

Adaptive Dynamics of Eye Movements and Pupillary Responses under Cognitive Load

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Abstract—This study investigated the adaptive dynamics of visual scanning and pupillary responses during a letter memorization task with varying cognitive demands. By combining eye tracking with pupillometry, we assessed how attention and information processing reorganize in response to increasing task complexity and sustained performance over time. The findings show that visual and pupillary responses adapt in a coordinated manner, reflecting changes in attentional control and effort across varying conditions of cognitive load. These findings underscore the value of multimodal physiological measures for capturing the mechanisms of attentional adaptation under cognitive load.

Index Terms—Eye tracking, pupillometry, working memory, attention, cognitive load, visual scanning

I. INTRODUCTION

The question of how humans allocate attention and maintain performance under conditions of increasing cognitive load remains one of the central problems in contemporary cognitive science [1]–[9]. While it is well established that task complexity influences information processing, the precise mechanisms through which these changes occur are not yet fully understood. Traditional behavioral measures such as accuracy or response time are informative but provide only an indirect view of the underlying processes [10], [11]. In order to understand how information is actually encoded, maintained, and retrieved in working memory, it is necessary to investigate the temporal and spatial dynamics of the processes that shape perception and attentional control. This is especially important because cognitive systems are required to flexibly adapt to rising demands, and failure to do so often manifests as reduced efficiency or even breakdowns in performance.

One of the promising methods for analysis such data are AI-based ones [12]–[16]. Among the various indices available for such analysis, oculomotor and pupillary measures are of particular importance. Eye movements provide a window into the unfolding strategies of visual scanning and reveal how

subjects distribute attention across the stimulus field, while pupillary responses capture variations in cognitive effort and resource allocation [17]. Together, these measures offer a direct means of linking moment-to-moment fluctuations in attentional engagement with the external conditions of the task. Eye tracking and pupillometry are valuable not only for advancing theoretical understanding but also because they are increasingly recognized as promising biomarkers of cognitive states [18], [19]. These methods are non-invasive, highly sensitive to small changes in attention and mental effort, and can be used in both basic research and applied settings, including clinical diagnostics and cognitive rehabilitation. The ability to quantify how attention is reorganized under load therefore provides a foundation for both advancing theoretical models of working memory and developing practical tools for clinical and applied domains.

Previous multimodal research has demonstrated that when subjective fatigue increases, task performance can still be maintained through compensatory effort and by preserving the functional efficiency of frontoparietal networks [20]. These results provided evidence for neural mechanisms of adaptation during sustained cognitive activity. In the present study we focus specifically on a detailed analysis of eye movement behavior in the same experimental framework. Our aim is to examine how scanning strategies change with increasing task complexity and with progression through successive blocks. The detailed analysis of eye movements presented here complements previous neural results and helps to clarify how attentional strategies change with increasing cognitive demands.

II. METHODS

The experimental paradigm was based on the presentation of letter sets with variable memory load that ranged from two to seven characters. The procedure consisted of four consecutive blocks of equal duration, each containing an equal number of trials for every level of difficulty. The analysis was

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concentrated on the encoding phase when the letter set was shown, although retention and probe periods were also taken into account in the processing of pupillary responses.

Fixations and saccades were identified from the recorded gaze trajectories. For each event we calculated fixation duration, saccade duration, and peak saccadic velocity. These measures were used to assess visual scanning strategies and oculomotor behavior as task complexity increased.

Pupil size data underwent several preprocessing steps in order to remove artifacts and achieve signal normalization. Samples within fifty milliseconds of each blink were excluded and the gaps were reconstructed with cubic spline interpolation to preserve continuity of the signal. A linear low pass FIR filter with zero phase lag and a cutoff at four hertz was then applied to suppress high frequency noise without distorting the temporal structure of the responses [21]. Finally baseline correction was performed by subtracting the mean pupil diameter measured in the one second interval preceding the onset of the stimulus. This procedure eliminated slow fluctuations unrelated to the task and highlighted stimulus related changes. From the processed signal we extracted the maximum pupil dilation, the latency of the first local dilation and the latency of the global maximum.

Visual attention in the foveal zone was modeled as a circle of approximately 102.8 pixels in diameter corresponding to two degrees of visual angle [22]. Each fixation was represented as a disk with this radius centered on the gaze point. The total coverage area was defined as the union of all disks within a trial whereas the overlap area was defined as the region that was fixated more than once. These measures captured the spatial characteristics of scanning behavior.

All eye movement and pupillary measures were averaged across trials within each block and normalized by within subject z transformation in order to reduce inter individual variability. Statistical evaluation was carried out with repeated measures analysis of variance that included two within subject factors, Block with four levels and Load with two to seven letters. The analyses were focused primarily on the encoding phase which most directly reflects visual scanning and cognitive effort.

III. RESULTS

The analysis of eye movement and pupillary measures revealed systematic changes in visual behavior as a function of task demands and progression through the experiment. Mean fixation duration decreased consistently across successive blocks, showing a strong main effect of block ($p < 0.001$). This pattern may indicate a training effect or a gradual shift toward more efficient scanning strategies. Task load alone did not produce a significant main effect, although the interaction between block and load approached significance ($p = 0.06$), suggesting that adaptation of gaze behavior may depend on the specific task conditions.

Neither saccade duration nor saccade peak velocity exhibited systematic changes across blocks. However, peak saccadic velocity showed a moderate increase with task load ($p =$

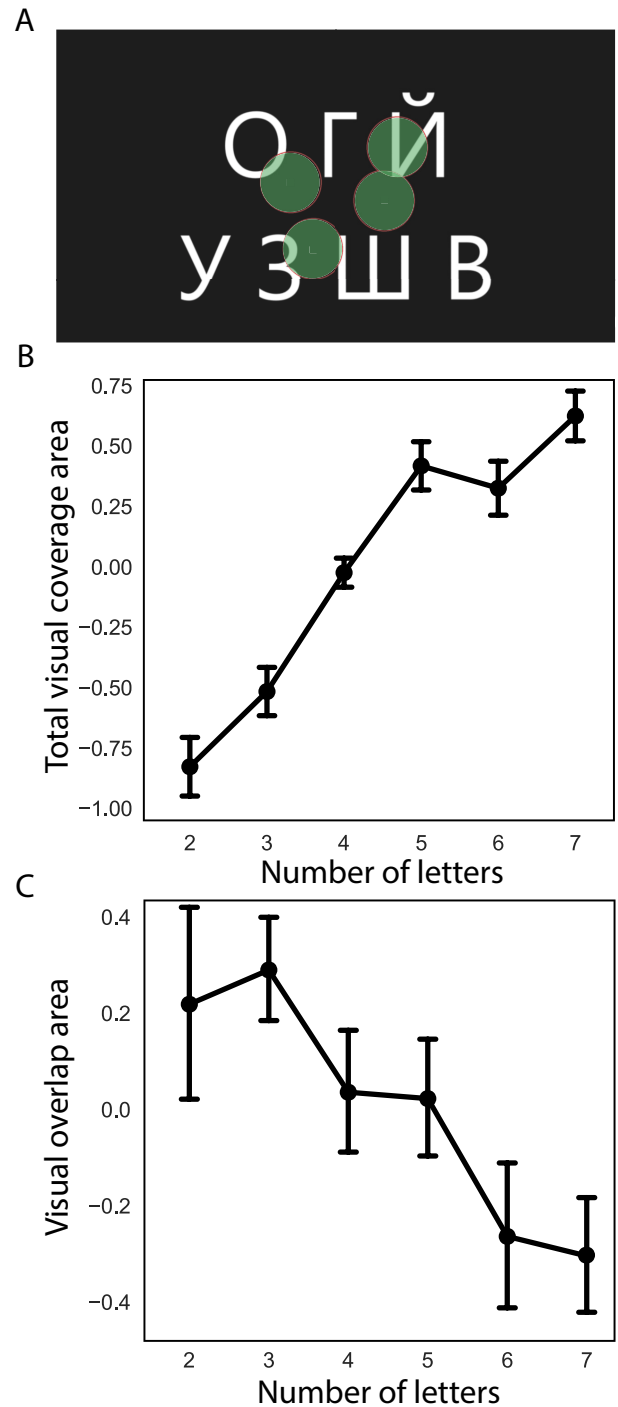


Fig. 1. Illustration of visual attention zones during a letter memorization task. (A) Each fixation is marked by a semi-transparent green circle with a red outline (radius ≈ 102.8 pixels, corresponding to 2° of visual angle). (B) Total visual coverage area as a function of the number of letters in the memorized set. (C) Visual overlap area, indicating regions that were fixated more than once. Error bars represent the standard error of the mean.

0.027), pointing to an enhancement of visuomotor activity as cognitive demands increased.

Pupillary responses demonstrated pronounced sensitivity to both experimental factors. The maximum pupil diameter was

significantly affected by task load ($p = 0.0099$) and block ($p = 0.0078$), with a significant interaction between these factors ($p = 0.045$). Pupil size decreased as the number of letters increased, likely reflecting the influence of stimulus luminance. In contrast, across blocks a gradual increase in pupil diameter was observed, which may reflect growing fatigue or changes in information processing strategies. In addition, the latency of the maximum pupil dilation increased significantly with task load ($p = 0.0055$), consistent with more prolonged cognitive processing under higher demands.

Spatial measures of visual attention illustrated in Fig. 1 also showed systematic effects. The total coverage area was strongly influenced by task load ($p < 0.001$), whereas neither block nor the interaction of factors reached significance. The coverage area expanded markedly with increasing set size up to five letters, after which the rate of increase slowed. Analysis of overlap area revealed a significant main effect of load ($p = 0.039$) but no significant effects of block or interaction. The proportion of repeatedly fixated regions decreased as task load increased, indicating reduced attentional stability and a shift toward more distributed scanning strategies.

Taken together, these results show that increasing task demands were accompanied by shorter fixations, higher saccadic velocities, delayed and more pronounced pupillary responses, as well as broader visual coverage with reduced overlap. These findings suggest a redistribution of attentional resources and an adaptation of scanning strategies to balance the rising cognitive load across successive stages of task performance.

IV. CONCLUSION

The present study examined eye movement behavior and pupillary responses during a letter memorization task with varying levels of cognitive load. The findings revealed systematic modulations in fixation patterns, saccadic dynamics, and pupil size as a function of task demands and progression through the experiment. These results suggest that both oculomotor and pupillary measures are sensitive to changes in cognitive requirements and temporal context, providing valuable markers of adaptive mechanisms in visual attention and working memory. The integration of eye tracking and pupillometry thus offers an effective approach for investigating how attentional strategies are reorganized under increasing cognitive demands.

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