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Article

Keywords:

Posted Date: November 17th, 2026

DOI: https://doi.org/10.21203/rs.3.rs-11177279/v1

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Additional Declarations: No competing interests reported.

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Abstract

Eye movement (EM) measures can provide objective information about cognitive performance during specific tasks, but their interpretation depends on the demands of each paradigm. We examined relationships between EM features and Montreal Cognitive Assessment (MoCA) performance in 67 healthy adults using an approximately 10-minute battery comprising the Rey Auditory Verbal Learning Test with pupillometry, smooth pursuit, a visuospatial memory task, and a modified rapid serial visual presentation task. These paradigms were selected to examine verbal learning and recall-related effort, oculomotor control, visuospatial memory and responses to visual changes, and rapid visual attention and information processing, respectively. Valid EM data were available for 66 participants. MoCA scores were examined continuously and through exploratory comparisons between groups defined by the sample median. At the uncorrected threshold, selected saccade, fixation, blink, pupil, and region-of-interest measures showed nominal differences between groups, with patterns varying across tasks. Associations with continuous MoCA scores also varied across features. None of the between-group feature differences remained significant after false discovery rate correction. Together, these findings characterize task-dependent variation in EM measures in relation to cognitive performance among healthy adults and identify candidate measures for replication and subsequent evaluation in older and clinical populations.

Keywords: Eye tracking; Cognitive performance; Healthy adults; Montreal Cognitive Assessment; Individual differences

1 Introduction

Cognitive performance varies across healthy adulthood, including differences in memory, attention, executive control, and processing speed. Characterizing these individual differences with objective measures is relevant to basic cognitive research and may also inform studies of aging, mild cognitive impairment (MCI), and Alzheimer's disease (AD). The Montreal Cognitive Assessment (MoCA) provides an overall score together with scores for several cognitive domains[1]. Although these scores describe cognitive performance at global and domain levels, individuals with similar scores may still perform particular tasks differently. Additional measures recorded throughout task performance may help characterize these differences.

Eye movement (EM) recording is a noninvasive method that provides continuous measures of gaze position, fixations, saccades, blinks, and pupil dynamics. These measures have been linked to attention, memory, cognitive control, and mental effort[2,3]. EM patterns also show reliable individual differences among healthy adults[4]. Clinical studies have reported alterations in saccades and visual exploration

during memory tasks in MCI and AD[5,6]. Together, these findings support the use of EM measures to characterize individual differences in cognitive performance among healthy adults and motivate further study in clinical populations.

However, EM features are task dependent because eye movements reflect current goals and cognitive demands[7,8]. A single paradigm captures only one combination of cognitive and oculomotor demands, whereas a battery of complementary paradigms samples multiple contexts. Such a battery can reveal whether associations with cognitive performance recur across tasks or vary with task demands.

On this basis, we assembled a brief battery comprising four paradigms. The Rey Auditory Verbal Learning Test (RAVLT) was selected to assess verbal memory[9,10]. In the current study, we simultaneously recorded pupillary responses during the RAVLT to index cognitive load, as pupil dilation reflects cholinergic system integrity and is attenuated in individuals with cognitive decline[11]. Throughout the RAVLT, a central fixation cross was presented, and participants were asked to fixate on it during both encoding and recall. The smooth pursuit task was selected to probe oculomotor control and executive processes through the ability to maintain continuous tracking and limit intrusive corrective saccades [12,13]. The visuospatial memory eye-tracking task (VisMET)[14] is modified from the Visual Paired Comparison (VPC) paradigm[6], which records the gaze difference between a familiar scene and one with a novel area. Prior relevant work showed reduced gaze preference for novel stimuli with cognitive decline, suggesting diminished capacity to integrate implicit memory and episodic memory[15]. The rapid serial visual presentation (RSVP) task was incorporated to probe attention and processing speed, as individuals with cognitive decline exhibit distractibility and reduced search efficiency under rapid presentation[16]. Performance on RSVP tasks relies on selective attention, interference suppression, and rapid information processing[17]. Our modified version distributed number streams across six screen locations and required participants to report the positions and presentation order of two targets. This design added spatial selection and order memory to conventional RSVP while allowing EM data to be recorded across multiple screen locations.

This study examined whether task-specific eye-tracking measures covaried with MoCA performance in healthy adults. We hypothesized that lower MoCA performance would be associated with: (1) less efficient memory-related oculomotor behavior during RAVLT and VisMET, including greater gaze-event variability and weaker novelty-related orienting; (2) poorer smooth-pursuit control, reflected by more frequent or prolonged saccades; and (3) less stable oculomotor behavior during RSVP under rapid attentional demands. Because the tasks place different demands on memory, attention, and oculomotor control, we expected the associated features to differ across tasks. MoCA scores were used to describe differences in cognitive performance within this healthy sample, not to assign a clinical diagnosis.

2 Materials and Methods

2.1 Participants

All participants were volunteers for the research project, recruited from community and university. The inclusion criteria were: 1) participants aged 20 years or older; 2) participants in good general health and able to complete the Montreal Cognitive Assessment and eye-tracking tasks. Exclusion criteria were: 1) any neurological disorder (e.g., stroke, epilepsy, Parkinson's disease); 2) any psychiatric disorder (e.g., major depression, schizophrenia, severe anxiety); 3) any ophthalmological disease affecting eye movements (e.g., glaucoma, strabismus, nystagmus); 4) uncontrolled systemic diseases (e.g., hypertension, diabetes); 5) use of medications affecting pupil or oculomotor function; 6) history of alcohol or drug dependence.

2.2 Study Design

This was a single-center, cross-sectional observational study evaluating a brief multi-paradigm eye-tracking battery in a healthy cohort. Associations between task-specific eye-tracking metrics and MoCA

performance were examined to characterize variation in cognitive performance within this nonclinical sample. The study was conducted from September 22, 2024, to March 19, 2026. This healthy-cohort stage was intended as an initial characterization of variation in cognitive performance within this nonclinical sample before evaluation in older and clinical populations.

The battery comprised four consecutive tasks selected to sample complementary processes: (1) the Rey Auditory Verbal Learning Test (RAVLT) with pupillometry for verbal learning and memory-related cognitive load; (2) smooth pursuit for oculomotor control; (3) the visuospatial memory eye-tracking task (VisMET) for visuospatial and novelty-related processing; and (4) a modified rapid serial visual presentation (RSVP) task for attention and processing speed.

In this study, we examined whether task-specific behavioral and EM measures were associated with MoCA total scores and, where relevant, its subdomain scores.

2.3 Procedure

The experiment consists of four tasks and lasts for 10 minutes in total, presented with PsychoPy-2025.1.1. A Schematic illustration of the experiment was listed in **Figure 1**.

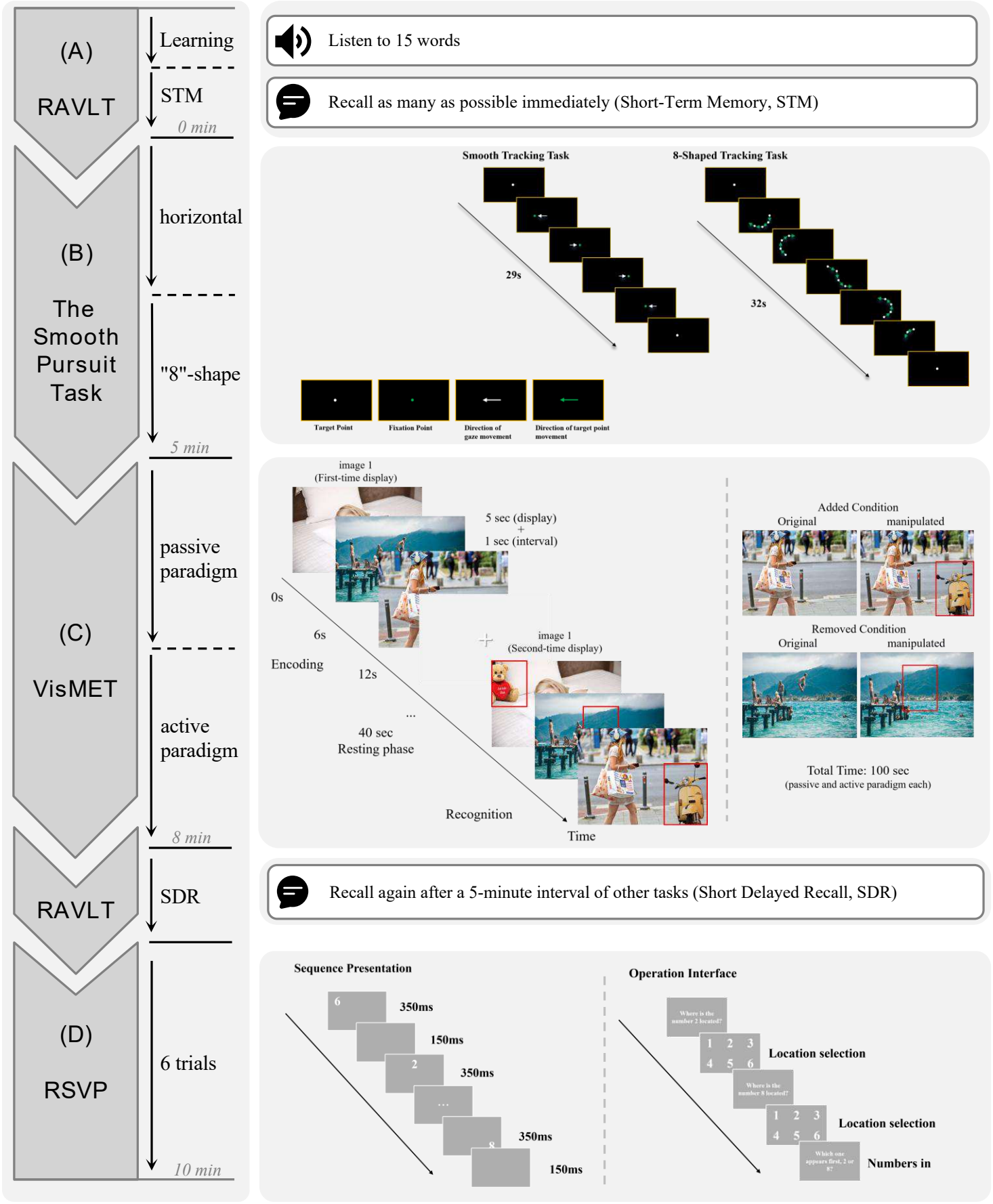


Figure 1. A Schematic illustration of the multi-paradigm eye-tracking battery

The protocol comprises four tasks completed sequentially:

(A) RAVLT with pupillometry (STM and SDR recall phases);

(B) smooth pursuit (horizontal and figure-eight tracking);

(C) VisMET (passive and active paradigms);

(D) modified RSVP. Arrows indicate the order of task progression. The total duration is approximately 10 minutes.

2.3.1 RAVLT and pupil measurement

We used a shortened RAVLT-based protocol comprising two phases. (1) Short-term memory (STM) phase: participants listened to a recording of 15 words in standard Mandarin presented at a rate of one word per second and were then asked to recall as many words as possible immediately after listening. (2) Short-delay recall (SDR) phase: five minutes after the STM phase, during which other study tasks were administered, participants were asked to recall the same word list again. Long-delay recall (LDR) was not included in this abbreviated protocol. A central fixation cross was displayed during listening and recall, and pupil diameter was recorded throughout both phases. Behavioral outcomes were the numbers of correctly recalled words during the STM and SDR phases. EM measures included mean pupil diameter and pupil-dilation amplitude in each phase. Further details of the protocol are provided in **Supplementary Fig. S1**.

2.3.2 The Smooth Pursuit Task

The smooth pursuit task lasted 65 seconds and was divided into two parts. In smooth horizontal tracking, the target moved back and forth in the horizontal direction at a constant speed, with an amplitude of ± 0.48° and a duration of 29 seconds. In "8"-shape tracking, the target followed a figure-eight trajectory (horizontal amplitude 0.40°, vertical amplitude 0.25°), completing each cycle in 16 seconds for two alternating cycles. During the whole process, participants were required to keep their gaze at the target.

2.3.3 VisMET

Two experimental paradigms mentioned above (passive and active) were used in this task, and EM trajectories were recorded.

In the passive paradigm, five images of natural scenes or objects were sequentially presented at the center of the screen, each displayed for 5 seconds with a one-second interval. Participants were instructed to observe the images. After the first set was presented, a 40-second rest interval followed. The same set of images was then presented again in the identical order, duration, and interval pattern, but with one detail altered in each image (e.g., an object was added or removed). Throughout this paradigm, participants simply viewed the images naturally and were not required to report any changes. The active paradigm was identical to the passive paradigm in stimulus presentation, with the key distinction being task instruction. Prior to the active condition, participants were explicitly informed that certain image details would be modified and were instructed to verbally report any detected changes during viewing.

Images were selected from the *Pixabay open-access database*. Images with moderate complexity were selected and edited using *Adobe Photoshop 2025*. The behavioral index was the accuracy of change detection in the active paradigm. Eye movement analysis focused on global metrics, including fixation duration, saccade parameters, and pupil diameter. Additionally, to quantify gaze allocation toward the changed regions, regions of interest (ROIs) were defined as the bounding boxes of the modified areas in each image, identified by comparing the original and modified image pairs using OpenCV. For each 5-second image presentation window, fixations were detected using the same I-VT algorithm, and fixations whose centroid fell within the ROI were counted. Three ROI metrics were computed per image: (1) ROI fixation count, (2) total ROI dwell time, and (3) time to first ROI fixation. Per-subject ROI metrics were

then averaged across images within each condition (passive original, passive modified, active original, active modified). The difference between modified and original ROI metrics was also calculated for each paradigm to isolate change-related gaze allocation. Image-level timestamps for each participant were extracted from the PsychoPy output files to ensure precise alignment between gaze data and stimulus presentation.

2.3.4 RSVP

This task represents a modification of the classic RSVP. It extends the traditional single-point sequence presentation to multi-spatial location presentation and incorporates location memory as well as eye-movement responses. Consequently, it integrates the measurement of multiple cognitive indices, such as saccade and spatial memory, within a single paradigm.

The task encompasses six fixed positions on the screen. At each position, a number is presented for 350 ms, followed by a 150 ms interval. Participants are informed, in advance, of two specific numbers as targets. These targets are presented at two of the six locations. The other four locations present numbers as distractions. Each number appears only once in each sequence. After all six numbers are presented in a single trial, participants are required to indicate the position and the appearing order of the two target numbers.

Behavioral indicators consist of the accuracy rate of judgments on time and order, as well as spatial position, and the comprehensive accuracy rate. EM indexes include fixation duration, saccade latency, and the gaze path during the response phase.

2.4 Data Processing and Analyses

2.4.1 Behavioral Data

Statistical analyses of behavioral data and MoCA scores were performed using SPSS version 27.0. Descriptive statistics were calculated for all variables; continuous variables were presented as mean±standard deviation, and categorical variables as frequencies (percentages). Normality was assessed using the Shapiro-Wilk test.

MoCA total scores were analyzed as both continuous and categorical variables. Spearman rank correlations examined associations between continuous MoCA total scores and eye-tracking features identified in the between-group comparisons; correlations of MoCA total and subdomain scores with age, education, and behavioral task scores were also calculated. For descriptive group comparisons, participants were divided at the observed median MoCA score (cut-off = 27) into lower- and higher-performance groups. This division represented relative performance within the healthy cohort and was not a diagnostic classification. Between-group comparisons used independent-samples t tests or Mann-Whitney U tests, as appropriate. All tests were two-sided, with alpha = 0.05.

To account for multiple testing, the Benjamini-Hochberg false discovery rate (FDR) procedure was applied separately within each experimental paradigm for trial-level features (44 tests per paradigm) and across the ROI-feature family (24 tests), with $q < 0.05$ defining FDR-adjusted significance[18]. Findings with raw $p < 0.05$ that did not survive FDR correction are reported as nominal descriptive patterns. Adjusted p values are provided in Supplementary Table S2.

2.4.2 Eye Movement Data

Eye movement data were recorded using a Tobii Pro X3-120 eye tracker at a sampling rate of 120Hz. Experiments were conducted in a dimly lit, quiet office. Prior to data collection, participants underwent position calibration using Tobii Pro Eye Tracker Manager. Raw data were exported as tab-separated text files containing timestamps, binocular gaze coordinates (normalized), pupil diameters, and data quality flags.

Data preprocessing was performed using custom Python scripts. Data quality was first assessed by calculating the proportion of valid samples for each eye. For binocular valid samples, gaze coordinates

and pupil diameters were averaged; for monocular valid samples, data from the available eye were used. Missing samples caused by blinks were identified as contiguous gaps with pupil diameter < 2.0 mm or missing gaze coordinates; only gaps lasting 50-400 ms were retained as blink events. Short gaps not related to blinks (≤3 consecutive missing samples) were linearly interpolated. Normalized gaze coordinates (X: −0.8 to 0.8, Y: −0.5 to 0.5) were converted to pixel coordinates based on screen resolution (2560 × 1600) and clipped to the visible screen area. Timestamps were converted from seconds to milliseconds for subsequent processing.

Event detection was performed using the pymovements library. After converting pixel coordinates to degrees of visual angle, fixations were detected using the velocity-based I-VT algorithm (threshold: 30°/s, minimum duration: 100 ms). Saccades were detected using the microsaccade detection algorithm [19], as implemented in the Microsaccade Toolbox [20], with a threshold factor of 6 and a minimum duration of 24 ms. Blinks were detected as described above. Skewness and kurtosis were computed using Fisher's definitions, reflecting the shape (asymmetry and tailedness, respectively) of the temporal distribution of the respective metric over the trial period.

At the trial level, features were aggregated across all events within each experimental block, including counts of each event type (these are raw frequencies per trial, not normalized to per-minute rates), descriptive statistics (mean, standard deviation, median, minimum, maximum) of event durations, summary statistics of saccade amplitudes and peak velocities, mean fixation dispersion, and scanpath length (cumulative Euclidean distance between consecutive event centroid positions). Global pupil statistics over the entire trial were also computed.

Finally, the continuous eye movement data were segmented into individual trials based on timestamp markers corresponding to the start and end of each experimental block. For each trial, the above event detection and feature extraction procedures were applied, and the resulting features were saved in CSV format for subsequent statistical analysis.

2.5 Ethics approval and informed consent

This study was conducted in accordance with the Declaration of Helsinki and relevant institutional guidelines and regulations. The study protocol was approved by the Institutional Review Board of Ruijin Hospital Luwan Branch, Shanghai Jiao Tong University School of Medicine (approval no. LWEC2023031(1)). Written informed consent was obtained from all participants before data collection.

2.6 Use of generative AI

ChatGPT (OpenAI) was used to assist with English-language editing, manuscript organization, and consistency checking. All AI-assisted outputs were reviewed and verified by the authors, who retained full responsibility for the scientific content, interpretations, and final manuscript.

3 Results

3.1 Demographic features

A total of 67 participants were recruited. One participant (ID 55) had no available eye-tracking data and was therefore not included in EM analyses. Consequently, behavioral and demographic analyses were performed on all 67 participants, whereas EM analyses were based on 66 participants. ROI-based analyses further excluded one participant(ID 47) because of complete loss of valid gaze data during the VisMET task, resulting in a final sample of 65 participants. **Table 1** summarizes sample size, age, gender, education level, and MoCA scores. Participants were stratified using the observed median MoCA score (cut-off = 27); Group A comprised participants with lower performance and Group B those with higher performance.

Characteristic	Participants			p value
	Overall (n=67)	Group A (n=37)	Group B (n=30)	
Age	35.54±11.55(21~78)	36.51±11.51(22~78)	34.33±11.68(21~64)	0.217
Gender, n(%)				0.470
Female	28(41.8%)	14(37.8%)	14(46.7%)	
Male	39(58.2%)	23(62.2%)	16(53.3%)	
Education, n(%)	63	36	27	0.029
Middle School	7(11.1%)	6(16.7%)	1(3.7%)	
Junior College	16(25.4%)	12(33.3%)	4(14.8%)	
Bachelor	38(60.3%)	16(44.4%)	22(81.5%)	
Above Bachelor	2(3.2%)	2(5.6%)	0(0%)	
MoCA score	27.48±1.57	26.35±1.06	28.87±0.78	

Table 1. Demographic and cognitive characteristics of the two MoCA performance groups

(4 cases without education information have been excluded)

(p values describe between-group comparisons and should not be interpreted as evidence of equivalence or successful matching)

3.2 Behavioral Metrics

Group A scored lower on the VisMET task and on the visuospatial/executive, attention, language, and delayed-recall subdomains of the MoCA (**Table 2**).

RAVLT and RSVP scores did not differ significantly between groups. Across participants, RSVP performance correlated negatively with age and positively with reverse-recitation scores (both $p < 0.05$). Group B had a higher educational level than Group A, whereas age and sex did not differ significantly between groups.

Indexes		M±SD			p
		Overall (n=67)	Group A (n=37)	Group B (n=30)	
Total Score		27.48±1.57	26.35±1.06	28.87±0.78	
Completion Time		6.60±1.63	6.86±1.64	6.27±1.60	0.131
Visuospatial and Executive Functions		4.75±0.56	4.59±0.69	4.93±0.25	0.01
Naming		2.99±0.12	2.97±0.16	3.00±0.00	0.384
Attention	Total Score	5.57±0.53	5.38±0.55	5.80±0.41	0.001
	Forward Recitation	1.00±0.00	1.00±0.00	1.00±0.00	1
	Reverse Recitation	0.96±0.21	0.95±0.23	0.97±0.18	0.699

	Tapping task	0.67±0.47	0.54±0.51	0.83±0.38	0.012
	100 minus 7	2.94±0.24	2.89±0.31	3.00±0.00	0.068
Abstraction		2.00±0.00	2.00±0.00	2.00±0.00	1
Language	Total Score	2.58±0.58	2.41±0.64	2.80±0.41	0.007
	Repetition	1.60±0.58	1.43±0.65	1.80±0.41	0.012
	Fluency	0.99±0.12	0.97±0.16	1.00±0.00	0.384
Delayed Recall		3.69±1.00	3.16±0.90	4.33±0.71	<0.001
Orientation		5.91±0.34	5.86±0.42	5.97±0.18	0.251
RAVLT	STM	4.76±1.91	4.32±1.55	5.30±2.18	0.097
	SDR	3.72±2.07	3.19±1.49	4.37±2.50	0.058
	Total score	8.48±3.78	7.51±2.74	9.67±4.52	0.059
VisMET		3.88±1.08	3.68±1.03	4.13±1.11	0.038
RSVP		7.45±1.54	7.27±1.24	7.67±1.85	0.101

Table 2. MoCA score and Behavioral data

(MoCA score includes overall score and scores in subdomains)

(features with nominally significant differences at uncorrected $p < 0.05$ were highlighted)

3.3 Correlation analysis of behavioral data

Age correlated negatively with STM, SDR, and RAVLT total scores and positively with MoCA completion time.MoCA total score correlated positively with the visuospatial/executive, language, and delayed-recall subdomain scores, as well as with STM, SDR, and RAVLT total scores. Reverse-recitation score correlated positively with RSVP performance.

The full correlation matrix is presented as a heatmap in **Figure 2**.

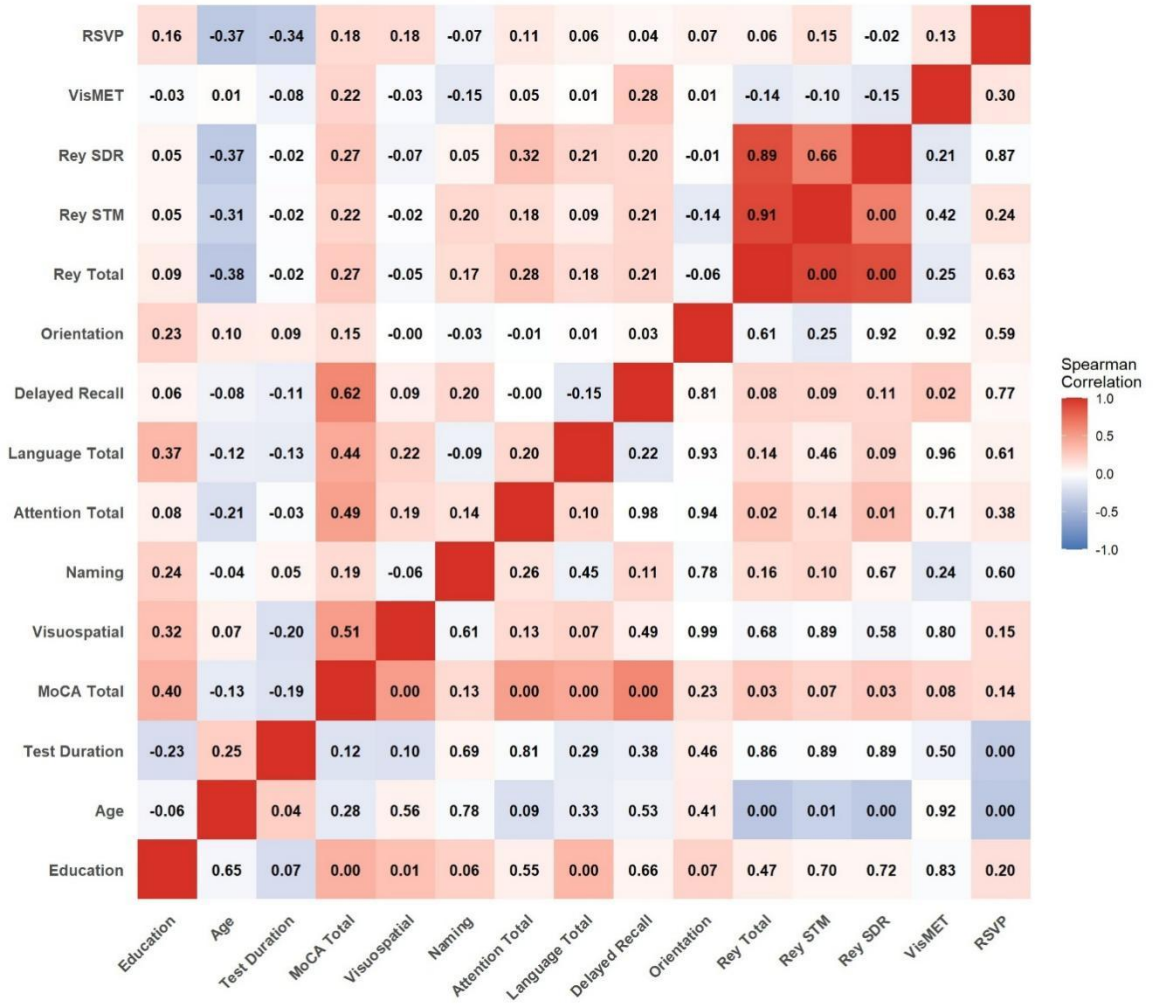


Figure 2. Correlation between behavioral data

The matrix displays Spearman correlation coefficients (r values) between demographic variables, MoCA scores, and behavioral outcomes of the four tests in the experiment. The upper values are Spearman correlation coefficients, and the lower values are p values. Red indicates positive correlations; blue indicates negative correlations; deeper shades represent stronger coefficients.

MoCA: Montreal Cognitive Assessment;

Orientation, delayed recall, language, attention, naming, visuospatial are subdomains of MoCA;

RAVLT: Rey Auditory Verbal Learning Test; STM: short-term memory; SDR: short delayed recall;

VisMET: visuospatial memory eye-tracking task;

RSVP: rapid serial visual presentation.

3.4 Eye movement metrics

Between-group comparisons identified several EM features with raw $p < 0.05$ (**Tables 3-6** and **Supplementary Tables S3-S4**). None remained significant after Benjamini-Hochberg FDR adjustment; these findings are therefore reported as descriptive patterns. Spearman rank correlations were also calculated between continuous MoCA total scores and the EM features identified in the group comparisons. Descriptive correlation coefficients and nominal p values are reported in **Supplementary Table S1**. FDR-adjusted p values for the between-group comparisons are reported in **Supplementary Table S2**.

During RAVLT, nominal differences were observed during subsequent memory retrieval phases (STM and SDR), primarily in saccade control and blink regulation(**Table 3**). No EM feature reached raw $p < 0.05$ during the learning phase. During STM, Group A exhibited poorer saccade control, characterized by longer mean and maximum saccade durations and greater saccade duration variability. During SDR, Group A showed longer minimum blink duration.

	Task	Learning Period		STM		SDR	
EM Features	Group	Group A	Group B	Group A	Group B	Group A	Group B
Maximum blink duration (ms)		245.41±88.99	233.81±75.15	300.71±86.09	321.68±81.28	284.40±96.05	320.43±82.42
Mean blink duration (ms)		147.15±36.37	148.25±32.10	146.74±30.40	152.05±25.13	152.22±44.41	154.97±27.63
Minimum blink duration (ms)		87.53±27.05	89.16±35.13	68.94±21.14	71.61±26.68	77.33±41.85	65.00±20.09
Pupil kurtosis		17.32±24.05	11.58±12.03	8.93±18.81	7.22±8.95	6.35±7.35	9.10±13.96
Maximum pupil diameter (mm)		4.23±0.57	4.35±0.65	4.49±0.65	4.65±0.62	4.47±0.56	4.65±0.65
Mean pupil diameter (mm)		3.76±0.56	3.86±0.64	3.72±0.60	3.81±0.61	3.70±0.56	3.83±0.60
Median pupil diameter (mm)		3.78±0.57	3.88±0.64	3.72±0.61	3.82±0.62	3.71±0.58	3.84±0.60
Minimum pupil diameter (mm)		1.89±0.57	2.05±0.65	1.73±0.55	1.66±0.58	1.92±0.64	1.82±0.63
Pupil diameter range (mm)		2.34±0.76	2.30±0.63	2.76±0.91	2.98±0.61	2.55±0.84	2.84±0.80
Pupil skewness		-2.14±1.77	-1.82±1.22	-0.93±1.46	-1.06±1.23	-0.88±1.31	-1.29±1.29
Pupil diameter standard deviation		0.20±0.07	0.20±0.07	0.26±0.07	0.27±0.07	0.27±0.10	0.29±0.10
Maximum saccade duration (ms)		64.13±39.64	57.85±21.59	62.79±17.33	54.06±15.03	56.83±18.19	56.48±17.60
Mean saccade duration (ms)		37.51±7.58	36.31±5.16	35.26±3.41	33.43±2.89	34.71±4.79	33.74±3.52
Minimum saccade duration (ms)		25.29±3.33	24.92±2.61	24.73±2.11	24.39±1.20	24.83±1.97	24.48±1.33
Saccade duration standard deviation		11.20±8.48	10.21±5.13	10.32±3.50	8.11±2.89	9.64±4.74	9.33±3.59

Table 3. EM Features in RAVLT

Features with nominal between-group differences are highlighted. Eye-movement analyses were performed on 66 participants (Group A, n = 36; Group B, n = 30).

In the smooth pursuit task, Group A made more saccades and showed longer saccade durations than Group B (**Table 4**).

Task	EM Features	Group A	Group B	p
Smooth pursuit	Saccade count	26.71±19.41	16.65±10.50	0.033
	Maximum saccade duration (ms)	60.50±17.51	52.13±15.02	0.044
	Mean saccade duration (ms)	34.37±3.84	32.80±3.81	
	Median saccade duration (ms)	32.00±3.41	30.19±2.80	0.039
	Minimum saccade duration (ms)	24.38±1.16	24.39±1.58	
	Saccade duration standard deviation (SD)	9.58±3.36	8.26±4.54	
	Scanpath length	30124.26±24218.57	24075.00±13655.71	

Table 4. EM Features in the Smooth Pursuit Task

Features with nominal between-group differences are highlighted. Eye-movement analyses were performed on 66 participants (Group A, n = 36; Group B, n = 30).

In the VisMET task, group differences emerged across both passive and active paradigms. Across the full task, Group B showed shorter minimum blink duration than Group A (**Table 5**).

During passive viewing, Group A showed a longer median saccade duration for original images and a longer median fixation duration for modified images. In the ROI analysis, Group B showed a larger increase in ROI dwell ratio from original to modified images (**Supplementary Table S3**). During the active paradigm, Group A showed greater saccade-duration variability in the original-image phase. ROI-based analyses also showed larger decreases in ROI dwell time and ROI fixation count in Group A when viewing modified images (**Supplementary Table S4**).

Task	EM Features	Group A	Group B	p
VisMET	Blink count	151.43±79.11	161.71±67.38	
	Mean blink duration (ms)	147.03±27.77	152.25±22.58	
	Minimum blink duration (ms)	57.14±10.52	53.29±4.66	0.013
	Fixation count	316.17±205.21	281.26±170.21	
	Maximum fixation duration (ms)	550.97±229.30	644.13±375.52	
	Mean fixation duration (ms)	163.40±30.62	159.95±22.15	
	Mean pupil diameter (mm)	3.52±0.51	3.57±0.55	
	Pupil diameter range (mm)	3.34±0.85	3.47±0.55	

Table 5. Overall EM Features in VisMET

Features with nominal between-group differences are highlighted. Eye-movement analyses were performed on 66 participants (Group A, n = 36; Group B, n = 30).

In RSVP, Group A showed fewer blinks, a longer maximum saccade duration, a shorter mean saccade duration, and greater saccade-duration variability (**Table 6**).

Task	EM Features	Group A	Group B	p
RSVP	Blink count	23.23±21.21	26.42±12.03	0.033
	Mean blink duration (ms)	151.67±33.30	145.70±26.03	
	Blink duration standard deviation (SD)	74.29±26.09	71.13±22.08	

Fixation count	69.46±50.64	63.06±39.95	
Mean fixation duration (ms)	158.84±23.67	155.69±22.53	
Fixation duration standard deviation (SD)	62.82±27.38	60.34±33.02	
Saccade count	54.57±31.18	48.94±21.83	
Maximum saccade duration (ms)	3942.38±2344.68	2676.52±2583.14	0.015
Mean saccade duration (ms)	159.09±72.17	179.80±342.79	0.031
Median saccade duration (ms)	32.97±2.33	118.65±480.57	
Minimum saccade duration (ms)	24.00±0.00	24.16±0.90	
Saccade duration standard deviation (SD)	620.21±298.37	472.79±465.24	0.013
Scanpath length	45939.49± 24533.81	44408.98± 22203.48	

Table 6. EM Features in RSVP

Features with nominal between-group differences are highlighted. Eye-movement analyses were performed on 66 participants (Group A, n = 36; Group B, n = 30).

4 Discussion

Our study administered four eye-tracking paradigms as a brief battery and examined their task-specific associations with standardized cognitive assessments in a healthy population. The patterns differed across RAVLT, smooth pursuit, VisMET, and RSVP rather than converging on a single EM profile. None of the feature-level comparisons remained significant after FDR adjustment, and the continuous associations varied across measures. The results therefore define a set of candidate features for replication while describing how EM measures vary across cognitive and oculomotor contexts within this sample.

4.1 Memory Function and Eye Movement Patterns

Delayed recall on the RAVLT correlated with both RAVLT total score and VisMET performance. Participants who performed better on verbal delayed recall therefore also tended to perform better on the visuospatial memory task, providing a behavioral link between the two memory paradigms without implying a shared mechanism.

4.1.1 Auditory Memory

Memory-related EM differences emerged primarily during memory retrieval rather than encoding. No EM feature reached raw $p < 0.05$ during the learning phase, whereas saccade-duration measures differed during STM and minimum blink duration differed during SDR.

In terms of auditory memory, during subsequent memory retrieval phases (STM and SDR), Group A exhibited longer saccade durations and more variable saccades. Because RAVLT was presented without visual-search demands, these EM events may have accompanied attentional shifts or memory search during recall[21,22]. The present data, however, do not distinguish among these processes.

In contrast, no pupillary metric met raw $p < 0.05$ during any RAVLT phase. Task-evoked pupil responses can vary with mental effort and autonomic regulation, but the restricted cognitive range of this healthy sample may have limited detectable between-participant variation[23]. Larger studies involving clinical populations are needed to determine whether more specific pupillary measures are informative [24].

4.1.2 Visuospatial memory

VisMET showed related behavioral and EM patterns. Group A had lower behavioral scores and showed longer fixation or saccade durations in selected conditions, together with differences in ROI allocation.

During passive viewing, Group A exhibited prolonged fixation and saccade durations, which may indicate weaker visual information extraction[25] and reduced efficiency in information processing[26]. Group B

showed a larger increase in ROI dwell ratio when viewing modified images. Because participants were not instructed to search for changes, this pattern is consistent with greater spontaneous allocation of viewing time to the modified regions [27].

During active encoding, Group A showed greater saccade duration variability in the original-image phase. In the ROI analysis, Group A also showed larger decreases in ROI dwell time and fixation count from original to modified images. Because both groups performed well behaviorally, these ROI changes may partly reflect task strategy after the modified region was detected; the current data do not allow this explanation to be distinguished from a ceiling effect.

Group A also scored lower on the visuospatial/executive subdomain of the MoCA. The parallel behavioral and EM patterns suggest that VisMET may capture individual variation in visuospatial task performance within a healthy sample, although the present data do not establish that the EM measures are specific to this cognitive domain.

In summary, passive VisMET viewing yielded candidate patterns related to visuospatial and novelty processing, whereas the active paradigm appeared susceptible to ceiling effects and strategic disengagement.

4.2 Oculomotor Performance

The smooth pursuit task is associated with fronto-parietal networks that support attention, sensorimotor integration, and executive function[13,28]. Abnormalities in these oculomotor measures have been linked to specific brain regions, particularly the occipital-parietal network for smooth pursuit, and show progressive alterations across the cognitive aging spectrum[29,30].

In this task, Group A made more saccades and showed longer saccade durations. Together, these measures describe less continuous target tracking and extend the task-specific EM profile from memory paradigms to visuomotor control. Replication with direct pursuit-quality measures, such as gain and tracking error, would clarify their functional significance [31].

4.3 Attention and Information Processing Speed

RSVP scores correlated negatively with age and positively with reverse recitation, confirming its sensitivity to age-related processing speed decline and its association with working memory capacity[17]. Regarding EM metrics, Group A showed a shorter mean but a longer maximum saccade duration, together with greater saccade-duration variability. This combination indicates that the group difference was concentrated in the distribution and occasional long-duration events rather than a uniform prolongation of saccades.Group A also showed fewer blinks during RSVP. Because blink suppression can occur during sustained visual engagement, this pattern may reflect stronger engagement with the rapid stimulus stream; however, blink count alone cannot distinguish cognitive load from other task-related influences [32].

Together, RSVP yielded a distinct EM pattern of greater saccade-duration variability and fewer blinks in Group A. These measures warrant replication as task-specific correlates of performance during rapid visual processing.

4.4 Main Findings and Future Perspectives

4.4.1 Summary of Key Findings

The approximately 10-minute battery provided standardized EM measurements across verbal memory, visuospatial memory, smooth pursuit, and rapid visual attention within a single session. Its main contribution is the comparison of task-specific EM patterns across these complementary contexts.

RAVLT patterns were concentrated in recall, smooth pursuit was characterized by saccade count and duration, passive VisMET showed fixation, saccade, and ROI-allocation patterns, and RSVP showed a

different combination of saccade variability and blink frequency. This variation across tasks supports interpreting EM features in relation to the paradigm in which they are elicited.

Together, the non-invasive, relatively low-cost, standardized, and time-efficient nature of the battery supports its further evaluation across broader age and education ranges.

4.4.2 Limitations

Several limitations should be considered. First, this cross-sectional study included a modest, predominantly young and healthy sample. It therefore describes differences in cognitive performance among participants at a single time point and cannot address changes over time. The MoCA groups were not individually matched, and the broad age range and between-group difference in education may have influenced the observed patterns. Although the median split provided a straightforward group comparison, it reduced the information contained in continuous MoCA scores. Future studies should use larger samples and prespecified multivariable models that retain MoCA as a continuous measure and account for relevant demographic factors.

Second, EM recordings may be affected by calibration quality, missing data, and fluctuations in attention. These factors may introduce measurement variability, particularly in pupil and duration-based measures.

The analysis also covered many EM features across multiple task conditions, increasing the possibility of chance findings. No individual feature remained significant after FDR correction. The patterns observed at the uncorrected threshold and their effect-size estimates are therefore most useful for selecting measures for replication rather than as confirmed associations.

Future studies should first evaluate these candidate measures in larger and more diverse healthy samples using prespecified continuous analyses. Once reproducible EM patterns have been established, their generalizability can be examined in older and clinical cohorts, together with their relationships to neural measures obtained using EEG or fMRI. Despite its limitations, the brief multi-paradigm battery provides a structured way to compare EM measures across distinct cognitive contexts and identifies a focused set of features for independent validation.

Data availability

The participant-level data generated and analysed during the current study are not publicly available because of privacy and ethical considerations. De-identified data supporting the findings of this study are available from the corresponding authors upon reasonable request, subject to applicable institutional and ethical requirements.

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Funding

This work was supported by the 2026 Youth Cultivation Program "Medicine-Engineering Intersection" Joint Project of Ruijin Hospital, Shanghai Jiao Tong University School of Medicine (Grant No. 2026JC192), the Shanghai Municipal Science and Technology Commission (Grant No. 22511106002), the NSFC Regional Innovation and Development Joint Fund (grant no. U24A20756), the National Key R&D Program of China (grant no. 2023YFC2410704), and the Shanghai Jiao Tong University Transmed Awards Research Program (grant no. YG2023LC02).

Author contributions

Zehan Huang, Yun Luo, and Yong Lu conceptualized the study. Zehan Huang, Yun Luo, and Zitong Zhang developed the methodology and performed the formal analyses, and Zehan Huang and Yun Luo validated the results. Zehan Huang, Zitong Zhang, Wulujiang Sailikeboli, and Hanqi Su contributed to participant recruitment, experimental implementation, and data collection. Zehan Huang, Yun Luo, and Zitong Zhang curated the data and prepared the visualizations. Zehan Huang, Zitong Zhang, Wulujiang Sailikeboli, and Hanqi Su drafted the manuscript, and Zehan Huang, Yun Luo, and Yong Lu reviewed and edited it. Yun Luo and Yong Lu provided resources and supervised the study. Zehan Huang, Yun Luo, and Yong Lu administered the project. Yong Lu acquired the funding. All authors read and approved the final manuscript.

Consent for publication

Not applicable. This manuscript contains no identifiable personal information or images of participants.

Competing interests

The authors declare no competing interests.

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