

Characteristics of Eye Movements in Patients with Bipolar Disorder and Schizophrenia When Recognizing Guide Signs and Their Association with Individual Factors

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Abstract

Background

Eye movements during guide-sign recognition may provide insight into visual information processing during driving; however, their relationships with individual characteristics in patients with psychiatric disorders remain unclear. This study examined associations of demographics and cognitive functions with eye movements during guide-sign recognition in patients with bipolar disorder (BD) and schizophrenia (S), and differences in eye movements compared with healthy controls.

Methods

Twenty-four healthy controls, 19 patients with BD, and 18 patients with S viewed on-board videos varying in driving speed (Slow/Fast) and guide-sign location (Front/Left). Fixation duration, number, and saccade amplitude and number were measured during guide-sign recognition and analyzed using generalized linear mixed models.

Results

A longer driving history was associated with a shorter fixation duration. Associations of age and education with eye movements varied by sign location, whereas associations between age and saccade measures varied by group. Useful field of view and visual memory associations with eye movements varied by driving speed; however, simple slopes within each speed condition were not significant. Group differences in fixation duration varied by speed and sign location, with shorter fixation durations in patient groups than in healthy controls. The BD group showed more fixations than healthy controls, and group differences in saccade number varied by sign location. Regardless of group, fixation number, saccade amplitude, and saccade number decreased under the Fast condition.

Conclusions

Eye movements during guide-sign recognition may vary according to psychiatric condition, individual characteristics, and driving conditions. These findings highlight the importance of considering individual characteristics and driving environments, in addition to diagnosis, when evaluating driving-related visual information processing in individuals with mental disorders.

Background

Driving is an essential part of daily life, supporting independence and social participation in the community [1, 2]. Individuals with bipolar disorder (BD) and schizophrenia (S) also drive regularly [3, 4]. However, individuals with these disorders may face restrictions on obtaining or retaining a driver's license when their symptoms impair their ability to drive safely [5, 6]. Nevertheless, driving ability is not necessarily impaired in patients with BD [4]. Although some studies report poorer driving ability in patients with S compared to healthy individuals [7, 8], others find no clear differences [9]. Therefore, evaluating driving ability should focus on objective assessments of individual patients and the associated factors rather than solely on diagnosis [3, 5].

Assessing driving performance through on-road tests or driving simulators is important, as is evaluating the cognitive functions necessary for safe driving [10]. Safe driving involves cognitive functions such as attention, processing speed, memory, and executive function [11, 12]. These cognitive functions may be impaired in BD and S and are associated with driving performance [13, 14, 15, 16].

Safe driving also requires drivers to acquire necessary visual information from the changing driving environment, with efficient eye movements associated with better driving behavior [17]. When recognizing guide signs, drivers must direct their gaze toward the signs and search for textual information within a limited time. Studies on guide sign recognition indicate that eye-movement behavior varies with sign characteristics, such as information density and the arrangement of place names [18, 19, 20]. Our previous research showed variations in eye-movement behavior during guide sign recognition that correlated with driving speed and sign location, as well as with drivers' cognitive functions and basic demographics [21].

However, our prior study included only healthy participants, leaving unclear the relationships between eye movements during guide sign recognition and cognitive functions or demographics in patients with BD and S. Furthermore, it remains unknown whether changes in eye-movement behavior with driving speed and guide sign location differ between healthy participants and those with these disorders. Clarifying these issues may provide foundational knowledge for understanding visual information processing during driving in individuals with psychiatric disorders and may provide a basis for future individualized assessment approaches that consider individual characteristics in addition to diagnosis.

This exploratory study aimed to examine (1) the relationships between eye movements during guide sign recognition and cognitive functions or demographics in patients with BD and S, and (2) differences in eye-movement behavior among healthy participants and patients with BD and S, as well as the effects of driving speed and guide sign location on these differences. We hypothesized that eye movements would correlate with cognitive functions and demographics in patients with BD and S, and that both patient groups would exhibit different eye tracking profiles compared to healthy participants.

Methods

Sample size

The sample size was calculated using G*Power [22]. Because G*Power does not directly support sample size calculations for generalized linear mixed models (GLMMs), the required sample size was estimated before the start of the study using methods that approximated the planned study design. For the interactions between group and repeated-measures conditions, a repeated-measures ANOVA with within-between interaction was employed. Assuming a medium effect size ($f = 0.25$), significance level of $\alpha = 0.05$, statistical power of $1 - \beta = 0.80$, three groups, four repeated measurements, correlation among repeated measures of 0.50, and a nonsphericity correction of $\epsilon = 0.50$, the required sample size was 48 participants. Additionally, for the relationships between cognitive functions and basic demographics and eye movements, a bivariate normal correlation model was used. Assuming a correlation coefficient of $|\rho| = 0.35$, significance level of $\alpha = 0.05$, statistical power of $1 - \beta = 0.80$, and a two-tailed test, the required sample size was 61 participants. To satisfy both sample-size considerations, the larger calculated sample size of 61 participants was adopted as the target sample size.

All participants were Japanese. Healthy participants were recruited primarily from medical institutions and health sciences universities via flyers and posters. Inclusion criteria for healthy participants included: (1) age between 20 and 59 years with a valid driver's license; (2) corrected or uncorrected visual acuity of ≥ 0.6 in decimal notation (equivalent to a logMAR value of 0.22); (3) no history of neuropsychological disorders; and (4) no history of ophthalmological diseases, such as cataracts or glaucoma.

Patients with BD and S were recruited from outpatient departments of community psychiatric clinics in Hokkaido, Japan [23]. The inclusion criteria required participants to have: (1) a diagnosis of bipolar disorder or schizophrenia according to the International Classification of Diseases, 10th Revision (ICD-10); (2) at least 5 years of driving history; and (3) an average driving frequency of at least once per week. Diagnoses of BD and S were established by the participants' primary physicians according to the International Classification of Diseases, 10th Revision (ICD-10) criteria.

Apparatus

We presented the on-board video stimuli on a 24-inch monitor (ProLite B2480HS; iiyama, Mouse Computer Co., Ltd., Tokyo, Japan) with a 1920×1080 pixel resolution, 300 cd/m^2 luminance, and $52.35 \text{ cm} \times 29.5 \text{ cm}$ display area. The viewing distance was fixed at 57 cm, corresponding to visual angles of approximately 49.4° horizontally and 29.1° vertically. Eye movements were recorded using a Tobii X60 Eye Tracker (Tobii, Danderyd Municipality, Sweden) at a sampling rate of 60 Hz.

Before data collection, Tobii X60 Eye Tracker was calibrated for stimulus presentation and eye-movement data processing using Tobii Studio version 3.1.6 software (Tobii). The calibration results were visually inspected and repeated until the gaze points showed no marked dispersion. No predefined quantitative thresholds based on calibration error, tracking ratio, or missing gaze data were used to determine the acceptability of the eye-tracking data.

Stimuli

The on-board videos used in this study were identical to those in our previous study [21]. The videos, recorded from the driver's perspective, were classified into four conditions based on driving speed (Slow and Fast) and guide sign location (Front and Left): Slow-Front, Slow-Left, Fast-Front, and Fast-Left. Ten videos were prepared for each condition, resulting in a total of 40 videos. The same set of 40 videos (ten videos per condition) was presented to all participants. The Slow condition included videos recorded on ordinary roads at 40–60 km/h, whereas the Fast condition comprised videos recorded on expressways at 100–120 km/h. The mean driving speeds were 51.1 km/h for Slow-Front, 49.9 km/h for Slow-Left, 103.1 km/h for Fast-Front, and 101.3 km/h for Fast-Left.

In the Front condition, guide signs were located directly ahead of the direction of travel, whereas in the Left condition, signs were to the left side of the driving lane. The visibility duration of the guide signs was standardized to 4 s in all videos, and external information, such as voice navigation and subtitles, was excluded. To minimize the effects of acceleration, deceleration, and steering, only stable driving segments with acceleration below 0.1 g (approximately 0.98 m/s^2) were included in the analysis.

The guide signs displayed place names, including municipalities, interchanges, and junctions. To minimize the influence of prior knowledge, we selected place names from geographical areas unfamiliar to the participants. Participants were recruited from Hokkaido, Japan, whereas the driving videos were recorded in the northern Kanto region of Japan. The recording locations were therefore chosen outside the participants' recruitment region to minimize the potential influence of prior road familiarity. Individual familiarity with the roads was not formally assessed. The number of place names displayed on each sign ranged from one to eight, with no significant differences among the four conditions. The display position and font size of the target place names as well as details regarding the preparation of the stimuli and other experimental conditions were identical to those used in our previous study [21].

Eye-movement measures

To assess eye movements during guide sign recognition, we used the same eye-movement measures as in our previous study [21]: fixation duration, number of fixations, saccade amplitude, and number of saccades.

Fixation duration was defined as the mean duration of fixations directed toward the target destination name on the guide sign. By contrast, the number of fixations was the total number of fixations occurring while viewing the target destination name. Based on previous studies indicating that the effective visual field during Japanese reading encompasses approximately five to six characters [24, 25], a visual angle of 5° was adopted in the present study. Because a dynamic area of interest (AOI) that tracked the moving target text could not be implemented with the eye-tracking system used in this study, the center of the

first character of each target destination name was used as the reference point, and gaze points located within a visual angle of 5° from this reference point were included in the analysis. During guide sign viewing, longer fixation duration indicates greater allocation of attention to the target [26]. The number of fixations reflects the distribution of visual attention [19], with a greater number indicating increased attention to the target.

Saccade amplitude was defined as the mean amplitude of saccades directed toward the target destination name on the guide sign. By contrast, the number of saccades was the total number of saccades directed toward the target destination name. In this study, eye movements from fixation points outside the guide sign to the target destination name within the sign, or between destination names within the guide sign, were analyzed as saccades. Larger saccade amplitude suggests clearer recognition of the target destination and more efficient eye movements [27]. The number of saccades reflects the extent of visual search during guide sign recognition; previous research shows that the number of saccades increases when guide signs are more complex and target destinations are harder to recognize [19].

Eye-movement measures were extracted using the I-VT fixation filter in Tobii Studio (Tobii) [28]. A fixation was defined as a gaze event lasting ≥ 60 ms with an angular difference of $< 1^\circ$ between two consecutive fixations, and a saccade was defined as an eye movement with a velocity of $\geq 30^\circ/\text{s}$. The mean values obtained from both eyes were used in the analysis.

Assessment of cognitive functions

The same measures from our previous study [21] were used to assess cognitive functions required for driving. Parts A and B of the Japanese version of the Trail Making Test (TMT-J) [29] assessed processing speed and attention necessary for driving. Visual memory was evaluated using the Wechsler Memory Scale-Revised (WMS-R) [30]. The Zoo Map Test from the Behavioral Assessment of the Dysexecutive Syndrome (BADS) [31] assessed planning ability as a component of executive function.

Additionally, the Double Decision task from BrainHQ® evaluated the useful field of view (UFOV) [32]. In this task, a car appeared at the center of the screen alongside a road sign in the peripheral visual field, presented with distractors for a specified duration. Participants identified the type of car and the location of the road sign.

Assessment of clinical characteristics, pharmacotherapy, and psychiatric symptoms

Clinical characteristics of the patient groups included age at onset and illness duration. Information regarding pharmacotherapy included the use of atypical antipsychotics, typical antipsychotics, and antiparkinsonian medications. Antipsychotic doses were calculated as chlorpromazine (CP) equivalents (mg/day).

Psychiatric symptoms in the BD group were assessed using the Hamilton Depression Rating Scale (HAMD) [33] and the Young Mania Rating Scale (YMRS) [34]. The HAMD evaluates the severity of depressive symptoms, while the YMRS evaluates the severity of manic symptoms. In the S group, psychiatric symptoms were assessed using the Positive and Negative Syndrome Scale (PANSS) [35]. Positive, Negative, and General Psychopathology subscale scores were calculated, and the sum of these three subscale scores constituted the PANSS total score.

Data collection procedure

Data collection was conducted in a quiet room shielded from external light. Before the experiment, a five-point calibration of the eye tracker was performed for each participant. As in previous studies [19, 21], participants were instructed to view on-board videos while imagining driving toward the specified destination. This instruction aimed to elicit natural attention allocation and eye movements during visual recognition from the driver's perspective, rather than passive video viewing.

During data collection, participants sat 57 cm from the monitor and viewed on-board videos under four conditions combining driving speed (Slow/Fast) and guide sign location (Front/Left) according to the instructions. In each trial, the target destination name was presented for 7 s, followed by a fixation cross displayed at the center of the screen for 3 s, and finally, an on-board video containing a guide sign for 7 s (Fig. 1). To reflect the natural progression of actual driving, the presentation order was fixed from the Slow condition (general roads) to the Fast condition (expressways). To minimize learning effects associated with the fixed presentation order, the position of the target destination name on each guide sign was systematically varied among the top, bottom, left, right, and center positions to prevent consecutive occurrences of the same position.

After each trial, all participants confirmed that they correctly recognized the target destination name.

Statistical analysis

Two analyses were conducted: one examining the relationships between eye movements during guide sign recognition and basic demographics and cognitive functions (Analysis 1), and another examining the effects of group, driving speed, and guide sign location on eye movements (Analysis 2). The dependent variables were fixation duration, number of fixations, saccade amplitude, and number of saccades, analyzed using a generalized linear mixed model (GLMM). A normal distribution with an identity link function was used for all eye movement measures. To account for the dependency of repeated measurements from the same participant and video, participant (ID) and video (Video ID) were included in the models as random intercepts.

In Analysis 1, Age, Driving history, Education, TMT-J A, TMT-J B, WMS-R Visual Memory, BADS Zoo Map Test, and UFOV were entered separately as covariates. Each model included the main effects of Group, Speed, Location, and the covariate; the two-way interactions among Group, Speed, and Location;

and the two-way interactions of the covariate with Group, Speed, and Location as fixed effects. Significant interactions involving a covariate prompted simple slope analysis or post hoc comparisons to further examine the relationship.

In Analysis 2, Group (Healthy, BD, and S), Speed (Slow and Fast), and Location (Front and Left) were included as fixed effects. The model included their main effects, all two-way interactions, and the three-way Group $\times$ Speed $\times$ Location interaction. Significant interactions led to an examination of simple main effects, followed by Tukey-adjusted pairwise comparisons when appropriate. When no significant interaction was observed, the main effects were interpreted.

In Analysis 1, the primary effects of interest included the main effects of each covariate and the interactions: Group $\times$ Covariate, Speed $\times$ Covariate, and Location $\times$ Covariate. The main effects of Group, Speed, and Location, as well as the interactions among these factors, were examined in Analysis 2.

For tests of fixed effects, F values, degrees of freedom, and p values were reported. For the effects of continuous covariates and simple slopes, regression coefficients (β) and 95% confidence intervals (95% CIs) were reported. For multiple comparisons, estimated differences, 95% CIs, and multiplicity-adjusted p values were reported. Statistical significance was set at $p < 0.05$.

Preprocessing: Correlations among basic demographics and cognitive functions

Before the GLMM analyses, Spearman's rank correlation analysis examined the relationships among demographics and cognitive function measures. A strong positive correlation was found between Age and Driving history ($\rho = 0.715$, $p < 0.001$). Several weak-to-moderate correlations among cognitive function measures were also identified ($|\rho| \leq 0.477$). Considering these covariate correlations, each demographic and cognitive function measure was entered separately as a covariate in the GLMMs. The complete correlation matrix is presented in Supplementary Table S1 and Supplementary Figure S1.

Analysis 1: Eye movements during guide sign recognition in relation to basic demographics and cognitive functions

In Analysis 1, Age, Driving history, Education, TMT-J A, TMT-J B, WMS-R Visual Memory, BADS Zoo Map Test, and UFOV were entered separately as covariates. The fixed effects in each model included the main effects of Group, Speed, and Location, along with each covariate; the two-way interactions among Group, Speed, and Location; and the two-way interactions of each covariate with Group, Speed, and Location. When an interaction involving a covariate was significant, simple slope analysis or multiple comparisons were performed to further examine the relationship.

The following model was applied separately for each covariate:

$$g(E[Y]) = \beta_0 + \beta_1 \text{Group} + \beta_2 \text{Speed} + \beta_3 \text{Location} + \beta_4 \text{Covariate} + \beta_5 (\text{Group} \times \text{Speed}) + \beta_6 (\text{Group} \times \text{Location}) + \beta_7 (\text{Speed} \times \text{Location})$$

In this model, β_0 represents the intercept, and β_1 – β_4 represent the main effects of Group, Speed, Location, and the covariate, respectively. β_5 – β_7 represent the two-way Group $\times$ Speed, Group $\times$ Location, and Speed $\times$ Location interactions, respectively. β_8 – β_{10} represent the extent to which the relationship between the covariate and the eye-movement measure varies according to Group, Speed, and Location, respectively. The terms (1 | ID) and (1 | Video ID) represent random intercepts for participant and video, respectively.

Analysis 2: Effects of group, driving speed, and guide sign location on eye movements during guide sign recognition

In Analysis 2, the effects of Group, Speed, and Location on eye-movement measures (fixation duration, number of fixations, saccade amplitude, and number of saccades) were examined. The fixed effects included the main effects of Group, Speed, and Location, all two-way interactions, and the three-way interaction. When an interaction was significant, simple main effects based on estimated marginal means and Tukey-adjusted pairwise comparisons were performed to further investigate the effects.

The following model was applied to each eye-movement measure:

$$g(E[Y]) = \beta_0 + \beta_1 \text{Group} + \beta_2 \text{Speed} + \beta_3 \text{Location} + \beta_4 (\text{Group} \times \text{Speed}) + \beta_5 (\text{Group} \times \text{Location}) + \beta_6 (\text{Speed} \times \text{Location}) +$$

In this model, β_0 represents the intercept, and β_1 – β_3 represent the main effects of Group, Speed, and Location, respectively. β_4 – β_6 represent the Group $\times$ Speed, Group $\times$ Location, and Speed $\times$ Location two-way interactions, respectively, and β_7 represents the three-way Group $\times$ Speed $\times$ Location interaction. The terms (1 | ID) and (1 | Video ID) represent random intercepts for participant and video, respectively.

Additional analysis: Relationships between clinical characteristics and eye movements in the patient groups

First, to examine the relationship between chlorpromazine (CP) equivalent dose and eye-movement measures in the BD and S groups, and to assess how this relationship varied by patient group and driving conditions, generalized linear mixed models (GLMMs) were fitted with each eye-movement measure as the dependent variable. The fixed effects included the main effects of Group, Speed, Location, and CP equivalent dose, along with the interactions: Group $\times$ Speed, Group $\times$ Location, Speed $\times$ Location, Group $\times$ Speed $\times$ Location, Group $\times$ CP, Speed $\times$ CP, and Location $\times$ CP. Participant ID and Video ID were included as random intercepts. CP equivalent dose was entered into the models on its original scale (mg/day).

The following model was applied to each eye-movement measure:

$$g(E[Y_{ij}]) = \beta_0 + \beta_1 \text{Group}_i + \beta_2 \text{Speed}_{ij} + \beta_3 \text{Location}_{ij} + \beta_4 \text{CP}_i + \beta_5 (\text{Group}_i \times \text{Speed}_{ij}) + \beta_6 (\text{Group}_i \times \text{Location}_{ij}) + \beta_7 (\text{Speed}_{ij} \times \text{Location}_{ij})$$

In this model, i indexes participants and j indexes video-level observations within participants. β_0 represents the intercept, and β_1 – β_4 represent the main effects of Group, Speed, Location, and CP equivalent dose, respectively. β_5 – β_8 represent the Group $\times$ Speed, Group $\times$ Location, Speed $\times$ Location, and Group $\times$ Speed $\times$ Location interactions, respectively. β_9 – β_{11} represent the extent to which the relationship between CP equivalent dose and the eye-movement measure varies according to Group, Speed, and Location, respectively. The terms (1 | ID) and (1 | Video ID) represent random intercepts for participant and video, respectively.

Next, to exploratorily examine the relationships between psychiatric symptom severity and eye movements, HAMD and YMRS scores in the BD group and the three PANSS subscale scores (Positive, Negative, and General Psychopathology) in the S group were entered separately as covariates in the GLMMs. Each model included the main effects of Speed, Location, and the psychiatric symptom measure, as well as the Speed $\times$ Location, Speed $\times$ psychiatric symptom measure, and Location $\times$ psychiatric symptom measure interactions as fixed effects. Participant ID and Video ID were included as random intercepts. Psychiatric symptom measures were mean-centered to facilitate interpretation of main effects in models with interaction terms.

The following model was applied to each eye-movement measure:

$$g(E[Y_{ij}]) = \beta_0 + \beta_1 Speed_{ij} + \beta_2 Location_{ij} + \beta_3 Symptom_{ci} + \beta_4 (Speed_{ij} \times Location_{ij}) + \beta_5 (Speed_{ij} \times Symptom_{ci}) + \beta_6 (Location_{ij} \times Symptom_{ci})$$

In this model, i indexes participants and j indexes video-level observations within participants. β_0 represents the intercept, and β_1 – β_3 represent the main effects of Speed, Location, and the mean-centered psychiatric symptom measure (Symptom_c), respectively. β_4 represents the Speed $\times$ Location interaction, while β_5 and β_6 denote the variation in the relationship between the psychiatric symptom measure and the eye-movement measure according to Speed and Location, respectively. The terms (1 | ID) and (1 | Video ID) denote random intercepts for participant and video, respectively. For Symptom_c, mean-centered HAMD or YMRS scores were used in the BD group, and mean-centered scores for each PANSS subscale were used in the S group.

To control for the increased risk of Type I error due to multiple testing in these analyses, false discovery rate (FDR) correction using the Benjamini–Hochberg procedure was applied. For CP equivalent dose analyses, the four tests comprising the main effect of CP equivalent dose and the Group $\times$ CP, Speed $\times$ CP, and Location $\times$ CP interactions were treated as one family for each eye-movement measure. For psychiatric symptom analyses, each eye-movement measure included six tests for the main effects of HAMD and YMRS and their interactions with Speed and Location in the BD group, treated as one family. Similarly, in the S group, the nine tests for the main effects of the three PANSS subscales and their interactions with Speed and Location were treated as one family. When an interaction remained significant after FDR correction, a simple slope test was planned as a post hoc analysis.

For the relationships of basic demographics and cognitive functions with eye movements, separate GLMMs were constructed for each demographic and cognitive function variable selected based on previous studies and prespecified research hypotheses; no adjustment for multiple testing across these GLMMs was applied. By contrast, the psychiatric symptom and CP-equivalent dose analyses involved multiple statistical tests and thus warranted FDR correction.

All statistical analyses were performed using R version 4.6.1. Statistical significance was set at $p < 0.05$. ChatGPT (OpenAI) was used to assist in generating R code for visualizing the results of generalized linear mixed models and correlation analyses. The generated code and resulting figures were reviewed and verified by the authors.

Results

Participant characteristics

Initially, 24 healthy participants, 20 with BD, and 20 with S were enrolled. However, one participant with BD and two participants with S were excluded due to equipment issues that prevented eye-movement recording. Consequently, 61 participants (24 Healthy, 19 BD, and 18 S) were included in the analysis. Basic demographics for each group are presented in Table 1. Significant differences were observed in age, sex, and years of education. Multiple comparisons indicated that the BD group was older than the Healthy group ($p = 0.046$), while the Healthy group had more years of education than the S group ($p = 0.009$). No significant difference in driving history was observed among the groups.

Table 1
Basic demographics of the participants in each group

Variable	Healthy group (n = 24)	BD group (n = 19)	S group (n = 18)	p
Age (years)	36.5 ± 13.1	46.8 ± 12.5	42.1 ± 8.5	0.035
Sex, n (%)				0.006 ¹
Male	8 (33.3)	10 (52.6)	15 (83.3)	
Female	16 (66.7)	9 (47.4)	3 (16.7)	
Driving history (years)	14.8 ± 14.7	17.0 ± 11.4	12.0 ± 12.1	0.432
Education (years)	15.0 ± 1.9	14.0 ± 2.2	13.0 ± 2.1	0.022

¹ Pearson's χ^2 test.

“Healthy” refers to healthy participants, “BD” refers to bipolar disorder, and “S” refers to schizophrenia. Comparisons of scales other than “Sex” were performed using the Kruskal–Wallis test, and when significant differences were observed, multiple comparisons were conducted using the Steel-Dwass test. Bold text indicates $p < 0.05$.

The clinical characteristics of the patient groups are presented in Table 2. The BD group had a higher age at onset than the S group ($p = 0.007$). The S group exhibited a higher CP equivalent dose ($p = 0.029$) and a greater proportion of participants using atypical antipsychotics ($p = 0.019$) compared to the BD group. No significant differences were observed between groups in duration of illness or in the proportions of participants using typical antipsychotics or antiparkinsonian medications. Medication use in each group is detailed in Supplementary Tables S2–S5.

Table 2
Clinical characteristics, medication status, and psychopathology scales of psychiatric disorder groups

Variable	BD group (n = 19)	S group (n = 18)	<i>p</i>
Age at onset (years)	27.5 ± 6.8	22.1 ± 3.6	0.007¹
Duration of illness (years)	19.3 ± 9.3	19.9 ± 9.0	0.823 ²
CP equivalent (mg/day)	271.4 ± 291.0	453.2 ± 257.6	0.029¹
Atypical antipsychotics (n, %)	11 (57.9)	17 (94.4)	0.019³
Typical antipsychotics (n, %)	3 (15.8)	4 (22.2)	0.693 ³
Antiparkinsonian medication (n, %)	5 (26.3)	5 (27.8)	1.000 ³
HAMD	3.3 ± 2.4	—	—
YMRS	4.8 ± 4.4	—	—
PANSS total	—	48.3 ± 10.5	—
PANSS positive	—	11.3 ± 3.7	—
PANSS negative	—	13.7 ± 4.4	—
PANSS general psychopathology	—	23.3 ± 5.7	—

¹ Wilcoxon rank-sum (Mann–Whitney U) test.

² Student's *t*-test.

³ Fisher's exact test.

Note

“BD” refers to bipolar disorder, and “S” refers to schizophrenia. CP indicates chlorpromazine; HAMD: Hamilton Depression Rating Scale; PANSS: Positive and Negative Syndrome Scale; YMRS: Young Mania Rating Scale. Bold text indicates $p < 0.05$.

Cognitive function measures for each group are presented in Table 3. Significant group differences were observed in TMT-J A, WMS-R Visual Memory, BADS Zoo Map Test, and UFOV. Multiple comparisons indicated that WMS-R Visual Memory and BADS Zoo Map Test scores were higher in the Healthy group than in both the BD and S groups, whereas UFOV performance was better in the Healthy group than in the BD group. No significant differences were identified in the multiple comparisons for TMT-J A, and no significant group difference was observed in TMT-J B.

Table 3
Summary of cognitive function assessment scales for each group

Variable	Healthy group (n = 24)	BD group (n = 19)	S group (n = 18)	p	Post hoc
TMT-J A (s)	33.9 ± 11.2	41.0 ± 11.3	40.9 ± 13.4	0.046	NS
TMT-J B (s)	63.2 ± 45.1	74.0 ± 47.7	67.4 ± 19.5	0.134	—
WMS-R Visual Memory	36.8 ± 4.3	32.4 ± 4.0	31.3 ± 4.6	< 0.001	Healthy > BD ($p = 0.003$); Healthy > S ($p = 0.002$)
BADS Zoo Map Test	15.6 ± 0.7	10.7 ± 3.4	11.2 ± 4.1	< 0.001	Healthy > BD ($p < 0.001$); Healthy > S ($p = 0.011$)
UFOV	50.2 ± 2.8	44.3 ± 8.9	48.1 ± 2.9	0.004	Healthy > BD ($p = 0.007$)
Note: "Healthy" refers to healthy participants, "BD" refers to bipolar disorder, and "S" refers to schizophrenia. BADS: Behavioral Assessment of the Dysexecutive Syndrome; TMT-J: Japanese version of the Trail Making Test; TMT-J A and B: Parts A and B of the Japanese version of the Trail Making Test; UFOV: useful field of view; WMS-R: Wechsler Memory Scale-Revised. Comparisons of scales were performed using the Kruskal-Wallis test, and when significant differences were observed, multiple comparisons were conducted using the Steel-Dwass test. Bold text indicates $p < 0.05$. Values are presented as the mean ± standard deviation. NS, not significant.					

Eye movements during guide sign recognition in relation to basic demographics and cognitive functions

Table 4 presents the significant main effects of covariates and their interactions with Group, Speed, and Location for each eye-movement measure. Results of all fixed-effect tests are presented in Supplementary Table S6.

Table 4
Significant associations of basic demographics and cognitive functions with eye-movement measures

Eye-movement measure	Covariate	Effect	F(df1, df2)	p
Fixation duration	Age	Main effect	5.69 (1, 51.55)	0.021
	Age	Location × Covariate	5.20 (1, 1754.01)	0.023
	Driving history	Main effect	15.34 (1, 52.88)	< 0.001
	Education	Main effect	5.16 (1, 52.70)	0.027
	Education	Location × Covariate	5.74 (1, 1754.38)	0.017
Number of fixations	UFOV	Speed × Covariate	12.31 (1, 1766.21)	< 0.001
Saccade amplitude	Age	Group × Covariate	3.21 (2, 53.12)	0.048
	WMS-R Visual Memory	Speed × Covariate	4.35 (1, 1801.61)	0.037
Number of saccades	Age	Group × Covariate	3.21 (2, 50.31)	0.049
	Education	Location × Covariate	3.91 (1, 1760.11)	0.048
	UFOV	Speed × Covariate	16.95 (1, 1764.34)	< 0.001

UFOV: useful field of view; WMS-R: Wechsler Memory Scale-Revised.

The relationships between basic demographics and cognitive functions and eye movements showed interactions with Group, Speed, or Location (Table 4). Significant Location × Age and Location × Education interactions were observed for fixation duration; a Speed × UFOV interaction for the number of fixations; and Group × Age and Speed × WMS-R Visual Memory interactions for saccade amplitude. Additionally, Group × Age, Location × Education, and Speed × UFOV interactions were found for the number of saccades. Significant main effects of Age, Driving history, and Education were also observed for fixation duration.

Simple slope analyses of the significant interactions indicated that fixation duration decreased with increasing age in the Left condition ($\beta = -5.306$, 95% CI [- 8.863, - 1.749], $p = 0.004$), whereas no significant relationship was observed in the Front condition ($\beta = -2.780$, 95% CI [- 6.348, 0.787], $p = 0.124$) (Supplementary Figure S2). Similarly, fixation duration decreased with increasing years of education in the Left condition ($\beta = -27.692$, 95% CI [- 46.470, - 8.914], $p = 0.004$), whereas no significant relationship was observed in the Front condition ($\beta = -12.678$, 95% CI [- 31.507, 6.151], $p = 0.183$) (Supplementary Figure S3).

For saccade amplitude, greater age was associated with larger saccade amplitude in the BD group ($\beta = 0.051$, 95% CI [0.001, 0.101], $p = 0.044$), whereas no significant relationships were observed in the Healthy ($\beta = -0.009$, 95% CI [- 0.044, 0.025], $p = 0.596$) or S groups ($\beta = -0.044$, 95% CI [- 0.107, 0.020], $p = 0.175$). However, pairwise comparisons of the slopes showed no significant differences among the groups (Supplementary Figure S4).

For the number of saccades, greater age was associated with a higher number of saccades in the BD group ($\beta = 0.031$, 95% CI [0.003, 0.059], $p = 0.031$), whereas no significant associations were observed in the Healthy ($\beta = 0.001$, 95% CI [- 0.018, 0.021], $p = 0.888$) or S groups ($\beta = -0.025$, 95% CI [- 0.061, 0.011], $p = 0.165$). Pairwise comparisons of the slopes showed a significant difference between the BD and S groups (estimate = 0.056, 95% CI [0.001, 0.111],

Tukey-adjusted $p = 0.044$), whereas the differences between the Healthy and BD groups (estimate = -0.030 , 95% CI [$-0.071, 0.012$], Tukey-adjusted $p = 0.204$) and between the Healthy and S groups (estimate = 0.027 , 95% CI [$-0.023, 0.076$], Tukey-adjusted $p = 0.399$) were not significant (Supplementary Figure S5).

For the other significant interactions, simple slope analyses revealed that none of the relationships between the covariates and eye-movement measures within the respective conditions were significant (Supplementary Table S7).

Effects of group, driving speed, and guide sign location on eye movements during guide sign recognition

Table 5 presents the significant main effects of Group, Speed, and Location, along with their interactions for each eye-movement measure. The results of all fixed-effect tests are in Supplementary Table S8.

Table 5
Significant fixed effects of Group, Speed, and Location, and their interactions on eye-movement measures

Eye-movement measure	Effect	$F(df1, df2)$	p
Fixation duration	Group	12.66 (2, 55.16)	< 0.001
	Group $\times$ Speed	3.97 (2, 1756.25)	0.019
	Group $\times$ Speed $\times$ Location	3.34 (2, 1762.07)	0.036
Number of fixations	Group	5.03 (2, 55.05)	0.010
	Speed	17.04 (1, 40.89)	< 0.001
Saccade amplitude	Speed	30.57 (1, 40.61)	< 0.001
Number of saccades	Group	5.77 (2, 54.19)	0.005
	Speed	19.37 (1, 40.80)	< 0.001
	Group $\times$ Location	3.79 (2, 1764.58)	0.023

The Group $\times$ Speed $\times$ Location interaction was significant [$F(2, 1762.07) = 3.34, p = 0.036$]. Post hoc comparisons indicated that, in the Slow–Front condition, fixation duration was longer in the Healthy group than in the BD group (estimate = 193.59 ms, 95% CI [$71.15, 316.04$], Tukey-adjusted $p < 0.001$). In the Slow–Left condition, fixation duration was longer in the Healthy group than in both the BD (estimate = 249.29 ms, 95% CI [$124.00, 374.58$], Tukey-adjusted $p < 0.001$) and S groups (estimate = 143.00 ms, 95% CI [$23.91, 262.10$], Tukey-adjusted $p = 0.014$). Similarly, in the Fast–Front condition, fixation duration was longer in the Healthy group than in both the BD (estimate = 256.26 ms, 95% CI [$127.68, 384.85$], Tukey-adjusted $p < 0.001$) and S groups (estimate = 208.91 ms, 95% CI [$86.03, 331.79$], Tukey-adjusted $p < 0.001$). In the Fast–Left condition, fixation duration was also longer in the Healthy group than in both the BD (estimate = 152.04 ms, 95% CI [$26.87, 277.21$], Tukey-adjusted $p = 0.013$) and S groups (estimate = 169.23 ms, 95% CI [$48.47, 289.99$], Tukey-adjusted $p = 0.003$). All other pairwise comparisons were not significant. Simple comparisons of Speed and Location within each group also showed no significant differences (all $p > 0.05$) (Fig. 2). The main effect of Group was significant [$F(2, 55.16) = 12.66, p < 0.001$], as was the Group $\times$ Speed interaction [$F(2, 1756.25) = 3.97, p = 0.019$].

For the number of fixations, none of the interactions involving Group were significant, whereas the main effects of Group and Speed were significant [Group: $F(2, 55.05) = 5.03, p = 0.010$; Speed: $F(1, 40.89) = 17.04, p < 0.001$]. Multiple comparisons indicated that the BD group exhibited more fixations than the Healthy group (estimate = $0.49, p = 0.009$). The number of fixations was also greater in the Slow condition than in the Fast condition (estimate = $0.28, p < 0.001$).

For saccade amplitude, no significant interactions were evident, and only the main effect of Speed was significant [$F(1, 40.61) = 30.57, p < 0.001$]. Saccade amplitude was larger in the Slow condition than in the Fast condition (estimate = $1.10^\circ, p < 0.001$).

For the number of saccades, the Group $\times$ Location interaction was significant [$F(2, 1764.58) = 3.79, p = 0.023$]. Post hoc comparisons showed that, in the Front condition, the Healthy group had fewer saccades than the BD group (estimate = -0.604 , 95% CI [$-1.130, -0.079$], Tukey-adjusted $p = 0.020$). In the Left condition, the Healthy group had fewer saccades than both the BD (estimate = -0.749 , 95% CI [$-1.274, -0.224$], Tukey-adjusted $p = 0.003$) and S groups (estimate = -0.626 , 95% CI [$-1.134, -0.117$], Tukey-adjusted $p = 0.012$). All other pairwise comparisons were not significant. Simple comparisons of Location within each group also showed no significant differences (all $p > 0.05$) (Fig. 3). The main effects of Group [$F(2, 54.19) = 5.77, p = 0.005$] and Speed [$F(1, 40.80) = 19.37, p < 0.001$] were also significant, with fewer saccades in the Fast condition than in the Slow condition.

Additional analysis: Relationships between clinical characteristics and eye movements in the patient groups

Relationship between CP equivalent dose and eye movements in the patient groups

The relationships between CP equivalent dose and eye-movement measures were examined in patient groups. The main effect of CP equivalent dose on saccade amplitude remained significant after FDR correction, with a higher CP equivalent dose associated with larger saccade amplitude [$F(1, 37.04) = 8.95$, FDR-adjusted $p = 0.020$]. By contrast, none of the Group $\times$ CP, Speed $\times$ CP, or Location $\times$ CP interactions were significant. For other eye-movement measures, no significant main effects or interactions involving CP equivalent dose were observed.

Relationship between psychiatric symptoms and eye movements across patient groups

The relationships between HAMD and YMRS scores with eye-movement measures in the BD group, and between PANSS Positive, Negative, and General Psychopathology subscale scores with eye-movement measures in the S group were examined. No significant main effects or interactions remained after FDR correction (all FDR-adjusted $p > 0.05$). Since no interactions were significant after FDR correction, post hoc simple slope analyses were not performed.

Discussion

This study examined the relationships of demographics and cognitive functions with eye movements during guide sign recognition in patients with bipolar disorder (BD) and schizophrenia (S), as well as differences in eye movement characteristics during guide sign recognition compared to healthy participants. The results showed that (1) the relationships of demographics and cognitive functions with eye movements varied according to patient group, guide sign location, and driving speed; and (2) patients with BD and S exhibited different patterns of eye movements during guide sign recognition compared to healthy participants, with some differences depending on driving speed and guide sign location.

Relationships of basic demographics and cognitive functions with eye movements during guide sign recognition

The relationships of basic demographics and cognitive functions with eye movements during guide sign recognition varied according to patient group and driving conditions. A longer driving history was associated with shorter fixation duration. Additionally, the relationships between age and years of education with eye movements interacted with guide sign location, whereas the relationships between age and saccade measures interacted with Group. The relationships of UFOV and WMS-R Visual Memory with eye movements also interacted with driving speed; however, none of the simple slopes within the individual speed conditions were significant.

First, a longer driving history was associated with a shorter fixation duration, with no clear differences across patient groups or driving conditions. Previous research has reported that experienced drivers exhibit shorter fixation durations and explore the surrounding traffic environment more broadly than novice drivers [36]. It has also been suggested that everyday driving history may alter gaze patterns and enhance visual search abilities [37]. Thus, the current findings may reflect changes in visual search strategies associated with accumulated driving history. However, age and driving history were strongly correlated and analyzed in separate models; caution is warranted when interpreting this finding as specific to driving history.

Second, fixation duration decreased with increasing age and years of education in the Left condition, whereas no significant relationships were observed in the Front condition. The Left condition requires attention to a lateral guide sign while monitoring the forward environment [21], suggesting that individual differences associated with age and educational history may be more evident under conditions that impose greater constraints on gaze allocation. Regarding education, differences in educational level have been reported to be associated with different visual search strategies [38], and the association observed in the present study may also reflect individual differences in such visual search strategies. Although an interaction between years of education and guide sign location was observed for the number of saccades, no significant simple slopes within the individual location conditions emerged.

The relationships between age and saccade measures differed by patient group. In the BD group, greater age was associated with larger saccade amplitude and a higher number of saccades, whereas no significant relationships were observed in the Healthy or S groups. A significant difference in slopes was noted only between the BD and S groups concerning the number of saccades. Although a previous study found no clear differences in eye-movement characteristics between BD and S groups [39], a recent exploratory eye-movement task identified differences in certain measures, including the number of fixations [40]. These findings suggest that differences in eye movements between BD and S may vary depending on the assessed measure and task characteristics. In the present study, participants were required to search for a target guide sign within a dynamic driving scene, which may have influenced the group differences in the relationships between age and saccade measures.

Furthermore, interactions with driving speed were observed for the relationships of UFOV with the number of fixations and saccades, and of WMS-R Visual Memory with saccade amplitude; however, none of the simple slopes within individual speed conditions were significant. Thus, while these findings suggest that these relationships may vary according to driving speed, their direction remains unclear. Since the useful field of view during driving narrows with increased driving speed [41], the temporal and attentional constraints associated with higher speeds may have contributed to these findings; however, further investigation is required.

Overall, driving history showed a consistent association with eye movements, whereas the relationships with age and educational history varied by guide sign location or patient group. By contrast, the relationships between cognitive functions and driving speed did not exhibit a sufficiently clear direction.

Group differences in eye movements during guide sign recognition

Group differences in eye movements during guide sign recognition were evident; however, these differences varied by driving speed and guide sign location.

For fixation duration, a Group $\times$ Speed $\times$ Location interaction was observed. Overall, fixation duration was shorter in the BD and S groups than in the Healthy group, particularly in the Fast condition, where both patient groups exhibited shorter fixation durations than the Healthy group under both the Front and Left conditions. Patients with schizophrenia have been reported to demonstrate shorter fixation durations than healthy individuals in the presence of distractors [42]. In this study, multiple visual information sources, including oncoming vehicles and pedestrians, were present alongside guide signs. In the S group, attention allocation to surrounding visual information may have influenced the maintenance of fixation on the guide signs.

The BD group also exhibited more fixations overall than the Healthy group and more saccades under both the Front and Left conditions. Previous research has reported differences across multiple eye-movement measures between BD patients and healthy individuals [43]. The increased number of fixations and saccades in this study suggests that the BD group exhibited a different visual search pattern from the Healthy group.

Regarding driving speed, the number of fixations and saccades and saccade amplitude decreased in the Fast condition across all groups, consistent with our earlier study of healthy participants [21]. Visual search may become constrained under high-speed driving conditions due to increased demands on forward environmental monitoring [27]. Accordingly, the reduced eye movements observed under the Fast condition in the present study may reflect differences in visual search for guide signs under greater temporal and visual constraints.

No main effect of guide sign location was found for any eye-movement measure; however, a Group $\times$ Location interaction was observed for the number of saccades. The BD group exhibited more saccades than the Healthy group under both the Front and Left conditions, whereas the S group showed more saccades than the Healthy group only under the Left condition. As noted, the BD group differed from the Healthy group regardless of guide sign location, while the S group's differences were limited to the Left condition. Impaired inhibition of reflexive saccades and increased saccade frequency in the presence of distractors have been reported in schizophrenia [42, 44]. The Left condition requires gaze allocation to a lateral guide sign while monitoring the forward environment, necessitating control of gaze across multiple visual information sources; thus, the exploratory eye movement characteristics in the S group may have been more pronounced under this condition.

Overall, patients with psychiatric disorders exhibited eye movement characteristics during guide sign recognition that differed from those of healthy participants, whereas some visual search constraints associated with driving speed were consistent across groups. These findings underscore the importance of considering both the patient group and its relationship with driving conditions, such as driving speed and guide sign location, when interpreting eye movements during driving-related visual information processing in individuals with psychiatric disorders.

Relationships of CP equivalent dose and psychiatric symptoms with eye movements in the patient groups

In the additional analyses, the relationship between antipsychotic dose and eye movements across patient groups was explored using the CP-equivalent dose. A higher CP-equivalent dose was associated with a larger saccade amplitude. By contrast, no interactions of CP equivalent dose with Group, Speed, or Location were observed. Regarding psychiatric symptoms, no significant relationships remained after FDR correction between eye movements and HAMD or YMRS scores in the BD group or PANSS scores in the S group.

A previous study indicated that treatment with antipsychotic medications may alter eye-movement measures, including saccades [45], and that saccade dynamics may vary according to antipsychotic dose [46]. However, the absence of interactions between CP equivalent dose and Group, Speed, or Location suggests that the relationship between CP equivalent dose and saccade amplitude is not specific to any particular patient group or driving condition. The observed association suggests that pharmacotherapy should be considered when interpreting eye-movement characteristics across patient groups.

In the BD group, no significant relationships were found between HAMD or YMRS scores and eye movements during guide sign recognition. Although previous studies have reported associations between depressive symptom severity and eye-movement measures such as fixations and saccades [47], other studies have found no clear relationships between eye movements and assessments such as the HAMD and YMRS [48]. Similarly, in the S group, no significant relationships were observed between the PANSS subscales and eye movements during guide sign recognition. A previous study of patients with schizophrenia indicated that, despite significant improvements in psychiatric symptoms assessed using the PANSS from the acute to the remission phase, these improvements did not correlate with changes in several eye-movement measures, including saccades and antisaccades. The authors suggested that these eye-movement measures may reflect relatively stable characteristics independent of changes in psychiatric symptoms [49]. Collectively, the characteristics of eye movements during guide sign recognition observed in the BD and S groups may not be adequately explained solely by the severity of psychiatric symptoms at the time of assessment.

Limitations

This study has several limitations.

First, on-board videos were used, which could not replicate the vehicle-control demands or cognitive workload associated with actual driving, as would occur during on-road driving or in a driving simulator. Eye-movement patterns during hazard perception differ between active driving tasks and passive viewing of driving videos [50]. Future studies involving individuals with psychiatric disorders should examine eye movements during guide sign recognition under conditions that more closely approximate actual driving environments, such as on-road driving or driving simulators.

Second, although the sample size was calculated using G*Power with a medium effect size, the number of participants in each group was limited. The analyses of the relationships among basic demographics and cognitive functions with eye movements within individual groups and driving conditions may not have had sufficient statistical power. Therefore, nonsignificant findings, particularly in the S group, should be interpreted cautiously. Additionally, the sex distribution differed among the groups, and the independent effect of sex was not examined. Consequently, the possibility that differences in sex distribution contributed to some observed group differences cannot be entirely ruled out; caution is warranted when generalizing the findings to broader populations of drivers. Replication with larger samples and better-controlled demographic characteristics is needed to enhance the reproducibility and generalizability of these findings.

Third, although an association between CP equivalent dose and saccade amplitude was observed, the pharmacological effects of individual medication types and concomitant medications were not separately examined. Thus, the effects of pharmacotherapy on the observed eye-movement characteristics

could not be fully disentangled. Antipsychotic medications have been shown to affect eye movements [51]; however, participants in the patient groups used a wide variety of medications (Supplementary Tables 2–5), making it impossible to determine the relationships between individual medications and saccade amplitude. Furthermore, as no significant interactions of CP equivalent dose with patient group, driving speed, or guide sign location were observed, it remains unclear whether the association between CP equivalent dose and saccade amplitude is specific to a particular patient group or driving condition. Future studies with larger samples are necessary to examine these relationships while accounting for medication type and concomitant medication use.

Conclusions

Despite several limitations, this study suggests that eye movements during guide sign recognition may vary with psychiatric condition, individual characteristics, and driving environment. The BD and S groups exhibited eye movement characteristics differing from those of the Healthy group; however, these differences were not uniform across driving speeds and guide sign locations. Similarly, the relationships between basic demographics, cognitive functions, and eye movements varied according to patient group and driving conditions. These findings indicate that visual search characteristics associated with psychiatric disorders may not be fixed but may manifest differently based on individual characteristics and the driving environment.

From the perspective of eye movements during guide sign recognition, these findings highlight the importance of considering not only diagnosis and psychiatric symptoms but also individual traits, including cognitive functions, age, driving history, and pharmacotherapy, alongside driving-environment factors such as speed and the location of visual targets when evaluating driving-related visual information processing in individuals with psychiatric disorders. In particular, differences in eye movements between the patient groups and the Healthy group may vary with driving conditions; thus, identifying the driving contexts in which individual patients exhibit specific visual search characteristics could inform future research on individualized approaches to driving-related assessment and support.

Future studies should employ on-road driving or driving simulators to examine the relationships between eye movement characteristics and actual driving behavior. Accumulating such evidence may ultimately contribute to tailored driving assessment and support based on individual patient characteristics and driving environments.

Abbreviations

<i>AOI</i>	Area of interest
<i>BADS</i>	Behavioral Assessment of the Dysexecutive Syndrome
<i>BD</i>	Bipolar disorder
<i>CP</i>	Chlorpromazine
<i>FDR</i>	False discovery rate
<i>GLMM</i>	Generalized linear mixed model
<i>HAMD</i>	Hamilton Depression Rating Scale
<i>ICD-10</i>	International Classification of Diseases, 10th Revision
<i>PANSS</i>	Positive and Negative Syndrome Scale
<i>S</i>	Schizophrenia
<i>TMT-J</i>	Japanese version of the Trail Making Test
<i>UFOV</i>	Useful field of view
<i>WMS-R</i>	Wechsler Memory Scale-Revised
<i>YMRS</i>	Young Mania Rating Scale

Declarations

Ethics approval and consent to participate

This study was conducted in accordance with the Declaration of Helsinki and was approved by the Ethics Committee of the Graduate School of Health Sciences, Hokkaido University (approval code: 23–75; approval date: 6 October 2023). Written informed consent was obtained from all participants before

participation in the study.

Consent for publication

Not applicable.

Competing interests

The authors declare that they have no competing interests.

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Author Contribution

TM contributed to conceptualization, methodology, software, validation, formal analysis, investigation, resources, data curation, writing the original draft, visualization, and project administration. HO contributed to conceptualization, methodology, software, validation, investigation, resources, review and editing of the manuscript, supervision, and project administration. DS contributed to resources, supervision, review and editing of the manuscript, and project administration. All authors read and approved the final manuscript.

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Availability of data and materials

The datasets generated and/or analysed during the current study are not publicly available due to participant privacy considerations but may be available from the corresponding author on reasonable request, subject to appropriate ethical and institutional approvals.

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Figures

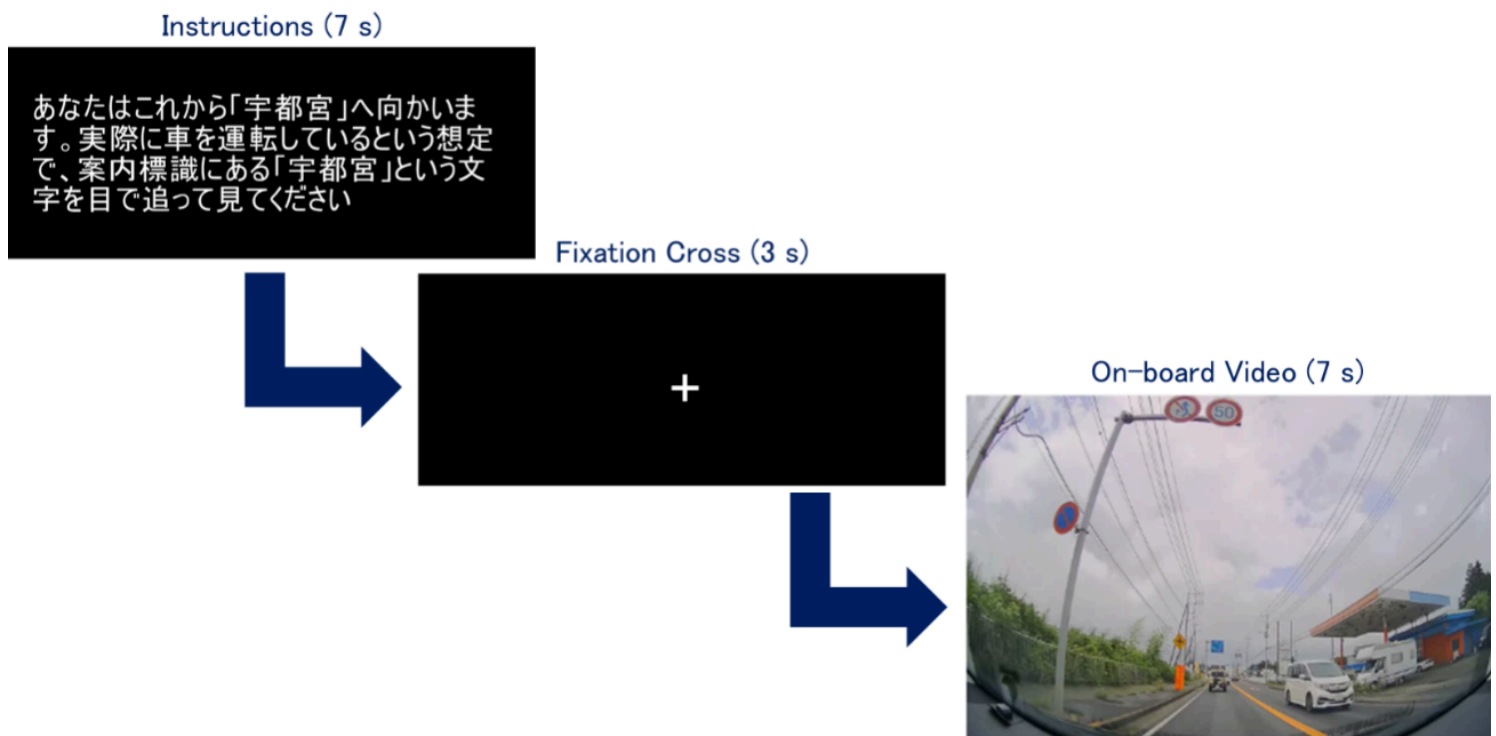


Figure 1
Flow of the data collection procedure. Participants were first shown instructions specifying the destination for seven seconds, followed by a fixation cross for three seconds, and then an on-board video containing guide signs for seven seconds. The figure shows an example trial with *Utsunomiya* as the destination. The instructions are written in Japanese, and the blue objects in the on-board video represent guide signs.

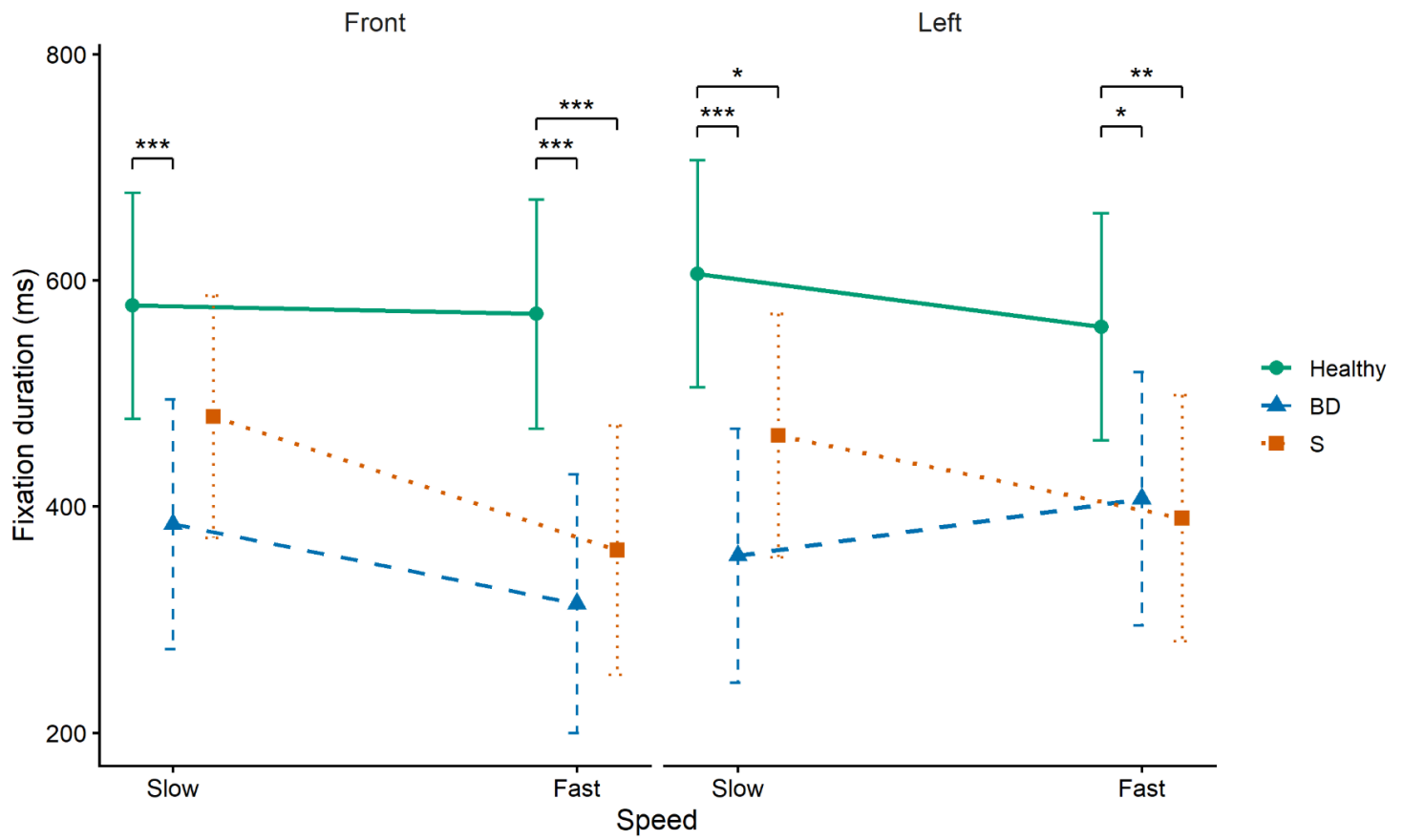


Figure 2

Interaction among group, speed, and location for fixation duration. Error bars indicate 95% confidence intervals. Asterisks indicate significant pairwise comparisons between groups using Tukey-adjusted p -values (* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$).

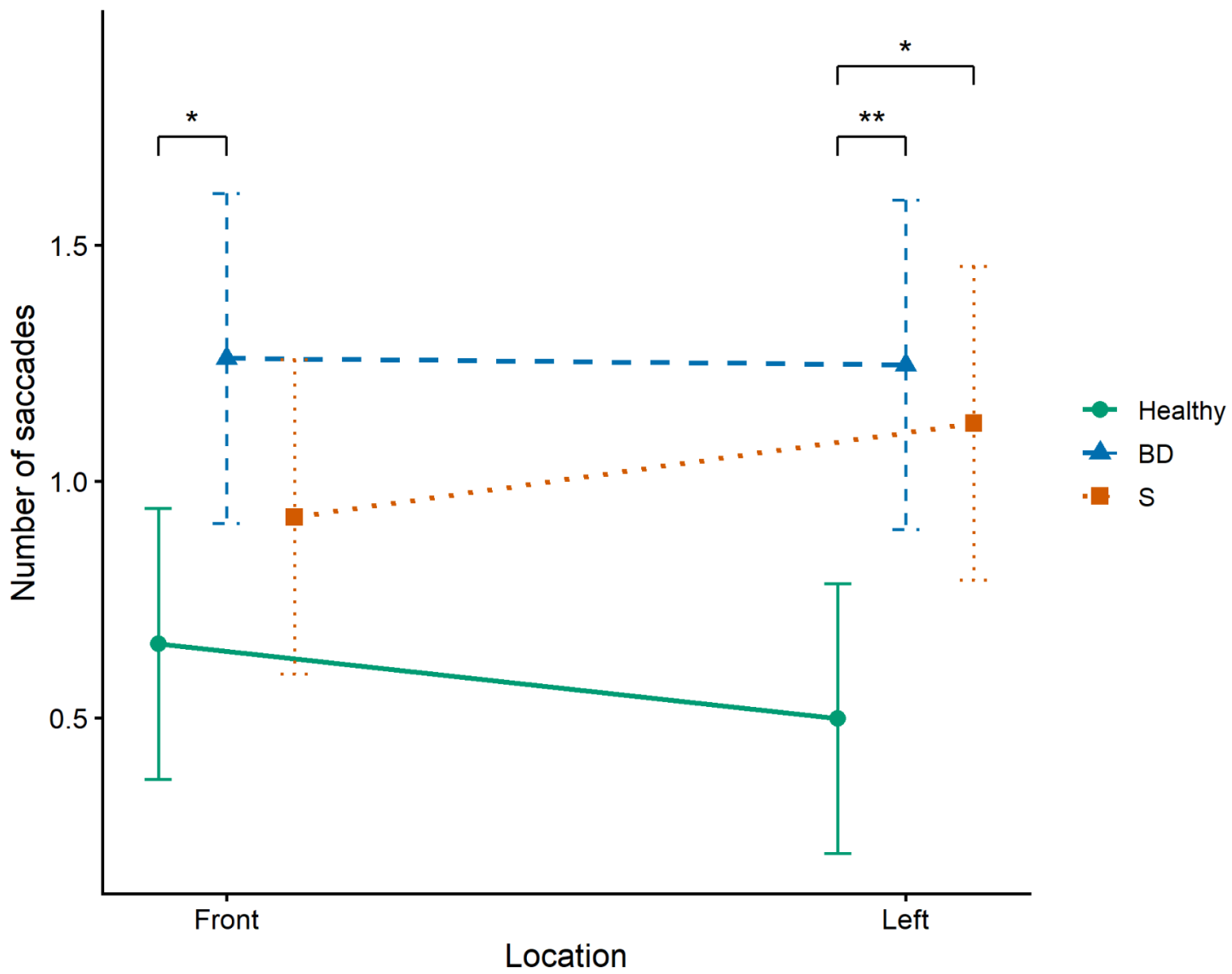


Figure 3

Interaction between group and location for number of saccades. Error bars indicate 95% confidence intervals. Asterisks indicate significant pairwise comparisons between groups using Tukey-adjusted p values ($*p < 0.05$, $**p < 0.01$).