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EYE MOVEMENT CORRELATES OF WORKING MEMORY CAPACITY: EVIDENCE FROM THE READING SPAN TASK

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Глазодвигательные корреляты объема рабочей памяти на материале задачи «Объем чтения»

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Abstract

In reading, eye movements are typically influenced by both higher-level and lower-level cognitive processes that are affected by individual differences such as working memory capacity. However, the extent to which working memory impacts reading under increasing task demands remains uncertain. Therefore, this study aimed to explore the influence of working memory capacity, assessed via the n-back task, on peak saccade velocity during reading when an additional memory task is introduced. Thirty-one healthy participants with normal or corrected-to-normal vision read sentences performing either comprehension task or dual task on comprehension and working memory span. The results of the comprehension task were used as a baseline to track the differences in eye movement measures in the dual task with the increasing task demand. Participants who performed well in the n-back task exhibited higher peak saccade velocity during both single and dual reading tasks, particularly as the task demands increased: reading for comprehension while simultaneously maintaining six items in working memory was associated with the highest peak saccade velocity. Conversely, those with n-back lower performance did not display significant changes in peak saccade velocity. This discrepancy is attributed to task-induced variations in arousal among high-performing individuals. The study underscores the importance of individual differences in working memory and suggests a potential link between arousal and cognitive processes involved in reading comprehension.

Keywords: reading, eye movements, working memory.

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Резюме

Движения глаз при чтении обусловлены особенностями восходящих и нисходящих когнитивных процессов. Кроме того, они связаны с индивидуальными различиями, в том числе в объеме рабочей памяти (РП). Тем не менее вопрос о том, в какой степени объем РП определяет движения глаз в условиях возрастающей нагрузки при чтении, остается во многом открытым. Целью данного исследования стало изучение влияния объема РП на пиковую скорость саккад во время чтения с задачей понимания текста и в условиях двойной задачи на понимание и удержание информации в рабочей памяти (методика «Объем чтения»). В обработку были включены как окуломоторные показатели по каждой задаче отдельно, так и соотношение показателей в задаче на понимание и двойной задаче. Участники с более высоким объемом РП демонстрировали более высокую пиковую скорость саккад, чем участники с низким объемом РП — как при чтении, так и при выполнении двойной задачи. При этом различия были наиболее значимы при условии максимальной нагрузки на РП: так, при задаче чтения и одновременного удержания шести элементов в рабочей памяти наблюдалась максимальная пиковая скорость саккад. Полученные результаты отражают различия в возбуждении ЦНС у людей с большим объемом РП, вызванным выполнением заданий, связанных с дополнительной нагрузкой на РП. Данное исследование подчеркивает важность индивидуальных различий в объеме РП при чтении, а также предполагает потенциальную связь между возбуждением ЦНС и когнитивными процессами, обеспечивающими понимание прочитанного.

Ключевые слова: чтение, движения глаз, рабочая память.

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Z. Chuikova prepared introduction, results and discussion sections. A. Izmalkova performed statistical analysis and edited discussion section. P. Shirokova and A. Izmalkova programmed the experiment in Experiment Builder. P. Shirokova performed data curation. Y. Shtyrov and A. Myachykov conceptualized the research, defined the research model and edited the final version of the paper.

Вклад авторов

Ж. Чуйкова подготовила теоретический обзор, описала результаты и провела их обсуждение. А. Измалкова провела статистическую обработку данных окулографии и внесла корректировки в обсуждение результатов. П. Широкова и А. Измалкова запрограммировали эксперимент в Experiment Builder. П. Широкова провела сбор и предобработку данных. Ю. Штыров и А. Мячиков сформулировали проблему исследования, определили исследуемые факторы и внесли финальные правки в статью.

Reading, the process of extracting information from a written text, is a critical skill involving complex oculomotor behavior. Contemporary research uses eye tracking (recording participants' gaze coordinates during task performance) to objectively measure attention distribution during reading, offering researchers insights into associated cognitive processes (Pokhoday et al., 2023; Radach et al., 2003). Eye movements in reading are closely linked to language processing (Rayner, 2009) with both higher- and lower-level factors shown to account for the length and the direction of saccades (fast ballistic eye movements) as well as for fixation durations (duration of eye rests on an object).

Two influential models of eye movement control in reading are E-Z Reader and SWIFT. In the E-Z Reader model eye movement progression relies on cognitive and lexical processes (Ibid.), whereas the SWIFT model suggests that saccades are generated autonomously, with little input from cognitive factors (Engbert et al., 2002; Engbert et al., 2005; Kliegl et al., 2004; Laurinavichyute et al., 2019). Furthermore, E-Z Reader relies on serial processing identifying words one at a time while SWIFT allows for parallel processing assuming that multiple words can be processed simultaneously at fixation.

Both models consider factors such as word length, frequency, and predictability, which impact fixation durations. According to SWIFT, more frequent words are processed quickly and outside of visual focus (i.e., beyond the center of current fixation), while longer words require more processing time than shorter ones. Additionally, highly predictable words are often skipped and receive shorter fixation durations (Kliegl et al., 2004; Laurinavichyute et al., 2019; Rayner, 2009; Rayner et al., 2006), that with gaze durations, word skipping, regressions, and saccade amplitude are the most popular measures of eye movement during reading (Laurinavichyute et al., 2019). Saccade velocity is generally less represented in eye reading tasks. Similarly, while the models of eye movement control in reading account for lower-level (i.e., processes that decode words) and higher-level processes (i.e., processes that retrieve both explicit and implicit information from text and combine with existing knowledge), the role of individual differences remains poorly understood (Hannon, 2012).

Nevertheless, existing evidence regarding the impact of individual differences on information processing suggests that individually measured working memory capacity (WMC) modulates oculomotor behavior during reading. Working memory (WM) is a multicomponent limited capacity store that holds task-relevant information over a short time (Baddeley, 2010). WMC represents an individual's ability to integrate stored information with incoming one supporting the maintenance, retrieval, and updating of the information presented in text (Cain et al., 2004) with higher WMC associated with working memory load (WML) (Guler & Aydin, 2023). Working memory updating (WMU) is a WM component of replacing existing information with the newer one (Miyake et al., 2000; Nyberg & Eriksson, 2016). It underpins adjustment of mental representations of text as new information is encountered (Linares & Pelegrina, 2023). As such, WMU is required when a new piece of information contradicts with the stored one.

Studies providing strong evidence for the WMC and WMU effects on reading comprehension (Gorin et al., 2024; Just & Carpenter, 1992; Kaakinen et al., 2003; Muijselaar & de Jong, 2015; Schurer et al., 2020) show that adults with higher WMC demonstrate faster and more accurate processing compared to those with lower WMC, which is particularly evident when dealing with challenging or unfamiliar content and grammatical structures (Just & Carpenter, 1992). Thus, WMC plays a crucial role in reading that requires deeper comprehension (García-Madruga et al., 2014; Potocki et al., 2017). Similarly, participants with higher WMU show better performance compared to low WMU participants, indicating challenges in inhibiting irrelevant information and accessing relevant information from working memory, particularly under high text complexity (Kendeou et al., 2014; Schurer et al., 2020; Wu et al., 2020).

Associated WML has also been shown to affect eye movements during reading. Mental workload (also known as WML, cognitive workload) is defined as "the degree of activation of a finite pool of resources, limited in capacity, while cognitively processing a primary task over time, mediated by external dynamic environmental and situational factors, as well as affected by definite internal characteristics of a human operator, for coping with static task demands, by devoted effort and attention" (Longo, 2022). As such it represents the cognitive capacity required for efficient task performance (Eggemeier & O'Donnell, 1982). The theoretical framework for workload assessment related to human information processing is Wicken's multiple resource model, positing that the attentional demands of the tasks competing for a shared pool of multiple resources, largely account for concurrent task performance (Wickens, 2008). Thus, both task demand increase (as in Bachurina & Arsalidou, 2022) and an introducing additional task (as in the dual task paradigm Emerson & Miyake, 2003) can be associated with additional WML.

Multiple studies showed WML related eye movements represent in fixation duration, saccade peak velocity (Bachurina & Arsalidou, 2022; Mallick et al., 2016; Tao et al., 2019; Zu et al., 2018), pupil size (Gorin et al., 2024; Mallick et al., 2016; Mathôt, 2018; Tao et al., 2019), and blinking rates (Bachurina & Arsalidou, 2022; Mallick et al., 2016; Tao et al., 2019). Fixation durations increase with higher WML indicating challenges in interpreting information (Liu et al., 2022). Saccade peak velocity decreases as WML increases indicating fatigue (App & Debus, 1998; Bachurina & Arsalidou, 2022; Chen et al., 2022). Pupil dilation studies show an increase in pupil size with increasing WML (Gorin et al., 2024). Additionally, there is a correlation between WML and endogenous blinks with higher WML corresponding to fewer blinks (Arezes et al., 2015; Gebrehiwot et al., 2016; Ledger, 2013; Nomura & Maruno, 2019). This reflects a suppression process aiming to avoid missing incoming information blinks disrupt visual sensory input (Holland & Tarlow, 1975; Volkmann et al., 1980). WMC effects in reading studies show that higher WMC is associated with larger saccade amplitudes and shorter fixation durations indicating more efficient information processing (Tanaka et al., 2014; Traxler et al., 2012). At the same time, studies using reading span task fail to register the effect of WML showing no difference between WM span groups in fixation times on the area before the target word and the time spent on the target word (Kaakinen & Hyönä, 2007).

Nevertheless, the role of WM span on eye movements associated with cognitive load remains unclear. Thus, the goal of this study is to investigate how WMC and WMU affect oculomotor behavior during reading with and without additional WML. We used single task (comprehension) and dual task (comprehension + verbal WM load) conditions in association with the classic n-back task for assessing WMC and WMU processes. The dual task was used to examine the impact of mental workload on shared resources in verbal WM. The dual task paradigm is used to study individual differences in WM and attention switching via manipulating resource availability and exploring the resulting change in performance (Emerson & Miyake, 2003; Izmalkova et al., 2022; Unsworth et al., 2014). We used the reading span task to assess the ability to store and manipulate information in WM as well as integrate new information (Daneman & Carpenter, 1980), particularly, the Russian adaptation of the reading span task (Pechenkova & Fedorova, 2007). The results of the reading for comprehension task were regarded as a baseline to track the differences in the eye movement measures in the dual task with the increasing task demand.

Previous research showed decrease in peak saccade velocity (PSV) with increasing task demand (Bachurina & Arsalidou, 2022; Di Stasi et al., 2010). Moreover, PSV tends to increase as a function of saccade amplitude, which, due to the features of the slope is sometimes referred to as saccadic “main sequence” (Gibaldi & Sabatini, 2021). This function is attributed to changes in the sympathetic nervous system activation with increasing arousal associated with higher PSV (Di Stasi et al., 2013). Therefore, we hypothesized that lower WM score would be associated with lower PSV (as an indicator of mental workload) in the reading span task (dual task), while no significant effect would be observed in the reading task.

Method

Participants

An a priori power analysis indicated that a minimum of 28 participants was needed to test our hypotheses assuming a medium effect size (f = .5) with .8 power and alpha set at .05. Thirty-one Russian native speakers aged from 18 to 37 (mean age = 22.4 ± 4.6, 27 females) with normal or corrected-to-normal vision were recruited via advertisements posted on social networks. Participants had no history of head injuries or consciousness loss, and they either held higher education degrees or had incomplete higher education. All participants gave written informed consent prior to taking part, and they received monetary compensation (250 RUR). The study was approved by the HSE Committee on Interuniversity Surveys and Ethical Assessment of Empirical Research. Testing was individual, and it took part at the Higher School of Economics, Center for Cognition and Decision Making.

Materials

Experimental procedure included three tasks: a spatial n-back task (SNB), a sentence reading task, and the reading span test.

The N-back task

We used a spatial n-back task (Jeter et al., 2011) to assess participants’ WMU and WMC. Participants detected the location of a square, which appeared randomly on a 3×3 grid. The task comprised 1-back, 2-back, and 3-back blocks. Each task block (60 trials) used random stimuli presentation with a trial duration of 2000 ms: 1000 ms for fixation point, 1000 ms for the stimulus (Figure 1). Participants responded with their right middle finger when target square was presented and with their right index finger when target letter was not presented. Participants responded when the currently presented square position matched the square position presented in the preceding trial (1-back), two (2-back) or three (3-back) trials prior. Participants with both 2-back and 3-back 75% correct answers were defined as high performers (21 individuals), and participants with 2-back or 3-back performance below 75% were defined as low performers (17 individuals). An example of the N-Back stimuli is given in Figure 1.

The Sentence Reading Task (the Single Task)

Text stimuli for both reading and reading span tasks were sampled from the Russian Sentence Corpus (Laurinavichyute et al., 2019). Progressive mental workload (from two to six sentences in the block with additional WM load in the reading span task) was employed in both tasks.

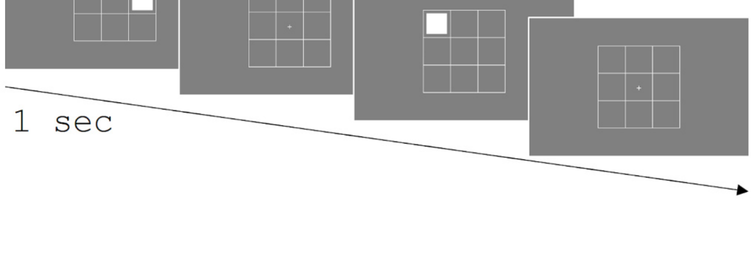
We used the sentence reading task to measure individual benchmark eye movement parameters. Following previous research on eye movements in reading in Russian, we used the Russian Sentence Corpus (RSC) (Ibid.). Participants read aloud 100 sentences separated by a 1000 ms interstimulus interval. All sentences were grouped into blocks of 2, 3, 4, 5 or 6 sentences (5 blocks of each type) and presented for 6500 ms with a 1000 ms delay progression to the next trial. Participants could proceed to the next sentence by pressing the space button. Each sentence appeared as a single line in the center of the screen against a light gray background. To confirm comprehension, participants answered simple three-choice comprehension questions after each trial, adapted from RSC. Responses were recorded using the keys “1”, “2”, and “3”. Average accuracy was 91.1% (SD = 5.7%), consistently exceeding 80%, a cut-off measure for reading the RSC (Ibid.). A typical experimental trial progression is portrayed in Figure 2.

The Reading Span Test (Dual Task)

A Russian adaptation of the reading span test (Daneman & Carpenter, 1980; Pechenkova & Fedorova, 2007) was used to assess verbal WM: with reading and memory tasks loading shared WM resources. This task followed the same procedure

Figure 1

Example of Stimuli and Procedure for the N-back Task



and presentation as the single task, with the addition of a new requirement: participants had to remember and recall target words highlighted in bold at the end of each trial. All target words were selected from the Frequency Dictionary of Modern Russian (Lyashevskaya & Sharov, 2009) and normalized for their class (adjectives, verbs, nouns, and adverbs), length (long or short), and position in a sentence (beginning, middle, or end). Target words were distributed equally across grammatical categories including gender, case, number, person, and tense. Stimuli example and a typical experimental trial procedure for the reading task is portrayed in Figure 3.

Figure 2

Example of Stimuli and Procedure for the Sentence Reading Task

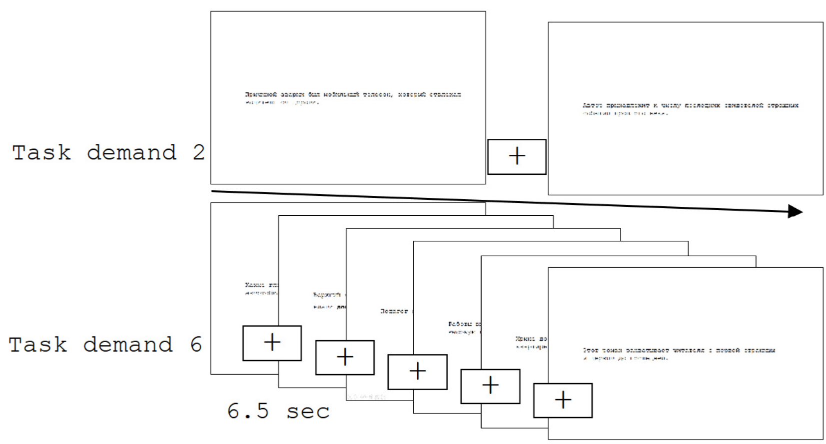
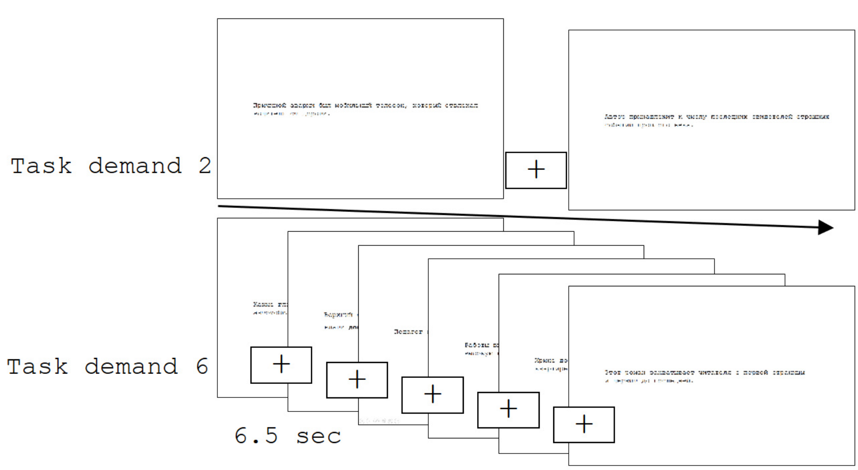


Figure 3

Example of Stimuli and Procedure for the Reading Span Task



Apparatus and Procedure

All tasks were displayed on a 24-inch ASUS VG248QE monitor with a resolution of 1920 × 1080 pixels, a 1-millisecond response time, a 144 Hz frame rate, and a 22-point Courier New font size. SR Research Experiment Builder v2.1.140 software was used for presentation and eye movement recording (SR Research Ltd., Ottawa, ON, Canada). Eye movements were recorded with the EyeLink 1000+ eye tracker (SR Research, 2024) at 1000 Hz frequency using chin support. The participants were positioned ~55 cm away from the camera and 90 cm away from the monitor with a visual angle of 0.29° for each character. Only the dominant eye was tracked at a rate of 1000 Hz. Using the saccade detection algorithm developed by SR Research within the Data Viewer, saccades and fixations were determined. The final stimulus in the visible block sequence remained visible throughout the trial, including the delay period, fixation point disappearance, and response period. In not-visible blocks, it disappeared from the screen after a 200-ms presentation, preceding the delay period. Each trial began with a fixation point at the first letter of the first word in the sentence. If the participant fixated it for at least 500 milliseconds, the sentence presentation would commence automatically; otherwise, after 2 seconds, the 9-point calibration process would be repeated.

Data analysis

Data preprocessing

Data preprocessing and eye movement event extraction were performed in Data Viewer software (SR Research, version 3.1.1). Saccades and fixations were identified using the Data Viewer saccade detection algorithm. Blinks were defined as a period of saccade-detector activity with the pupil data missing for three or more samples in a sequence. Eye movement events before and after the blinks were eliminated. Saccadic measures included peak saccade velocity (degrees of visual angle/millisecond) (PSV) and saccade amplitude (SA) (degrees of visual angle); fixation duration (FD) and blink rate (BR) were also considered.

Statistical Analyses

Statistical data analyses were performed in Python packages (scipy and statsmodels). The Kolmogorov-Smirnov-test (K-S-test; one sample test) was applied to test the data for distribution normality. The null hypothesis (H0) of normality was rejected for PSV and SA, and the eye tracking data were therefore log10 transformed (Yan & Pan, 2023). Therefore, the following measures were included in the analysis: WMC (measured with n-back task); PSV, and SA in different WML conditions.

The two-way ANOVA was used to estimate how the means of peak saccade velocity and saccade amplitude change according to the levels of the two independent variables: working memory updating (measured with n-back task); in single and dual task (with additional memory load) conditions.

Results

The data from the reading span task were split by median and the n-back task results were rated as "high" and "low" with 17 high performers (both 2-back or 3-back performance above 75%) and 14 low performers (either 2-back or 3-back result below 75%). Performance on N-back and reading span tasks was moderately and positively correlated in dual task data and combined 2-back and 3-back data $\chi^2(1; 774) = 18.6, p < .01$.

Repeated measures two-way (WMC × Task) ANOVA showed no significant interaction effect for PSV (F (1, 1549) = .07, *p* = .79). However, significant main effects of WMC (F (1, 1549) = 124.6, p < .01) and Task (F (1, 1549 = 1424.71, *p* < .01) on PSV were registered. The effects of WMC and Task factors are presented in Figure 4 (a, b); pairwise comparisons — in Table 1. Furthermore, repeated measures two-way (WMC × WML) ANOVA showed significant interaction effect for PSV (F(1, 774) = 15.49, *p* < .01) with significant main effects of WMC (F(1, 774 = 195.7, *p* < .01) and WML (F(1, 774 = 6.21, *p* < .01) on PSV in the Dual task condition.

The pattern of SPV with increasing task demand in participants with higher and lower WM span is presented in Figure 5. Repeated measures two-way (WMC x WML) ANOVA showed significant interaction effect for the PSV ratio (F (1, 774) = 20.7, p < 0.01), with significant main effect of WMC (F (1,774 = 32.7, p < 0.01), but no significant main effect of WML (F (1,774 = 3.37, p = 0.07) on PSV. Pairwise comparisons are presented in Table 1.

FD differed significantly in the reading for comprehension and the reading span tasks (t(736) = 31.4, p < 0.01), with longer FD in reading for comprehension (M = 224, SD = 24) and shorter FD in reading with the dual task (M = 209, SD = 19.5). BR was more prone to individual differences in WMU (t(736) = 14.0, p < 0.01), with BR rate in lower WMU group (M = 0.35, SD = 0.32) and lower BR in higher

Figure 4

Means of Saccadic Peak Velocity (without Log10 Transformation) in Subjects with Different WM Capacity in Reading Tasks: Single and Dual Task, with Standard Errors

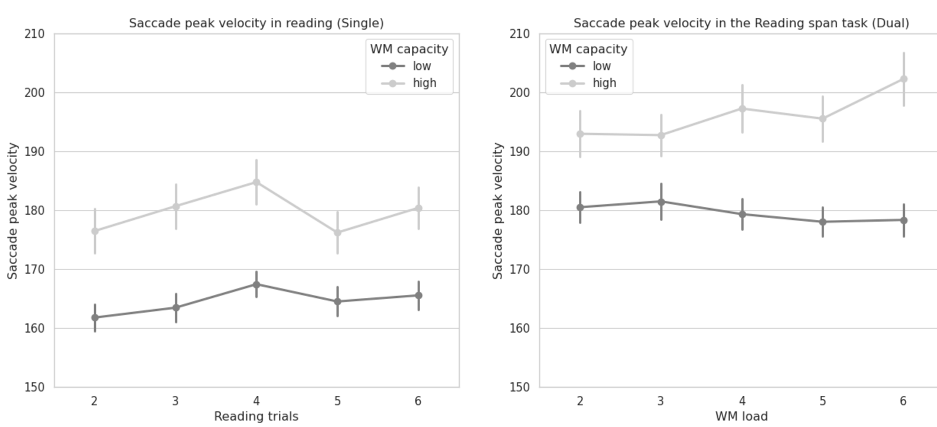


Table 1

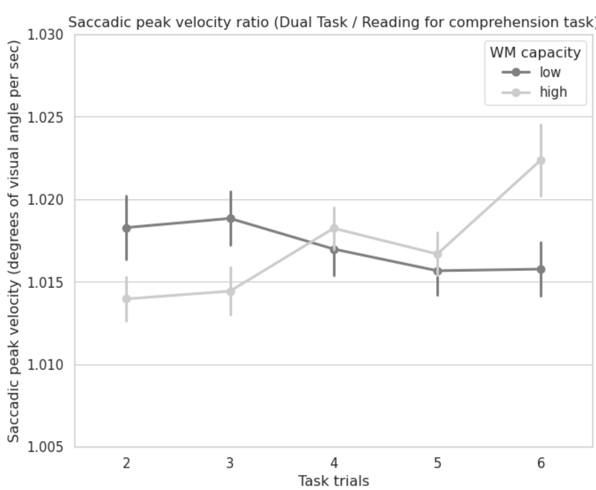
Pairwise T-tests and Effect Sizes for Peak Velocity Ratio, Log10 Transformed (Dual Task / Reading for Comprehension)

Task demand level		Saccade peak velocity high WMC	Saccade peak velocity low WMC
		t(df), p-value, Cohen's d	t(df), p-value, Cohen's d
2	3	$t(420) = -0.18$, $p = .85$, $d = -0.03$	$t(345) = -0.29$, $p = .78$, $d = -0.05$
2	4	$t(420) = -1.84$, $p = .07$, $d = -0.31$	$t(345) = 0.55$, $p = .60$, $d = 0.09$
2	5	$t(420) = -1.16$, $p = .14$, $d = -0.19$	$t(345) = 1.12$, $p = .28$, $d = 0.19$
2	6	$t(420) = -4.03$, $p < .01$*, $d = -0.61$	$t(345) = 1.07$, $p = .29$, $d = 0.18$
3	4	$t(420) = -1.66$, $p < .05$*, $d = -0.28$	$t(345) = 0.83$, $p = .39$, $d = 0.14$
3	5	$t(420) = -0.98$, $p = .22$, $d = -0.17$	$t(345) = 1.41$, $p = .14$, $d = 0.24$
3	6	$t(420) = -3.85$, $p < .01$*, $d = -0.58$	$t(345) =1.35$, $p = .17$, $d = 0.23$
4	5	$t(420) = 0.68$, $p = .38$, $d = 0.11$	$t(345) = 0.57$, $p = .10$, $d = 0.53$
4	6	$t(345) = -2.19$, $p = .09$, $d = -0.30$	$t(345) = 0.52$, $p = .59$, $d = 0.09$
5	6	$t(420) = -2.87$, $p < .05$*, $d = -0.41$	$t(345) = -0.05$, $p = .95$, $d = -0.01$

Note. * indicates significant differences.

Figure 5

Saccadic Peak Velocity Ratio, Log10 Transformed (Dual Task / Reading for Comprehension) in Subjects with Different WM Capacity in Reading Tasks, with Standard Errors



WMU group (M = 0.17, SD = 0.18). However, when the ratio of these measures in the two tasks was calculated, no significant interaction effect of WMU group and WML for the FD was established ($F(4, 736) = 1.3$, $p = .26$) and while the interaction effect for BR ratio was significant ($F(4, 736) = 2.5$, $p < .05$), post-hoc Bonferroni test revealed that the effect was associated only with the 5th WML level.

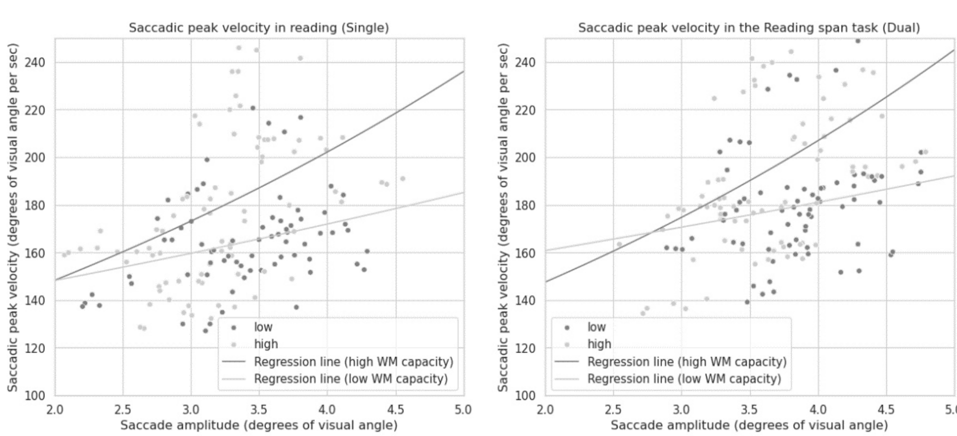
Moreover, while SPV was higher in high performers, SA was lower – both for the reading comprehension task ($t(1; 774) = 4.8$, $p < .01$) and for the reading span task ($t(1, 774) = 5.85$, $p < .01$). The saccadic “main sequence” (PSV increase as a function of SA) for high and low performers with increasing mental workload is shown in Figure 6. Exponential model was opted as it has been shown to have the highest explanatory capability in the “main sequence” research (Gibaldi & Sabatini, 2021).

Discussion

Here, we examined the effect of increasing task demand in reading tasks (reading for comprehension and reading dual task) on PSV in participants with high and low WMC. Peak saccadic velocity was associated with the relative WMC: high performers demonstrated higher PSV and lower SA in both tasks contradicting previous research where higher WMC has been associated with higher saccade amplitude and longer fixation duration (Traxler et al., 2012). This opposite direction of WMC effect on PSV and SA can be explained in terms of variations in the saccadic “main sequence” (PSV increasing as a function of SA), where higher PSV was associated with an increase of arousal (Di Stasi et al., 2013). Moreover, higher WMC was associated with higher variability in PSV across trials with highest increase in PSV in the most demanding task (maintaining six items in WM and simultaneously reading for comprehension). Low performers, on the other hand,

Figure 6

Model Fitting for Peak Saccade Velocity in High and Low Performers with Increasing Mental Workload



did not demonstrate this variation across trials, which can be attributed to lower arousal induced by the complex dual task.

On the other hand, the source of distinctions in PSV in different WMC could be related to the features of cognitive strategy implementation in reading span: Kaakinen and Hyönä (2007) showed that individuals with high WM span use semantic elaboration strategy more frequently and efficiently than individuals with low WM span who mainly used rehearsal strategy. Therefore, the increase in PSV in high performers could be attributed to the strategy-induced arousal. However, further research is necessary to investigate the effect of cognitive strategy use on arousal in complex reading tasks.

PSV was higher in the dual task than in the single reading task, with a specific increase at the highest level of task demand, but only in high performers. The increase in PSV with increasing task demands contradicts previous research (Bachurina & Arsalidou, 2022). However, this can be attributed to the nature of the dual task, which included reading and memorizing target words while in previous eye tracking research using reading span task, the participants distributed their attention in favor of the target words (Kaakinen & Hyönä, 2007). This could result in higher SA and PSV values due to frequent target word area revisits.

Overall, the results of this study emphasize the role of individual differences in working memory in information processing, particularly in reading. Also, PSV has been demonstrated to be a useful eye movement measure in reading studies. Future research should consider the role of working memory in cognitive strategies of information processing, with peak saccade velocity as an indicator of arousal in task performance. Overall, our study provides new insights into the complex interaction between WMC and eye movements in reading with important implications for our understanding of cognitive processes involved in information processing.

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