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Visual Search Behavior Towards Reference Areas During an S-Curve Driving Task in Elderly Drivers with Mild Cognitive Impairment

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Abstract

Age- and cognitive-related changes in visual search behavior may affect driving performance, particularly during complex road maneuvers requiring continuous steering adjustments. The aim of this study was to clarify the characteristics of visual search behavior in elderly drivers during S-curve driving. Seven elderly drivers with a high prevalence of mild cognitive impairment (MCI) and ten expert drivers working as professional driving instructors performed crank and S-curve driving tasks. Their visual search behavior toward reference points and surrounding reference areas was monitored using an eye tracker (Tobii Pro Glasses 2). Linear mixed-effects model analysis revealed a significant Group × Area of Interest interaction: elderly drivers allocated significantly longer gaze dwell percentages to inner reference areas (specifically, Reference Areas 11 and 13) during the second half of the S-curve compared to expert drivers ($p < 0.001$). These findings imply that expanded gaze allocation toward reference areas may serve as a potential compensatory mechanism in elderly drivers with MCI features to construct spatial awareness under dynamic driving demands, representing one of several plausible interpretations alongside cognitive and task-related factors. These preliminary insights could contribute to understanding visual search mechanisms in elderly clinical populations.

Keywords: eye tracker; visual search behavior; elderly driver; S-curve; driving; reference area; mild cognitive impairment

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1. Introduction

The change in visual search behavior with aging is one of the factors that influence decreased driving performance among elderly drivers [1]. For example, Romoser et al. reported that elderly drivers tended to focus too much on the vehicle's direction, failing to monitor areas where hazards may arise [2]. Similarly, Dukic and Broberg reported that elderly drivers focused more on static environmental cues, including road markings and traffic signs at intersections than young drivers; elderly drivers may consequently overlook approaching vehicles, thereby increasing the risk of intersection-related errors [3]. These findings suggest that not only decreased visual function with aging (e.g., visual field, visual acuity) but also changes of visual search behavior—which may be further pronounced in the presence of subtle cognitive decline, such as mild cognitive impairment (MCI) [4]—are important factors that affect the decline in driving performance among elderly drivers.

In addition to static environmental cues such as road markings and traffic signs, a virtual reference point could also be utilized by drivers to establish a positional relationship between their vehicles and the surrounding environment during driving (e.g., Tangent Point or the center line of a lane) [5–8]. Identifying an appropriate reference point enables smooth steering control. On a straight road, the reference point is typically represented by the Center Point located at the center of the driver's lane [8]. Drivers fixate on the Center Point using their central vision to keep their vehicles centered within the lane while simultaneously broadening their attentional focus through peripheral vision to gather information about the surrounding environment [9]. Central vision primarily supports precise vehicle positioning and steering control by estimating the curvature of the road ahead, whereas peripheral vision facilitates the detection of environmental information necessary for safe driving decisions, such as speed adjustments and lane changes [10]. Furthermore, drivers move the Center Point onto the future path that their vehicles will reach in a few seconds and obtain information to adjust vehicle speed and steering [6]. Such anticipatory look-ahead fixations integrate spatial information to produce smooth and physically feasible trajectories [11]. Compared with younger drivers, elderly drivers allocate greater attentional resources to reference points for vehicle position adjustment. This increased reliance on reference points may reduce attention and vigilance toward the surrounding road environment, thereby increasing the risk of traffic accidents such as collisions [3].

Reference points are utilized in various driving situations. During curve driving, the Tangent Point on the inside of the curve serves as a visual reference for effective and stable steering [5]. In fact, a previous study revealed that drivers gazed at the Tangent Point in 94% of the driving trials before entering the curve and spent about half of the time gazing at the Tangent Point during curve driving [12]. In addition, during reverse perpendicular parking, drivers establish a reference point at the vertex of the parking space, which serves as the Tangent Point and provides a visual reference for effective steering control [13]. Among elderly drivers, however, the total gaze duration directed toward these reference points was reduced, resulting in an increased number of parking attempts [13]. These findings also suggest that the way elderly drivers utilize reference points varies depending on the driving task and road conditions.

As mentioned above, reference points serve as effective spatial anchors for drivers to guide vehicle positioning. However, this concept has mainly been investigated in single-direction driving environments, and discussions regarding road environments that require dynamic speed adjustment and steering control remain insufficient. Considering that driving strategies can be flexibly switched, clarifying the existence and role of reference points in continuously changing road geometries is essential for elucidating safe driving behavior. Therefore, this study focused on the spatial and temporal features of reference points in

an S-shaped curve (S-curve). The S-curve is a road layout with geometric parameters consisting of two curves in opposite directions connected by a short segment [14]. Such a road geometry poses a greater safety risk than straight roads or single curves, requiring continuous adjustments to steering and greater visual attention. In fact, previous studies focusing on the geometric characteristics of S-curves have indicated that their structural properties are factors involved in an increased risk of traffic accidents [15].

Another factor to consider when analyzing reference points during S-curve driving is how drivers expand their visual search behavior to integrate information between reference points and their surrounding environment. When utilizing reference points, drivers also direct their gaze toward the surrounding area to perceive the spatial relationship between reference points and the upcoming road geometry, thereby predicting road curvature and simplifying steering control [5]. Directing gaze toward the area surrounding reference points may serve as a visual guide that facilitates coherent spatial awareness of the continuous road layout [8,9]. Therefore, it is essential to clarify not only gaze directed at reference points but also gaze directed at surrounding areas. Accordingly, in the present study, gaze directed toward reference points was evaluated as an indicator of focal visual search, whereas gaze directed toward the area surrounding reference points was analyzed as an indicator of broader spatial gaze allocation.

The aim of this study was to clarify the visual search behavior during S-curve driving among elderly drivers, a cohort including individuals with MCI. Specifically, we compared the gaze dwell percentage directed toward reference points and reference areas between elderly and expert drivers to characterize differences in focal visual search and broader spatial gaze allocation behavior. In addition, as a secondary aim, this study conducted an exploratory analysis to investigate how visual search behavior during narrow-road driving relates to driving attitudes. Because gaze allocation may be closely related to individual driving traits, clarifying these relationships will offer a broader understanding of the psychosocial impact of visual behavior.

2. Materials and Methods

2.1. Participants

Seven elderly drivers (1 male and 6 females, median age 73.7 years [Interquartile Range (IQR): 71.7, 74.8] years) who visited a local driving school to renew their licenses were recruited. Inclusion criteria were as follows: (1) holding a valid driver's license with a corrected visual acuity of 0.7 or better (meeting legal renewal requirements), (2) being without eye disease, and (3) having the ability to follow commands. Exclusion criteria were as follows: (1) a clinical diagnosis of dementia and (2) having physical issues that affect driving. To identify the characteristics of the elderly drivers, data from ten expert drivers (8 males and 2 females, median age 35.2 years [IQR: 31.0, 48.8]) working at the same driving school were collected. This study was approved by the University Ethical Review Board for Medical Research Involving Human Subjects, and all participants provided written informed consent.

2.2. Driving Task in Crank and S-Curve

All participants performed narrow-road driving using a right-hand-drive vehicle equipped with a double pedal device on the passenger side. The driving task was attempted only once. The participants sat in the driver's seat and were asked to adjust their seat position and mirrors. A driving instructor sat in the passenger seat to guide participants through the course, while the experimenters were seated in the rear seats. The expert drivers conducted the same task without a driving instructor in the passenger seat; however, to align the experimental conditions as closely as possible, an experimenter and an assistant

were seated in the front passenger and rear seats, respectively. Before reaching the narrow-road driving course, all participants were required to drive through various sections within the driving course, including straight roads, curves, intersections, and parking spaces. In addition, all drivers were instructed to drive at their own pace.

The narrow-road driving included a crank-shaped turn (Crank) and the S-curve with a road width of about one car (Figure 1). Figure 2 shows the layout and dimensions of the Crank and the S-curve on the driving course. The Crank had two consecutive 90-degree turns in opposite directions, requiring first a right turn (Crank 1st half) and then a left turn (Crank 2nd half). The Crank was 3.5 m wide, the distance between the corners was 12.0 m, and the entrance/exit section was 4.0 m long. The S-curve consisted of two consecutive curves in opposite directions: first a left curve (S-curve 1st half), followed by a right curve (S-curve 2nd half). The S-curve was also 3.5 m wide, with an outer curve boundary radius of 7.5 m and an inner curve boundary radius of 4.0 m relative to the center of curvature (arc center), spanning an arc angle of 135° for each curve. Both the Crank and S-curve sections were bordered by curbs along the road edges, and no visual obstructions were present, except for poles located in the Crank section.

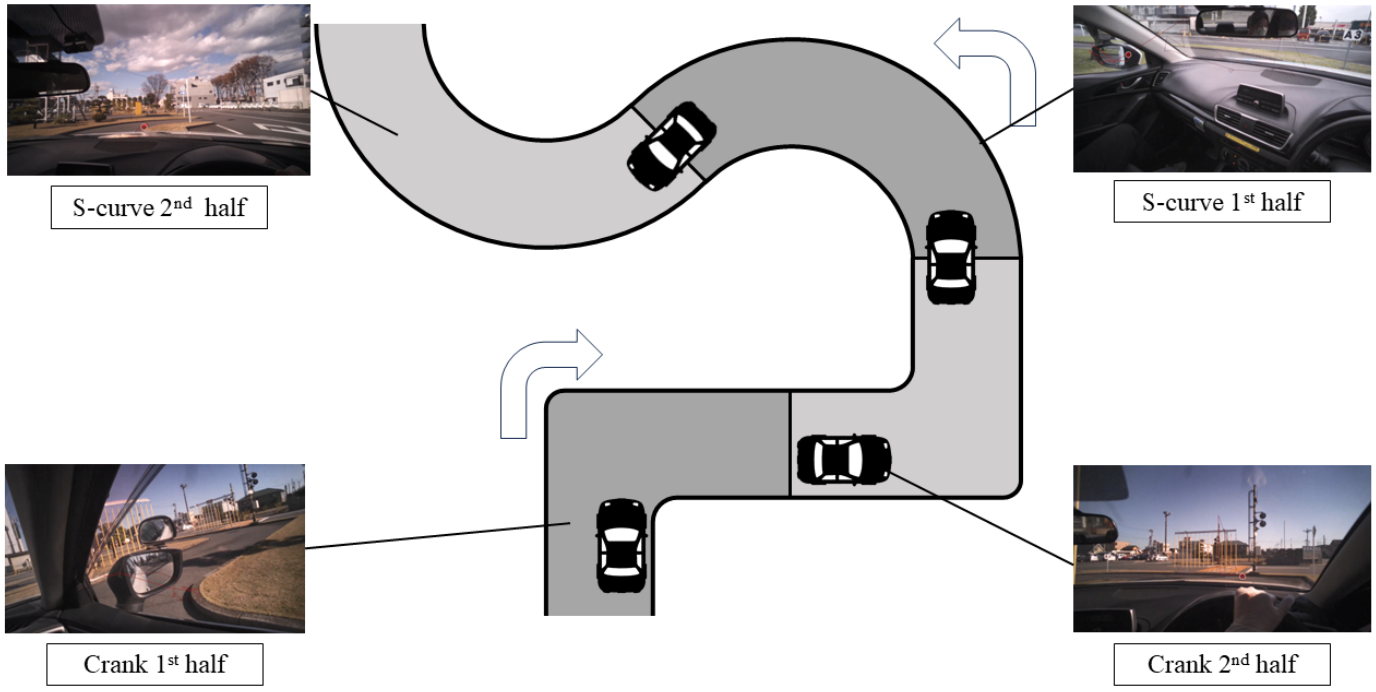


Figure 1. Overview of the driving course. Drivers entered from the Crank, turned right, turned left, and entered the S-curve. In the S-curve, drivers first turned left and then turned right again. The Crank and the S-curve were each divided into the 1st and 2nd halves.

2.3. Eye-Tracking System and Main Outcomes

An eye-tracking device (Tobii Pro Glasses 2, Tobii Technology Inc., Danderyd, Sweden) was used to measure participants' visual search behavior during the driving task. The device was designed with a high-precision, ultra-light, and non-invasive head-tracking module that ensures comfort and freedom of movement [16]. The drivers' visual search behavior was recorded at a sampling rate of 50 Hz (20 ms per sample), while a forward scene camera built into the eye-tracking glasses recorded their field of view at 25 fps (40 ms per frame) [16]. The camera has a 90-degree field of view and can record videos during the task with a range of 52° degrees and 82° degrees in the horizontal and vertical plane, respectively. All participants were equipped with this device before data collection, and they performed a single-point calibration using the calibration card. Participants were instructed to fixate

on the target point for 1–2 s, and calibration accuracy was calculated by Tobii Glasses Controller software (version 1.114; Tobii AB, Stockholm, Sweden). Recalibration was conducted if necessary.

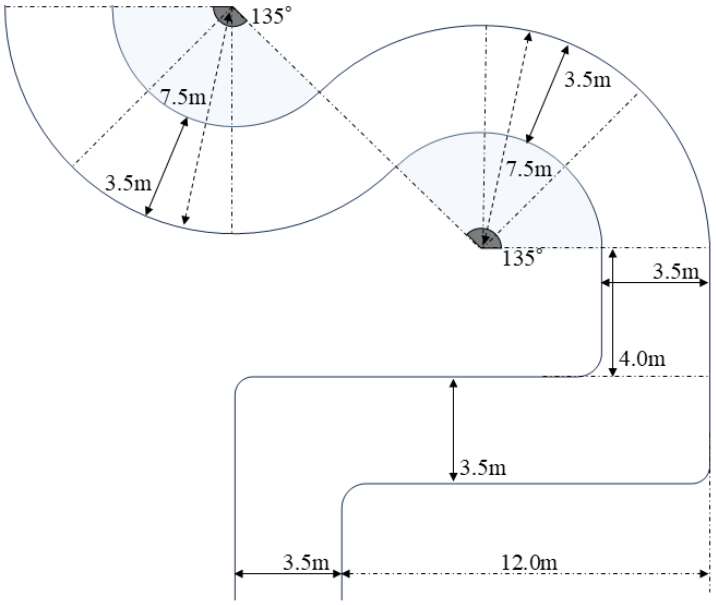


Figure 2. Layout and dimensions of the crank and S-curve in the driving course.

Reference points and reference areas were selected based on the findings of previous studies [5–7,13,17,18]. Based on the Tangent Point model [5], Table 1 represents the definition of reference points and reference areas established across four functional regions of the driving course: Crank (Points and Areas 1, 2, 3, and 4), Outer arcs of the S-curve (Points and Areas 5, 7, 12, and 14), Inner arcs of the S-curve (Points and Areas 6, 8, 11, and 13), and Transition of the S-curve (Points and Areas 9 and 10). Figure 3 illustrates the arrangement of reference points and reference areas, which strictly corresponds to the classifications defined in Table 1. A total of 14 reference points were geometrically defined, each corresponding to a single curb block (approximately 0.6 m in length) positioned at the vertices of road alignments or the intersection points of geometric lines relative to the inner and outer curve centers. A circular zone with a diameter three times that of the reference point was established as the reference area. The total gaze dwell time for each reference point and reference area, as well as the combined gaze dwell time for corresponding points and areas on both sides of the road across the S-curve sections, was calculated as a percentage of each section duration (% of gaze dwell).

Table 1. Definition of reference point and reference area on the driving course.

Region	Reference Points/Areas	Geometric Definition
Crank	1, 2, 3, 4	Vertices of the crank section.
Outer arcs of the S-curve	5, 7, 12, 14	Intersections between radial lines drawn from the center of curvature (arc center) and the outer arc in the S-curve.
Inner arcs of the S-curve	6, 8, 11, 13	Intersections between radial lines drawn from the center of curvature (arc center) and the inner arc in the S-curve.
Transition of the S-curve	9, 10	Intersections of the line connecting the two centers of curvature with the S-curve.

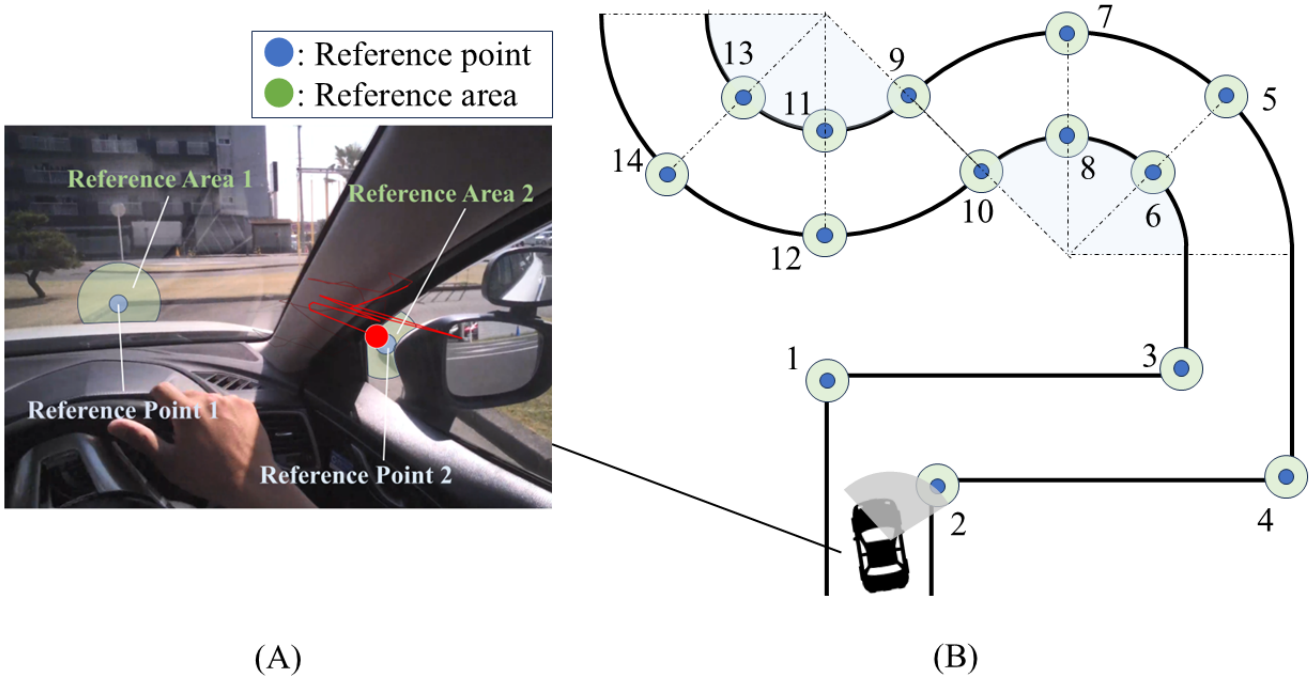


Figure 3. (**A**) Representative example of driver's gaze allocation from the driver's perspective. The red line and circle represent the gaze sequence and the final gaze point, respectively. (**B**) Schematic illustration of reference points (blue circles) and reference areas (green circles) on the driving course (points 1–14; see Table 1 for geometric definitions). The grey shaded sector in (**B**) indicates the driver's field of view, corresponding to the egocentric perspective depicted in (**A**).

After completing the task, we used Tobii Pro Lab software (version 1.171) to analyze the drivers' eye movements during the task, in addition to task duration and curb incursions. Based on the Dynamic Area of Interest method [19], the mapping of world-fixed reference points and areas (defined in the plan view) to the moving egocentric scene video was conducted through manual sample-by-sample inspection (at 20 ms intervals using Tobii Pro Lab's replay) by a single trained analyst. To ensure objective and consistent data extraction, coding rules were established through research team consensus based on criteria validated in prior work [13,20]. Furthermore, any ambiguous or borderline frames were jointly reviewed and adjudicated in consultation with co-authors; no independent duplicate coding by a second reviewer was conducted. In this process, each reference point and reference area was designated as an Area of Interest (AOI). Gaze points on the software overlapping a reference point were extracted as gaze dwell time on the reference point, whereas those located solely within a reference area were extracted as gaze dwell time on the reference area. While a 100 ms threshold is conventionally used for extracting gaze dwell events in standard tasks, shorter minimum duration criteria have also been adopted in previous eye-tracking research; for example, Hessels et al. used a minimum gaze dwell of 40 ms in their criteria [20]. Driving through narrow roads—specifically the "Crank" and "S-curve" sections—may require rapid spatial sampling and brief glances to ensure safety. Therefore, to comprehensively capture visual search behavior while matching the device's native temporal resolution (50 Hz; 20 ms per sample) and following Akiyama et al. [21], gaze dwell events exceeding 20 ms in either region were included in the analysis. The data exclusion criterion was a tracking success rate below 70%.

2.4. Conventional Tests in Elderly Drivers

We collected information on educational history, traffic accident history, and medical history. Cognitive status was assessed using the Montreal Cognitive Assessment

(MoCA) [22]. A cutoff score of 26 out of 30 points has been reported to detect mild cognitive impairment (MCI) with a sensitivity of 90% [22].

Self-reported driving attitudes were assessed in both elderly and expert drivers using the Driving Style Questionnaire (DSQ). The DSQ is an 18-item Japanese questionnaire developed to evaluate individual drivers' attitudes as a technical basis for the personalization of driver assistance [23]. Each item is scored from 1 to 4: 1 = strongly disagree, 2 = disagree, 3 = agree, and 4 = strongly agree. Total scores range from 18 to 72 points.

2.5. Statistical Analysis

Due to the small sample size, formal tests for normality have limited statistical power; therefore, non-parametric analyses were conducted to accommodate potential distributional deviations for preliminary group comparisons. Initially, differences in demographic data, task duration, and DSQ scores between the elderly and expert drivers were examined using the Mann–Whitney and chi–squared test. To account for variations in task completion time, the gaze dwell percentage for each reference point and reference area was expressed as a percentage of each task duration (i.e., calculated by dividing total gaze dwell time by task duration and multiplying by 100).

To examine group differences in gaze dwell percentages, a linear mixed model (LMM) was performed. The model specified group (elderly vs. expert), AOI (28 areas comprising 14 reference points and 14 reference areas), and their interaction (group × AOI) as fixed effects, with gender included as a covariate. To account for within-subject repeated measures across AOIs, participant ID was included as a random effect (random intercept) with a Compound Symmetry (CS) covariance structure. Bonferroni corrections were applied for post hoc group comparisons across individual Areas of Interest (AOIs), with the adjusted significance threshold set at $p < 0.0017$ (0.05/28). Similarly, a secondary LMM was performed using the same group and gender specifications, incorporating 10 combined regions across both sides of the S-curve as the AOIs (adjusted threshold: $p < 0.005$, 0.05/10).

To clarify the relationship between gaze dwell time and each DSQ score, we conducted an exploratory partial correlation analysis with 5000 bootstrap resamples—controlling for gender and group—to calculate bias-corrected and accelerated (BCa) 95% confidence intervals (CIs). In line with the exploratory design, no multiplicity adjustments were applied across these correlation tests.

The statistical software SPSS ver.29.0 J for Windows (SPSS Japan, Tokyo, Japan) was used for the analysis. All statistical tests were two-tailed, the significance level was set at $p < 0.05$, and adjusted for multiple comparisons using Bonferroni corrections as described above.

3. Results

Table 2 shows the demographic characteristics and driving performance of the elderly and expert drivers. The median age and the proportion of females were higher among elderly drivers. In addition, five participants in the elderly driver group scored below the MoCA cutoff threshold of 26 points and were classified as having MCI.

The number of errors (e.g., curb incursions) was significantly higher among elderly drivers. In addition, the total task duration and task durations during 1st and 2nd half of S-curve driving were significantly longer among elderly drivers.

Figure 4 shows the visual search behaviors of a representative driver in each group. The red circle indicates the last gaze point, and the line indicates the sequence of gaze points. In the 2nd half of Crank, the elderly driver gazed at the pole in front of the vehicle (Figure 4a), whereas the expert driver gazed at Reference Area 4 at the outside corner (Figure 4b), indicating that the expert driver gazed at the reference area to adjust the vehicle

position. In the 1st half of the S-curve, both drivers gazed toward the inside of the curve (Figure 4c,d). Then in the 2nd half of the S-curve, the elderly driver gazed at Reference Point 13 on the inside curb (Figure 4e,g). In contrast, the expert driver showed a gaze pattern toward Reference Area 14 on the left-front curb and the future path (Figure 4f,h), indicating that the expert driver gazed more at the future path than the elderly driver.

Table 2. Demographic characteristics and driving performance of elderly and expert drivers.

	Elderly Drivers (n = 7)	Expert Drivers (n = 10)	p-Value
Age	**73.7 [71.7, 74.8]**	**35.2[31.0, 48.8]**	**<0.01** [a]
Gender(male/female)	**1/6**	**8/2**	**<0.01** [b]
Education history (years)	14.0 [12.0, 14.0]		
Traffic accident history (yes/no)	2/5		
Medical history (yes/no)	0/7		
MoCA median score	25.0 [23.0, 27.0]		
Participants below cutoff (<26)	5		
Years of Driving Instructor (years)		11.5 [4.8, 24.8]	
Driving Style Questionnaire	45.0 [39.0, 46.0]	41.5 [37.5, 49.3]	0.67 [a]
Number of errors	**1.0 [0.0, 2.0]**	**0.0 [0.0, 0.0]**	**0.01** [a]
Total task duration (ms)	**68,470.0 [45,000.0, 84,259.0]**	**35,870.0 [29,380.3, 45,464.8]**	**<0.01** [a]
Crank 1st half	13,925.0 [12,621.0, 23,812.0]	13,612.0 [10,077.3, 15,623.5]	0.36 [a]
2nd half	7583.0 [6626.0, 11,512.0]	6718.5 [5177.5, 9012.0]	0.23 [a]
S-curve 1st half	**35,271.0 [15,370.0, 41,106.0]**	**9808.0 [6952.0, 11,568.3]**	**<0.01** [a]
2nd half	**9697.0 [8231.0, 12,309.0]**	**7474.0 [5842.0, 8799.8]**	**0.04** [a]

Values are presented as median [IQR (interquartile range)]. [a] Mann–Whitney's U-test; [b] Chi-square test. Bold values indicate significant differences ($p < 0.05$). MoCA: Montreal Cognitive Assessment.

Figure 5 shows the result of the LMM for gaze dwell percentages. The main effect of group was not significant, F (1, 14) = 2.66, p = 0.13, whereas the main effect of AOI was significant, F (27, 405) = 12.70, $p < 0.01$. Importantly, the group × AOI interaction was significant, F (27, 405) = 3.36, $p < 0.01$. The effect of gender as a covariate was also not significant, F (1, 14) = 0.09, p = 0.77. Post hoc comparisons revealed that elderly drivers exhibited a significantly higher gaze dwell percentage for Reference Areas 11, 13, and 14 (all $p < 0.001$, meeting the Bonferroni-adjusted significance threshold; detailed values are provided in Supplementary Table S1). In addition, the secondary LMM focusing on the combined regions revealed significant group differences for Reference Points 13 + 14 as well as Reference Areas 11 + 12 and 13 + 14 (Supplementary Figure S1 and Table S2).

Table 3 shows the DSQ results in both groups. Following the Bonferroni correction for multiple comparisons across individual items, none of the items exhibited significant group differences.

The results of the exploratory partial correlation analysis between the gaze dwell percentages of both sides of the road and each DSQ score are shown in Table 4. Overall, most pairs demonstrated negative correlations. Specifically, the gaze dwell for Reference Point 5 + 6 showed a strong negative correlation with DSQ Item 4 ("I check safety carefully when changing lanes and at intersections."; partial $r = -0.71$, 95% BCa CI [−0.92, −0.27]). Similarly, the gaze dwell percentage for Reference Area 5 + 6 was strongly and negatively correlated with DSQ Item 13 ("I will ensure that I perform driving maneuvers such as going slowly and stopping temporarily."; partial $r = -0.75$, 95% BCa CI [−0.94, −0.37]); implying that fixating on reference points and reference areas during the initial phase of curve may be associated with cautious driving attitude.

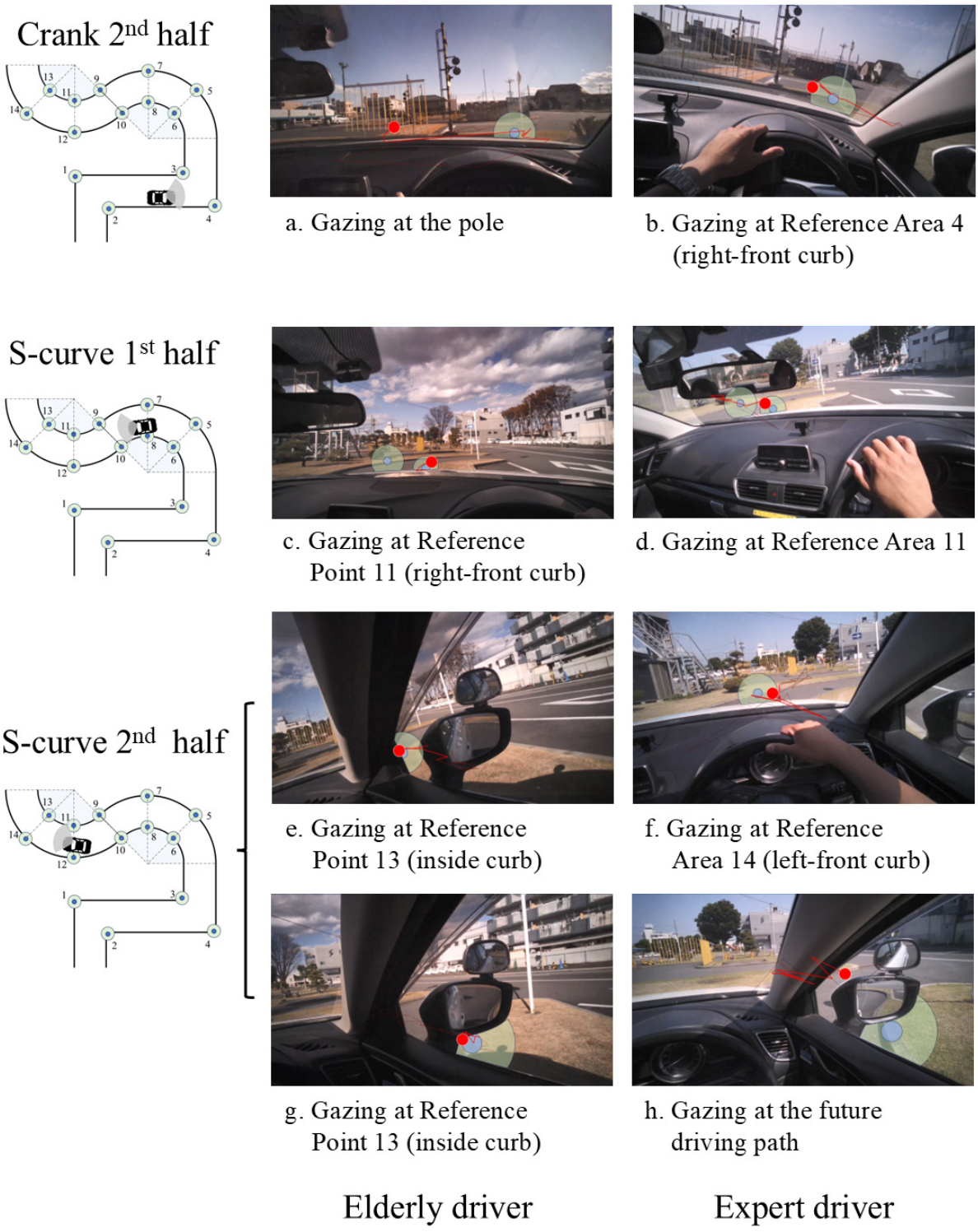


Figure 4. The visual search behavior during the course driving in each driver group. The blue circles (reference points), green areas (reference areas), and grey shaded sectors (driver's field of view) in the course map on the left correspond directly to those shown in the panels on the right (**a**–**h**). The red circle indicates the final gaze point, and the line indicates the sequence of gaze points. In the second half of the Crank, the elderly driver gazed at the pole in front of the vehicle (**a**), whereas the expert driver gazed at Reference Area 4 near the outside corner (**b**). In the first half of the S-curve, both drivers gazed toward the inside of the curve (**c**,**d**). In the second half of the S-curve, the elderly driver gazed at Reference Point 13 on the inside curb (**e**,**g**), whereas the expert driver gazed toward Reference Area 14 and the future path (**f**,**h**).

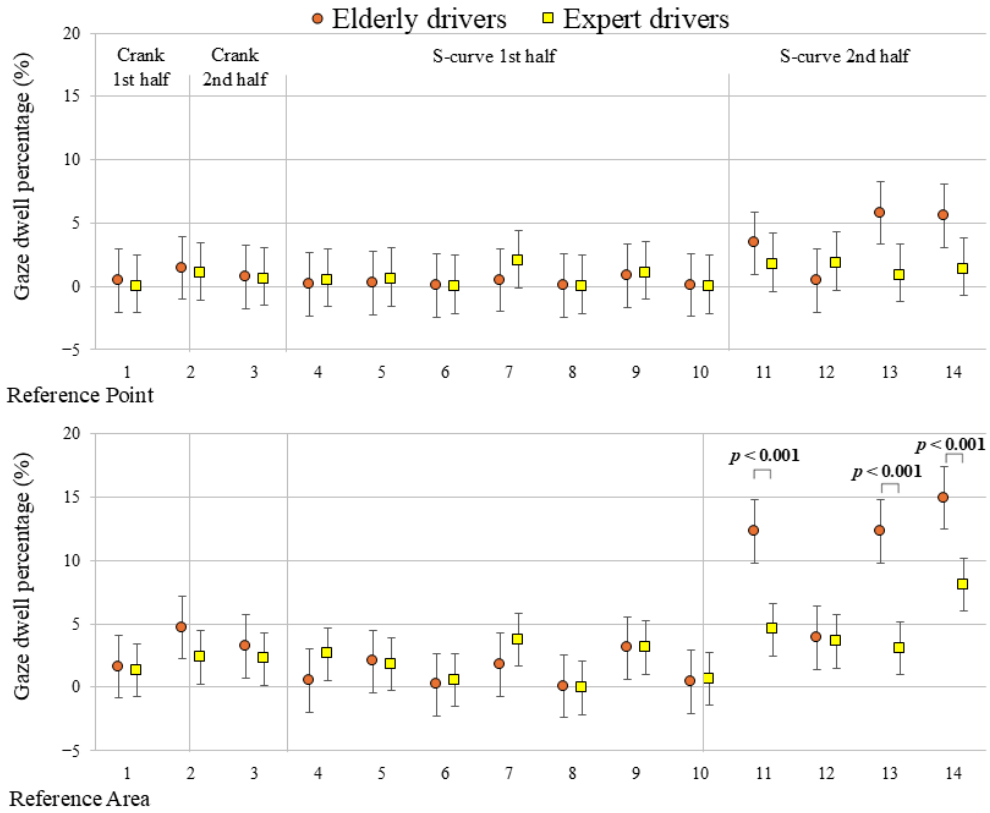


Figure 5. Results of the linear mixed model for gaze dwell percentages. Bar charts indicate estimated marginal means and 95% confidence intervals. Based on Bonferroni-corrected significance levels, elderly drivers demonstrated significantly higher gaze dwell percentages at Reference Areas 11, 13, and 14.

Table 3. Comparison of Driving Style Questionnaire (DSQ) item scores between both groups.

	DSQ Items/Content	Elderly Drivers (n = 7)	Expert Drivers (n = 10)
1.	I have confidence in my sense of vehicle width.	2.0 [2.0–3.0]	2.5 [2.0–3.0]
2.	When driving, I choose wide, well-maintained roads with traffic signals rather than back roads.	4.0 [3.0–4.0]	2.0 [2.0–3.0]
3.	I want to get as far ahead as possible even if it means changing lanes.	1.0 [1.0–1.0]	1.5 [1.0–2.0]
4.	I check safety carefully when changing lanes and at intersections.	3.0 [2.0–4.0]	3.0 [3.0–4.0]
5.	I adjust vehicle speed to avoid stopping at traffic lights.	2.0 [1.0–2.0]	2.0 [1.8–3.0]
6.	I think the car is my status (I want a cool car).	2.0 [1.0–3.0]	2.0 [1.8–3.3]
7.	I neglect my driving depending on how good or bad I am feeling.	1.0 [1.0–2.0]	1.0 [1.0–2.3]
8.	I am concerned about having an accident with my car.	2.0 [2.0–3.0]	4.0 [1.8–4.0]
9.	I always obey the speed limit.	3.0 [2.0–4.0]	2.5 [2.0–3.0]
10.	I am not good at changing lanes when there is traffic.	3.0 [2.0–4.0]	2.0 [1.8–2.3]
11.	I take the bus or train rather than the car if the time required is the same.	1.0 [1.0–2.0]	1.0 [1.0–2.3]
12.	I keep a good distance from other cars, even if they might cut in.	4.0 [2.0–4.0]	3.0 [2.0–4.0]
13.	I will ensure that I perform driving maneuvers such as going slowly and stopping temporarily.	3.0 [3.0–4.0]	3.0 [2.8–4.0]
14.	When I see a traffic light, I slow down or speed up beforehand.	2.0 [1.0–3.0]	2.0 [1.8–3.0]
15.	I think a car is a means of transportation and is only as good as it can run.	2.0 [1.0–4.0]	2.0 [1.0–2.3]
16.	Sometimes I do not feel like driving when I have problems or concerns.	2.0 [1.0–2.0]	2.0 [1.0–2.0]
17.	I am always worried about running someone over.	3.0 [2.0–4.0]	2.0 [2.0–4.0]
18.	Even if it is for a short time, I avoid parking where it is prohibited.	4.0 [3.0–4.0]	3.0 [1.8–4.0]

Values are presented as median (IQR). Group comparisons were evaluated using the Mann–Whitney U test with Bonferroni correction. No items showed statistically significant differences.

Table 4. Partial correlation coefficient between gaze dwell percentages at reference points/areas and individual DSQ item scores.

Gaze Dwell		DSQ 1	DSQ 2	DSQ 3	DSQ 4	DSQ 5	DSQ 6	DSQ 7	DSQ 8	DSQ 9
RP	5 + 6	−0.67 [−0.9, −0.01]	0.00 [−0.41, 0.72]	−0.21 [−0.75, 0.56]	**−0.71 [−0.92, −0.27]**	−0.33 [−0.77, 0.26]	−0.44 [−0.77, 0.32]	−0.06 [−0.51, 0.79]	−0.40 [−0.83, 0.42]	**−0.43 [−0.81, −0.25]**
	7 + 8	−0.26 [−0.75, 0.61]	−0.05 [−0.55, 0.52]	0.16 [−0.54, 0.80]	−0.39 [−0.75, 0.41]	−0.23 [−0.67, 0.28]	−0.22 [−0.66, 0.55]	0.38 [−0.35, 0.86]	−0.16 [−0.69, 0.49]	−0.10 [−0.56, 0.52]
	9 + 10	−0.48 [−0.85, 0.46]	−0.02 [−0.46, 0.58]	−0.12 [−0.70, 0.58]	−0.52 [−0.84, 0.52]	−0.26 [−0.74, 0.39]	−0.27 [−0.68, 0.57]	0.12 [−0.39, 0.77]	−0.31 [−0.74, 0.53]	−0.20 [−0.61, 0.42]
	11 + 12	0.08 [−0.38, 0.53]	0.24 [−0.21, 0.78]	0.26 [−0.27, 0.68]	0.29 [−0.32, 0.72]	−0.18 [−0.61, 0.29]	0.32 [−0.32, 0.80]	−0.15 [−0.58, 0.46]	−0.05 [−0.71, 0.74]	0.28 [−0.38, 0.64]
	13 + 14	0.29 [−0.30, 0.77]	0.40 [−0.36, 0.87]	0.09 [−0.52, 0.56]	0.15 [−0.36, 0.69]	0.03 [−0.50, 0.47]	0.38 [−0.17, 0.80]	−0.27 [−0.69, 0.22]	0.06 [−0.44, 0.54]	0.15 [−0.30, 0.61]
RA	5 + 6	−0.47 [−0.81, 0.43]	0.05 [−0.49, 0.56]	0.17 [−0.50, 0.77]	−0.43 [−0.82, 0.35]	−0.28 [−0.73, 0.26]	−0.51 [−0.82, 0.10]	0.02 [−0.45, 0.64]	−0.06 [−0.65, 0.68]	−0.19 [−0.65, 0.39]
	7 + 8	0.04 [−0.54, 0.80]	−0.05 [−0.63, 0.44]	0.22 [−0.55, 0.81]	−0.16 [−0.59, 0.59]	−0.28 [−0.69, 0.18]	0.08 [−0.42, 0.74]	0.27 [−0.35, 0.76]	−0.16 [−0.64, 0.50]	0.12 [−0.39, 0.65]
	9 + 10	−0.25 [−0.77, 0.39]	0.34 [−0.08, 0.75]	−0.04 [−0.61, 0.46]	−0.42 [−0.78, 0.42]	−0.14 [−0.73, 0.48]	0.03 [−0.57, 0.63]	0.08 [−0.69, 0.63]	−0.07 [−0.64, 0.59]	−0.39 [−0.74, 0.12]
	11 + 12	0.14 [−0.36, 0.66]	0.39 [−0.13, 0.86]	0.25 [−0.25, 0.73]	0.39 [−0.17, 0.82]	−0.40 [−0.77, 0.03]	0.20 [−0.46, 0.83]	−0.28 [−0.65, 0.13]	0.15 [−0.55, 0.74]	0.41 [−0.27, 0.75]
	13 + 14	**0.44 [0.01, 0.74]**	0.10 [−0.54, 0.71]	−0.01 [−0.45, 0.42]	0.35 [−0.10, 0.75]	−0.30 [−0.68, 0.26]	0.27 [−0.31, 0.73]	−0.23 [−0.79, 0.30]	0.13 [−0.35, 0.61]	0.19 [−0.23, 0.64]
Gaze dwell		DSQ 10	DSQ 11	DSQ 12	DSQ 13	DSQ 14	DSQ 15	DSQ 16	DSQ 17	DSQ 18
RP	5 + 6	−0.25 [−0.68, 0.47]	0.51 [−0.44, 0.89]	**−0.62 [−0.85, −0.21]**	−0.51 [−0.85, 0.13]	−0.34 [−0.76, 0.49]	−0.01 [−0.51, 0.38]	−0.25 [−0.65, 0.62]	−0.34 [−0.69, 0.52]	−0.51 [−0.90, 0.39]
	7 + 8	−0.07 [−0.59, 0.55]	0.50 [−0.12, 0.95]	−0.43 [−0.78, 0.23]	−0.42 [−0.89, 0.20]	−0.06 [−0.63, 0.64]	−0.07 [−0.45, 0.36]	−0.07 [−0.63, 0.62]	0.04 [−0.58, 0.77]	−0.09 [−0.77, 0.73]
	9 + 10	−0.15 [−0.59, 0.65]	**0.62 [0.00, 0.92]**	−0.38 [−0.79, 0.72]	−0.45 [−0.87, 0.25]	−0.18 [−0.70, 0.62]	−0.20 [−0.63, 0.14]	−0.21 [−0.64, 0.66]	−0.24 [−0.65, 0.66]	−0.23 [−0.80, 0.83]
	11 + 12	0.27 [−0.18, 0.75]	−0.11 [−0.58, 0.44]	0.14 [−0.31, 0.62]	0.24 [−0.47, 0.70]	−0.02 [−0.54, 0.55]	**−0.55 [−0.82, −0.34]**	−0.36 [−0.71, 0.39]	−0.33 [−0.74, 0.35]	0.21 [−0.20, 0.68]
	13 + 14	−0.26 [−0.69, 0.42]	0.20 [−0.34, 0.66]	0.38 [−0.31, 0.89]	−0.16 [−0.68, 0.53]	0.00 [−0.60, 0.41]	**−0.56 [−0.86, −0.07]**	−0.35 [−0.70, 0.29]	−0.46 [−0.79, 0.24]	0.16 [−0.35, 0.68]
RA	5 + 6	−0.24 [−0.72, 0.30]	0.36 [−0.42, 0.86]	**−0.60 [−0.88, −0.07]**	**−0.75 [−0.94, −0.37]**	−0.39 [−0.78, 0.30]	−0.01 [−0.48, 0.48]	−0.49 [−0.84, 0.11]	−0.30 [−0.71, 0.39]	−0.49 [−0.89, 0.18]
	7 + 8	−0.14 [−0.64, 0.46]	0.43 [−0.13, 0.85]	−0.17 [−0.64, 0.49]	−0.25 [−0.81, 0.41]	−0.07 [−0.59, 0.59]	−0.18 [−0.56, 0.27]	−0.10 [−0.60, 0.54]	0.02 [−0.53, 0.65]	0.00 [−0.65, 0.82]
	9 + 10	−0.09 [−0.69, 0.68]	**0.58 [0.04, 0.93]**	−0.17 [−0.62, 0.59]	−0.40 [−0.77, 0.09]	0.09 [−0.63, 0.65]	−0.24 [−0.60, 0.23]	0.00 [−0.60, 0.58]	−0.04 [−0.64, 0.57]	0.03 [−0.70, 0.73]
	11 + 12	0.24 [−0.29, 0.72]	−0.04 [−0.50, 0.62]	0.18 [−0.37, 0.67]	0.16 [−0.56, 0.70]	−0.25 [−0.64, 0.31]	−0.52 [−0.80, −0.13]	**−0.52 [−0.81, −0.01]**	−0.56 [−0.88, 0.04]	0.11 [−0.35, 0.62]
	13 + 14	0.18 [−0.30, 0.72]	−0.21 [−0.62, 0.33]	0.40 [−0.08, 0.79]	−0.10 [−0.56, 0.53]	−0.13 [−0.56, 0.34]	−0.25 [−0.72, 0.26]	−0.28 [−0.73, 0.24]	−0.35 [−0.84, 0.18]	0.27 [−0.19, 0.62]

RP: Reference Point, RA: Reference Area, DSQ: Driving Style Questionnaire. Values are presented as partial correlation coefficient *r* [95% BCa confidence interval]. Bold values indicate statistically significant differences ($p < 0.05$).

4. Discussion

We found that elderly drivers gazed longer at the reference areas during the S-curve than expert drivers. Specifically, they gazed longer at Reference Areas 11 and 13, whereas no significant difference was observed for Reference Points 11 and 13. In addition, the gaze dwell for reference areas on both sides of the S-curve was negatively correlated with DSQ scores.

One key finding of this study was that the gaze dwell for reference areas was prolonged in elderly drivers during the second half of the S-curve. The prolonged gaze directed toward reference areas might reflect a compensatory strategy to acquire broader environmental information during steering. Kim et al. demonstrated that reduced visual exploration during the initial phase of a parking task was associated with increased visual search behavior during the later phase in elderly drivers [13]. Likewise, in the present study, insufficient visual search or delayed information processing during the S-curve 1st half may have led to a compensatory increase in gaze behavior during the 2nd half. This interpretation is supported by the behavior of expert drivers, who proactively gazed toward the future path during the 2nd half of the S-curve (Figure 4h).

However, caution is required when interpreting the above results as general age-related differences. Notably, five out of the seven elderly drivers in this study were classified with MCI based on MoCA scores. Therefore, the observed increase in visual search behavior during the S-curve may reflect altered processing speed and spatial perception specific to elderly drivers with mild cognitive impairment, rather than a proactive broader spatial gaze allocation in healthy aging. These findings highlight the need to distinguish cognitive impairment from typical age-related changes when investigating visual search behaviors in complex driving situations.

Furthermore, it is noteworthy that elderly drivers exhibited significantly higher gaze dwell percentages for Reference Areas 11 and 13 than expert drivers, whereas no significant difference was observed for Reference Points 11 and 13, which corresponds to the inner apex of the second curve in the S-curve sequence. This finding may suggest that elderly drivers tend to allocate gaze to the area surrounding the reference point for longer durations, rather than relying on focal visual search on the point itself, potentially representing a visual adaptation during continuous S-curve negotiation. By allocating gaze to these broader reference areas, elderly drivers continuously process road geometry and evaluate vehicle clearance. Land and Lee [5] suggested that the tangent point on the inside of a curve serves as a primary reference point for steering control, enabling drivers to perceive the spatial relationship between the vehicle and the road. In accordance with this well-documented visual mechanism in single-curve negotiation [6–8], our findings highlight its specific role under the more complex demands of continuous S-curve driving. In an S-curve, where drivers must seamlessly transition between opposing curve directions, allocating gaze toward the area surrounding the second curve's apex (Reference Areas 11 and 13) may act as a critical spatial anchor for elderly drivers. This expanded spatial gaze allocation may help drivers to integrate scene gist across continuous directional changes, thereby potentially supporting the construction of coherent spatial awareness necessary to safely execute the complex steering transition. Collectively, these findings suggest that the compensatory strategy employed by elderly drivers does not operate merely through heightened focus on a discrete reference point, but rather through the active utilization of the surrounding reference area to construct the necessary spatial relationships between the vehicle and the driving environment.

A negative correlation was observed between DSQ scores reflecting cautious driving attitudes (e.g., DSQ 4, 9, 12, and 13) and gaze dwell percentages on reference areas and points during the initial phase of the S-curve (RP 5 + 6 and RA 5 + 6; Table 4). This

finding may suggest that cautious drivers spend less time fixating on immediate entry areas, possibly conserving attentional resources during the initial phase of the curve negotiation. Interestingly, although the associations for these DSQ items did not reach statistical significance during the later phase, they showed a non-significant positive trend with gaze dwell percentages during the second half of the S-curve. Taken together, our finding raises the possibility that reduced gaze allocation at curve entry may allow drivers to preserve attentional resources for subsequent stages of curve negotiation. Such resource allocation may support compensatory gaze behavior during the second half of the curve, when more complex steering adjustments and spatial processing are required.

There are several limitations in the present study. Firstly, there was the issue of participant characteristics. Due to recruitment constraints and practical challenges in the study design, only a small number of elderly drivers (n = 7) and expert drivers (n = 10) participated. Moreover, there was a notable gender imbalance between the groups: six of the elderly drivers were female, while eight of the expert drivers were male. Because gender differences are known to influence driving attitudes [24], these biases may limit the generalizability of the present findings. Furthermore, among the elderly participants in this study, five out of seven were classified with MCI based on MoCA scores. Since cognitive decline may influence driving behavior, it may not be appropriate to generalize these results directly to healthy elderly individuals. Similarly, while the expert group was intentionally selected to serve as a benchmark for optimal visual-motor coordination, it comprised professional driving instructors who possessed not only superior driving proficiency but also high familiarity with the specific test course layout. Furthermore, evaluation apprehension induced by the presence of an in-vehicle evaluator represents a residual confound in the passenger conditions that may have also affected these group differences. Although we applied 5000 bootstrap resampling, the small sample size (n = 17) offers limited resampling diversity, making the resulting BCa confidence intervals fragile. Therefore, potential residual confounding associated with driving proficiency, evaluative conditions, and gender variances cannot be entirely ruled out. Future studies should examine a larger, more homogeneous sample to better define the characteristics of elderly drivers when navigating S-curves. Secondly, methodological limitations concern the spatial definition and dynamic mapping of reference areas. Although the Tangent Point model highlights the functional role of visual regions surrounding geometric features [5], the optimal spatial extent of such areas remains no consensus exists regarding the optimal spatial extent. Here, AOIs were physically anchored to three curb blocks, yet the exact boundaries that serve as effective spatial anchors bridging a reference point to the road environment are still unclear. In addition, to capture these dynamic spatial representations in moving egocentric video, gaze dwell samples were manually projected sample-by-sample by a single analyst. Although this manual projection aligns with established Dynamic Area of Interest protocols in driving research [19], the absence of an inter-rater reliability assessment remains a methodological constraint. Consequently, alongside sampling constraints, these conceptual and procedural limitations mean our conclusions should be interpreted with caution as suggestive rather than definitive. Finally, the data were collected under controlled conditions within a driving school course. It is known that attention to other vehicles is crucial and visual search behavior is influenced in actual driving environments [25]. Under the low-risk conditions of the present study, the absence of competing information-processing demands may have allowed participants to allocate surplus attentional resources to reference areas. Therefore, future research should be conducted under on-road or controlled driving simulator conditions with systematically varied geometry, traffic, and cognitive load to assess how attentional resources are allocated in environments with realistic driving demands.

5. Conclusions

In the present study, to clarify visual search behavior during the S-curve in elderly drivers with a high prevalence of MCI, we compared the gaze dwell percentages directed toward reference points and their surrounding reference areas with those of expert drivers. The results revealed that elderly drivers allocated higher gaze dwell percentages to the reference area during the late phase of S-curve. While this expanded gaze allocation is consistent with a potential compensatory mechanism to construct spatial awareness under dynamic driving demands, it represents one of several plausible interpretations alongside cognitive and task-related factors. Furthermore, group differences were localized to reference areas rather than discrete reference points, suggesting that broader spatial gaze allocation may support spatial orientation on complex road geometries. These preliminary findings offer valuable insights for future research aimed at understanding visual search behavior and driving mechanisms in elderly clinical populations.

Practically, these findings may provide preliminary insights with potential engineering and clinical implications based on the observed group-specific gaze allocation patterns. Specifically, these observations may help inform the design of predictive Human–Machine Interfaces or Advanced Driver-Assistance Systems that assist drivers in monitoring key curve boundaries, as well as dynamic driver assessment protocols and the visual design of narrow road geometry.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/vehicles8100259/s1, Table S1: Post hoc pairwise comparisons of gaze dwell percentages between Elderly and Expert drivers for individual AOIs (LMM); Table S2: Post hoc pairwise comparisons of gaze dwell percentages between Elderly and Expert drivers for both roadsides AOIs (LMM); Figure S1: Results of the linear mixed model for gaze dwell percentages for both roadsides AOIs. Bar charts indicate estimated marginal means and 95% confidence intervals. Based on Bonferroni-corrected significance levels, elderly drivers demonstrated significantly higher gaze dwell percentages at Reference Points 13 + 14 as well as Reference Areas 11 + 12 and 13 + 14.

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Data Availability Statement: The data presented in this study is available upon request from the corresponding author. The data is not publicly available due to ethical reasons.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

S-curve	S-shaped curve
Crank	Crank-shaped turn
MCI	Mild Cognitive Impairment
MoCA	Montreal Cognitive Assessment
DSQ	Driving Style Questionnaire

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