.

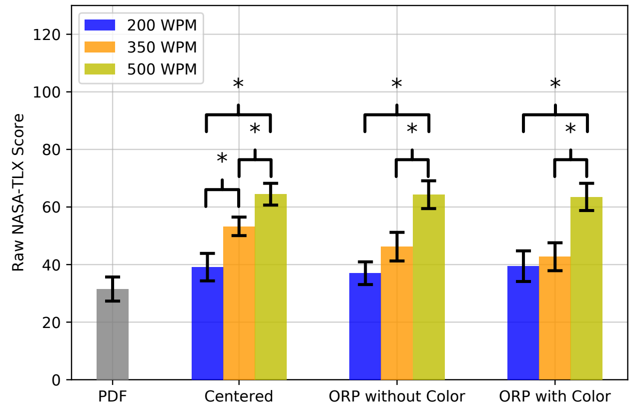


Figure 6. Mean raw NASA-TLX scores per condition. Less WPM induce less subjective compared to higher WPM. The error bars depict the standard error. Brackets indicate significant differences.

	Parameter	F	p	ω^2
Reading Comprehension	*Presentation Speed*	3.68	.04	0.08
	Text Alignment	0.85	.44	0.00
	Text Align. $\times$ *Pr. Sp.*	0.60	.67	0.00
Subjective Workload	*Presentation Speed*	18.5	<.001	0.27
	Text Alignment	1.39	.26	0.00
	Text Align. $\times$ *Pr. Sp.*	1.02	.40	0.00
IAF Power	*Presentation Speed*	491.19	<.001	0.61
	Text Alignment	2.37	.13	0.00
	Text Align. $\times$ *Pr. Sp.*	2.48	.11	0.00
Theta Power	*Presentation Speed*	338.09	<.001	0.58
	Text Alignment	1.00	.38	0.00
	Text Align. $\times$ *Pr. Sp.*	0.42	.79	0.00

Table 1. Summary of the confirmatory ANOVA results.

resting-state EEG activity for when the participants' eyes were opened and closed [30]. Next, we requested participants to read a one-page PDF text excerpt that was presented all at once via a PDF viewer. With this, we established the baseline for each participants' reading time and individual cortical activity. Ten comprehension questions and a raw NASA-TLX questionnaire were conducted after each reading trial. Testing consisted of nine RSVP presentation conditions which were counter-balanced according to the balanced Latin square [11]. After each condition, participants were presented with ten questions that tested for reading comprehension and a NASA-TLX questionnaire for evaluating subjective workload [26]. The full study took approximately 90 minutes to complete. Briefing and debriefing of the study purpose were performed before and after the study respectively. All participants provided signed informed consent.

Data Preprocessing

Four seconds of data were removed from the beginning and end of each recording to remove signals that are unrelated to cortical activity. The IAF bandwidth [30] was determined for each participant based on the separate spectral analyses of the EEG recording when the participants' opened their eyes and closed them; the mean power around the maximum difference peak (± 2 Hz) was submitted to a spatio-spectral decomposition filter [41, 48]. The spatio-spectral decomposition derives the bandwidth power based on neighboring electrodes. A decomposition of recordings maximizes the signal power of the chosen frequency while simultaneously minimizing it at the neighboring electrodes, thus mitigating the appearance of noise for frequencies outside the alpha frequency bandwidth. We performed a short-time Fourier transform by dividing the signal into one-second slices with an overlap of half a second. After estimating the IAF from each of those electrodes, we averaged the individual frequency band per electrode. This procedure was applied to the electrodes *Pz*, *P3*, *P7*, *O1*, *Oz*, *O2*, *P4*, and *P8* located at the occipital lobe [21]. (see Figure 3). A similar procedure was applied to extract theta power. The signal was filtered using a spatio-spectral decomposition (5 ± 2 Hz). Again, a short-time Fourier transform was carried out by dividing the signal into one-second slices with an overlap of half a second and were mean averaged to obtain the final theta power. This procedure was applied to the electrodes *Fp1*, *Fp2*, *F7*, *F3*, *Fz*, *F4*, and *F8* (see Figure 3).

RESULTS

The RSVP test conditions provided three measurements for each participant that we submitted for further analyses with a 3×3 repeated measures analysis of variance (ANOVA) for the factors of *Text Alignment* (*centered*; *ORP*; *ORP* with red color) and *Presentation Speed* (200, 350, 500). They were reading comprehension, raw NASA-TLX workload score, and IAF power. They respectively represented performance, subjective workload, and cortical activity. A Shapiro-Wilk test did not reveal a deviation of normality from the measures ($p \geq .05$).

We adopted an alpha-level of 0.05 for statistical significance testing and report the ω^2 for effect sizes of significant results. Greenhouse-Geisser corrections are reported when violations of sphericity are detected. Post hoc Bonferroni-corrected tests were performed between test conditions to investigate the significant main effect of *Text Alignment*. Planned linear contrasts were performed to understand significant main effects or interactions that included *Presentation Speed*. Post hoc pair-wise comparisons to baseline measures, derived from normal reading, was performed when applicable. A summary of the results can be found in Table 1.

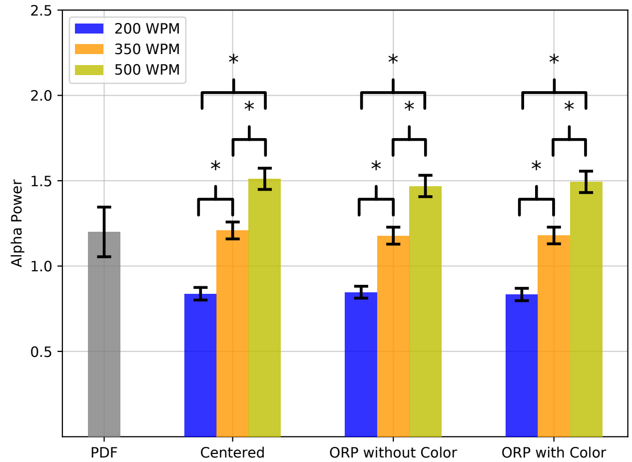


Figure 7. Normalized mean IAF band power per condition. Increasing the WPM yields an increase in alpha power band while slower speeds elicits lower alpha powers. The error bars depict the standard error. Brackets indicate significant differences.

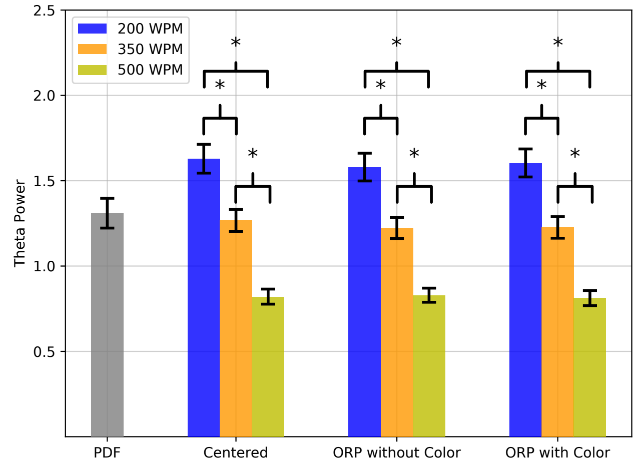


Figure 8. Normalized mean theta power per condition. Lower *Presentation Speeds* lead to higher theta power. The error bars depict the standard error. Brackets indicate significant differences.

Time-savings of RSVP

To evaluate the time-savings of RSVP, we subtracted the normal non-RSVP reading times of our participants from 200, 350, and 500 WPM. The mean reading time was 293.4 WPM ($SD = 59.3$). Hence, the mean time-savings were -93.4 WPM, 56.6 WPM, and 206.6 WPM, for the *Presentation Speed* levels of 200 WPM, 350 WPM, and 500 WPM respectively. Figure 4 illustrates these time-savings. One-sample t-tests show that participants were significantly slower at the *Presentation speed* of 200 WPM ($t(16) = -6.69, p < .001, d = -1.58$) and significantly faster at 350 and 500 WPM ($t(16) = 4.05, p < .001, d = 0.95$; $t(16) = 14.8, p < .001, d = 3.49$), relative to their normal reading times.

Reading Comprehension

Reading comprehension was operationalized in terms of the number of correct answers out of the ten questions that were posed during each questionnaire. Figure 5 illustrates the mean number of correct answers per participant and condition. We found a significant main effect for *Presentation Speed* with a medium effect size, whereas no significant effect was found for *Presentation Speed* and *Text Alignment* $\times$ *Presentation Speed*.

Subjective Workload

The subjective workload was operationalized as raw NASA-TLX scores. Figure 6 shows the mean averaged raw NASA-TLX for each condition. There was a significant main effect of *Presentation Speed* with a large effect size. No significant effect was found for *Presentation Speed* and *Text Alignment* $\times$ *Presentation Speed*.

Cortical Activity for Cognitive Workload

Cortical activity was operationalized in terms of the mean power within the IAF bandwidth (ca. 10 ± 2 Hz) and theta bandwidth (ca. 5 ± 2 Hz). Deviations from resting-state EEG activity result in lower alpha power and higher theta power [31, 32]. This is referred to as alpha-desynchronization and theta-synchronization. This is a reliable classification feature for working memory [1], which describes the cognitive processing of information that is kept in short-term memory. The alpha bandwidth, characterized by a unimodal peak in spatio-spectral power, varies across individuals and age [30]. Thus, we determined the IAF bandwidth for each participant based on their peak frequency value across the eyes-opened and eyes-closed pre-test conditions. We defined ±2 Hz around the peak frequency as the individual alpha band. The mean alpha peak was $M = 9.5$ Hz ($SD = 1.95$), which provides a mean bandwidth of $7.5 - 11.5$ Hz. Since alpha and theta power are individual metrics which are different among participants, we normalized the bandwidths by their individual bandwidth power that is elicited during the PDF reading trial before aggregating the data.

IAF Power

There was a significant main effect for *Presentation Speed* with a large effect size. This was a significant linear trend whereby IAF power increased with increasing *Presentation Speed*. The main effect of *Text Alignment* and *Text Alignment* $\times$ *Presentation Speed* interaction were not statistically significant. Figure 7 shows the normalized mean IAF power for the employed *Text Alignments* and *Presentation Speeds*. Interestingly, the linear trend for cortical activity contradicts the percept of our participants for subjective workload. The current results suggest that there is less cognitive workload with increasing *Presentation Speed* based on cortical activity. This raises the possibility that high *Presentation Speed* might introduce subjective workload while restricting our participants' neuro-cognitive ability to process the presented words. To evaluate this possibility, we performed a post hoc tests to find a significant effect between 200 and 350 WPM ($t(16) = -21.77, p < .001, d = -5.28$), 200 and 500 WPM ($t(16) = -22.72, p < .001, d = -5.5$) as well as 350 and 500 WPM ($t(16) = -20.45, p < .001, d = -4.96$).

Theta Power

The analysis of theta power results in a significant main effect for *Presentation Speed* with a large effect size. No significant

	IAF					Theta				
	F	p	R	R^2	RMSE	F	p	R	R^2	RMSE
Reading Speed Gain	3681.95	< .001	**.980**	**.961**	**0.11**	2266.56	< .001	**.984**	**.968**	**0.10**
Subjective Workload	25.24	< .001	.378	.143	20.88	28.95	< .001	.401	.161	20.66
Text Comprehension	7.47	.007	.217	.047	1.83	8.43	.004	.230	.053	1.82

Table 2. Results of the predictive models using a linear regression. All dependent variables derive a significant regression equation (p < .05). The normalized IAF and theta powers are reliable predictors for the current gain in reading speed according to the large R^2 value and low Root Mean Square Errors (RMSE). However, subjective workload and text comprehension provide less accurate predictive models. Bold values represent the most efficient results.

main effect was found for *Text Alignment* and *Text Alignment* $\times$ *Presentation Speed*. Similar to the analysis in the IAF bandwidth, a significant linear trend presented here indicates the possibility to restrict the participants' possibility to process words. Figure 8 depicts the normalized mean theta power per condition.

Number of Eye Blinks

We counted the number of eye blinks to investigate if the number of eye blinks significantly change with different *Presentation Speeds*. An increased number of eye blinks is an indicator of visual fatigue [8] that could arise from different presentation speeds. Since eye blinks introduce noise in EEG measures, we want to ensure that our EEG recordings result from cortical activity and not from noise. We use Python MNE to automatically count eye blinks using the electrodes *Fp1* and *Fp2* [57] to detect EOG artifacts using a threshold-based approach which was set to $200\,\mu V$. We found that 200 WPM elicited the highest number of eye blinks ($M = 44.88$, $SD = 33.12$) followed by 350 WPM ($M = 23.55$, $SD = 8.99$) and 500 WPM ($M = 18.8$, $SD = 7.6$). Normalizing the results to blinks per minute shows 16.38 blinks per minute for 200 WPM, 15.04 blinks per minute for 350 WPM, and 17.16 for 500 WPM. Comparing each *Presentation Speed* using pair-wise t-tests did not yield a significant effect. Due to minimal differences in blinks per minute and non-significant differences for each *Presentation Speed*, we do not assess distorted alpha or theta measures due to eye closure.

Presentation Speed Compared to Regular Reading

The main effect of *Presentation Speed* was consistently significant across all three measures. Therefore, we performed pair-wise comparisons between normal reading and the three levels of *Presentation Speed* on each measure. The median score of the three *Text Alignment* levels were treated as the representative score of the corresponding level. Subjective workload was the only measure with significant differences, whereby the *Presentation Speed* of 350 and 500 WPM resulted in significantly higher values of subjective workload compared to normal reading ($t(16) = 4.06, p < .001, d = 0.96; t(16) = 7.35, p < .001, d = 1.73$). There were no significant differences between the *Presentation Speed* levels and normal reading for reading comprehension and cortical activity. To summarize, the time-savings of RSVP at 350 and 500 WPM was associated with the cost of increasing subjective workload, without significant improvements in reading comprehension or changes in cortical activity.

EVALUATING EEG AS PREDICTIVE METRIC

The results show significant differences in alpha and theta power for reading with different *Presentation Speeds*. We evaluate the efficiency of models that utilize EEG frequency bands to predict current gains in reading speed, subjective workload, and text comprehension using a linear regression analysis.

Independent and Dependent Variables

We use the IAF and theta power as independent variables for the regression analysis. Similar to the previous analysis and to mitigate person-dependent differences in the alpha and theta bandwidths, both bandwidths are normalized relative to the full-text baseline reading trial. For each RSVP condition concerning *Presentation Speeds* and *Text Alignments*, we calculated the mean bandwidth for the IAF and theta power for each RSVP reading trial. This resulted in nine data points for each bandwidth and for each participant. Hence, a total of 153 data points were used to fit a function for the IAF and theta power. We use these data points to evaluate a predictive model using linear regression to evaluate the forecasting efficiency for the current gain in reading speed relative to the full-text reading trial, subjectively perceived workload, and text comprehension.

Predictive Performance

We describe the results of the regression analysis in the following. We report the significance of the regression equations and the accuracy of the fitted model. A summary of the results can be obtained from Table 2.

A significant regression equation was found for gains in reading speed ($F(1,151) = 3681.95, p < .001, R^2 = .961$) with a linear trend for increasing *Presentation Speeds* and IAF power. In contrary, theta power resulted in a significant regression equation ($F(1,151) = 2266.56, p < .001, R^2 = .968$), where theta power shows a decreasing linear trend with higher *Presentation Speeds*. This indicates a strong linear trend between the EEG frequency bands and gains in reading speed as suggested by the previous results. Similarly, a significant regression equation ($F(1,151) = 25.24, p < .001, R^2 = .143$) between increasing raw NASA-TLX scores and IAF power was confirmed. Furthermore, we find a significant regression equation ($F(1,151) = 28.95, p < .001, R^2 = .161$) between decreasing theta power and increasing raw NASA-TLX scores. However, the low R and R^2 scores show that the variance of the raw NASA-TLX scores is large, thus indicating a low predictive performance. Finally, we apply the same regression analysis for the text comprehension scores. Again, this results in

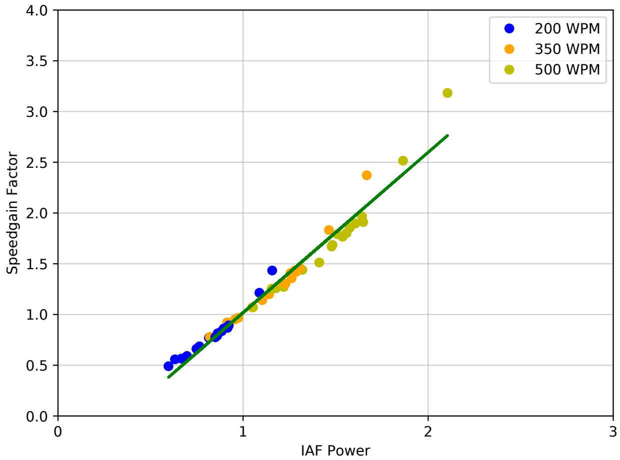


Figure 9. A linear regression of the normalized IAF power results in an efficient prediction for gains in reading speed. The green line denotes the regression function. The colors resemble the *Presentation Speed*.

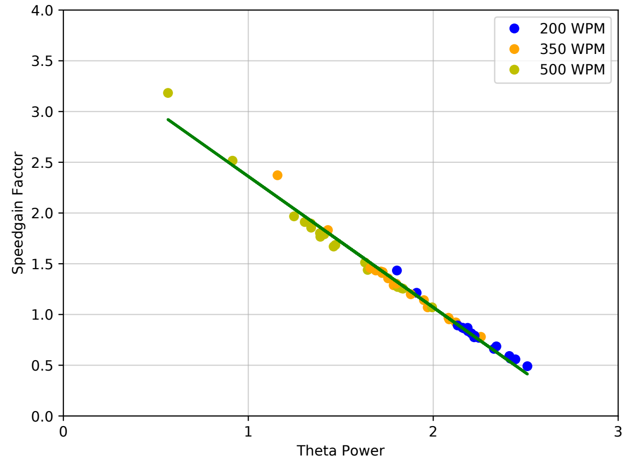


Figure 10. A linear regression of the normalized theta power results in an efficient prediction for gains in reading speed. The green line denotes the regression function. The colors resemble the *Presentation Speed*.

a significant equation ($F(1,151) = 7.47, p = .007, R^2 = .047$) with decreasing text comprehension for increasing *Presentation Speeds*. Theta power also shows a significant equation ($F(1,151) = 8.43, p < .001, R^2 = .161$), where text comprehension decreases with decreasing theta power. Similar to the raw NASA-TLX scores, the R and R^2 denote large variances among the data points and, therefore, a low predictive performance.

Towards a General Model for Predicting Reading Speed

The IAF and theta power show a strong linear trend regarding the current gain in reading speed. These results suggest a functional relationship between gains in reading speed and the employed EEG frequency bands that generalize to the individual user, hence obviating a dedicated calibration phase. First, we averaged the *Presentation Speeds* for each *Text Alignment*, resulting in 51 data points for all participants. We then performed a leave-one-participant-out validation between gains in reading speed and the measured frequency bandwidths. More specifically, we iteratively derived a linear regression model using all participants except one and used the remaining one for the validation. This resulted in a low averaged error rate for the IAF (RMSE = 0.12, R^2 = .94) and theta (RMSE = 0.11, R^2 = .97) power, indicating that the model fits interpersonal differences that may not require individual user calibration. Figure 9 and Figure 10 show the regression lines for the IAF and theta power relative to the gains in reading speed for each participant and for each *Presentation Speed*.

DISCUSSION

We conducted a study to investigate the influence of *Text Alignments* and *Presentation Speeds* on text comprehension, subjective workload, and cortical activity. Our results show that time-savings are achieved from the *Presentation Speeds* of 350 WPM onwards which corresponds with increased alpha power and decreased theta power in EEG. Faster *Presentation Speeds* significantly increases subjective workload and impairs text comprehension. Interestingly, *Text Alignment* did not influence any of our measurements. Thus, it is clear that *Presentation Speed* will continue to be a limiting factor. Until this is resolved, spatial factors such as the ideal presentation of text, which includes font readability could be relatively less important and should only be considered after optimizing *Presentation Speeds*. It is worth noting that *Text Alignment* could have minimal impact on wearable displays, which are small and unlikely to subtend to a larger visual angle than the fovea (i.e., 2°). Thus, we focus on the implications for *Presentation Speeds* on future developments of RSVP readers.

Cognitive Workload of RSVP

Our results show that the physical manipulation of *Presentation Speeds* does not simply bring gains in reading speed. It has a notable impact on our limited capacity for information processing at the cortical level. While 350 and 500 WPM induced significant gains in reading speeds, relative to regular reading, this was accompanied by a significant cost in subjective workload as well as comprehension scores. These performance findings agree with previous findings [53]. We show that this is measurable in terms of EEG correlates with established cognitive processes, whereby higher *Presentation Speeds* commensurate with reduced working memory and engagement as respectively measured by IAF and theta power [51]. At 200 WPM, our participants were forced to read slower than their regular speed, which increased text comprehension scores that were commensurate with the EEG correlates of higher working memory load and engagement [51]. Thus, we show that physical manipulation of the speed of RSVP readers exerts an influence on how we process information for comprehension that can be measured with EEG. Thus, we show that ongoing measurements of cortical activity can reliably indicate the rate at which we can process and comprehend presented stimuli. In many cases, it could be desirable to manipulate RSVP speeds to facilitate information processing, in a way that could be verified by EEG measurements, as long as fast reading is not a pressing requirement.

Evaluating EEG as Measure for Predictive Models

We use the mean power in the IAF and theta bands to predict gains in reading speed, subjective workload, and text comprehension scores. We found that only gains in reading speed could be reliably predicted with both IAF and theta power. This implies a linear relationship between *Presentation Speeds* and the measured IAF and theta bandwidths. This forecast can support the dynamic selection of RSVP parameters according to the current context (i.e., reading in private or mobile spaces, reading a novel or a scientific article) to maximize time-savings, supporting the development of adaptive brain-computer interfaces. In contrast, subjective workload and text comprehension were not reliably associated with our EEG measurements. Non-linear models might be necessary to estimate subjective workload and text comprehension, given that NASA-TLX questionnaires are susceptible to differences in subjective perception.

Real-Time Assessment of RSVP Parameter Selections

EEG affords high sampling rates and can be employed as a real-time indicator for the evaluation of RSVP reader designs [17]. Since RSVP can be ubiquitously employed on devices with limited screen space, the reading performance can be evaluated in short time frames using EEG. Our predictive model shows that workload-aware computer interfaces can implicitly sense the current gain in reading speed depending on the bandwidth powers relative to a reading baseline. The *Presentation Speed* can be adjusted to a suitable reading level depending on the current level of cortical activity. Adaptive RSVP *Presentation Speeds* can then be deployed on-the-go, where textual information is available at refresh rates suitable for mental processing. With the ubiquitous availability of RSVP-enabled devices, baselines of regular reading speeds can be collected in any context to evaluate the current RSVP reading speed using EEG. RSVP systems can then dynamically select *Presentation Speeds* which implicitly suits the users' reading ability.

Limitations

The current study has several design limitations. We limited our manipulations to three *Presentation Speeds*. Therefore, it is not clear how cortical activity is affected for slower *Presentation Speeds* than outlined in the study. However, due to our findings, we expect a similar engagement of mental resources for slower *Presentation Speeds*. Furthermore, the comprehension tests may be confounded by knowledgeable participants who were aware of the answers without reading the text. Although we made sure that the participants were not knowledgeable about the used text excerpts, we can not exclude the use of common knowledge during the tests. Finally, our sample consisted of people who exclusively did not use RSVP regularly. Therefore, our results only confirm the observed effects of non-trained RSVP users.

Future Work and Outlook

Although our findings show the feasibility of relying on EEG measurements to predict gains in reading speed. Any gains due to *Presentation Speed* depends on the baseline reading speed of the individual user. Being able to predict gains means that RSVP readers can adaptively determine the tradeoff of reading speed gains to ensure that *Presentation Speed* is maintained at a level that allows for meaningful text comprehension. Aspects, such as mobile use, reading interruptions, outdoor scenarios, or different viewing postures have to be determined before RSVP-based brain-computer interfaces can be implemented in a way that allows for good signal acquisition. These are open research questions that were not addressed in our experimental design. However, our findings provide a first step towards the adaptive selection of *Presentation Speed* for RSVP readers, which would need to be manually determined otherwise. To address this, we will evaluate our approach and methodology in mobile scenarios. Wearable EEG is present in recent research [58] and is becoming accessible to the consumer market by manufacturers such as mBrainTrain[4] or Emotiv[5]. We intend to create a framework that utilizes EEG-tailored RSVP parameters according to the mental demand of the individual user. Finally, we will evaluate this framework in controlled and mobile in-the-wild scenarios to research the feasibility of workload-aware RSVP interfaces.

CONCLUSION

In this paper, we present a user study that investigates the cognitive workload raised by the Rapid Serial Visual Presentation (RSVP) design parameters *Text Alignment* and *Presentation Speed* using Electroencephalography (EEG). We find that a *Presentation Speed* of 350 words per minute (WPM) increases the reading speed compared to regular reading while preserving a similar level of cortical activity and text comprehension. However, faster *Presentation Speeds* increase the subjectively perceived workload with a decrease in the overall text comprehension and cortical activity. No effect was observed for different *Text Alignments*, making *Presentation Speed* the critical design parameter that needs to be optimized first before modifying *Text Alignments*. Due to linear trends in the EEG measures and *Presentation Speeds*, we perform a linear regression analysis to evaluate the robustness of predictive models for gains in reading speed, subjective workload, and text comprehension. While we find that the current individual gains in reading speed can be reliably forecasted using EEG, subjective workload and text comprehension are less suitable variables for reliable predictions. Our results show that future RSVP interface designer benefit from the presented approach to design workload-aware user interfaces that dynamically select RSVP parameters to suit the individuals' cognitive workload using EEG measures. We publish our data set to foster and encourage research in this area[6].

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[4] www.mbraintrain.com - last access 2020-01-08
[5] www.emotiv.com - last access 2020-01-08
[6] www.github.com/hcum/one-does-not-simply-rsvp - last access 2020-01-08

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