EFFECTS OF AUTISM SPECTRUM DISORDERS AND HAZARD WARNING SYSTEMS ON RESPONSES TO PEDESTRIAN HAZARDS

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This manuscript has been read and accepted by the Thesis Committee in satisfaction of the thesis requirement for the degree of Master of Science.

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ABSTRACT

EFFECTS OF AUTISM SPECTRUM DISORDERS AND HAZARD WARNING SYSTEMS ON RESPONSES TO PEDESTRIAN HAZARDS

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Purpose: Autistic people are less likely to obtain a driver's license than neurotypical peers and may face higher collision risks when driving. While advanced driver assistance systems (e.g. hazard warnings) could enhance driving safety for this population, their efficacy remains understudied for this group. The present work is an exploratory study to investigate the relationship between autistic trait level, driving behaviors, and the use of a hazard warning system. I expected that those with more autistic traits may take longer to fixate the pedestrian hazards, and thus could benefit the most from the warning system.

Methods: In a driving simulator, licensed drivers followed pre-determined routes through a city, with and without a vibrotactile hazard warning device. Participants were grouped by autistic trait level (low, high, and non-autistic controls), determined by scores combined from 2 questionnaires, the AQ-50 and RAADS-14. Participants completed 4 simulated drives while trying to avoid collisions with pedestrian hazards. The warning device was a seat cover that gave a vibration on the left or right side, corresponding to the direction of the hazard. Gaze fixation, braking responses, and subjective workload were compared across warning conditions and between groups.

Results: Without warnings, autistic trait level had no effect on gaze fixation or brake responses to hazards. However, when driving with warnings, drivers low in autistic traits exhibited delayed initial fixation, shorter total fixation duration, and slower braking responses, but did not have increased collisions. While drivers with high autistic traits showed no behavioral changes when using warnings and reported high frustration, they achieved the greatest reduction in collisions. Unique gaze patterns were seen among drivers high in autistic traits, which might suggest individual-specific adaptive behaviors in this group to manage hazard situations.

Discussion: Grouping participants by degree of autistic traits rather than by diagnosis alone revealed distinctions in fixation and driving behaviors between the low-ASD and high-ASD group, which may not have been detected with a binary classification of non-ASD vs ASD. The hazard warnings were most beneficial in reducing collisions of the high-ASD group.

Conclusions: To my knowledge, this is the first study exploring the effects of autistic trait levels on gaze fixation behaviors and pedestrian hazard responses in a population of licensed drivers in a driving simulator. These findings highlight the potential of driver assistance systems to enhance safety in the autistic population and demonstrate the need to consider autistic trait levels when evaluating driving and driver assistance systems.

List of Figures and Tables

1. Introduction

Autism spectrum disorder (ASD) or autism is an atypical form of neurodevelopment that is particularly known for affecting the person's social experiences, but which also affects many other aspects of life due primarily to sensory differences (DSM-5, American Psychiatric Association 2017). The estimated prevalence of ASD in the U.S. in 2022 among 8-year-old children was 32.2 in 1000 (or about 1 in 31) (Shaw et al. 2025), with males diagnosed more than females (3.4:1), though prevalence continues to increase and there have been fluctuations in the degree of the gender gap in diagnosis as providers learn more about its presentations and improve early detection strategies (Chiarotti & Venerosi 2020, Shaw et al. 2025).

ASD can affect cognitive processes such as executive function and theory of mind. These involve planning, attention, and inhibition, and the ability to take the perspective of others to infer their thoughts, intentions, and actions (Hill 2004, Baron-Cohen 2000, Bednarz et al. 2021). These certainly relate to the mental skills required to operate an automobile safely, particularly when it comes to monitoring the roadway for hazards and predicting the behavior of pedestrians and other drivers.

Atypicalities in gaze behavior and vision processing have also been noted in individuals with ASD. For example, eye tracking studies comparing time spent gazing at non-social stimuli (e.g. the background of a scene) versus social stimuli (e.g. a person in the scene) have found that autistic participants spent longer looking at the non-social stimuli than the social stimuli, which was not the case in non-autistic peers (Frazier et al. 2017). Additionally, when autistic participants did fixate on social stimuli, they spent less time looking at the eyes and whole face than non-autistic participants (Frazier et al. 2017). These differences are consistent with social processing difficulties.

The prevalence of refractive errors, strabismus and oculomotor problems, and cerebral visual impairment are increased in the ASD population (Little 2018); but even in the absence of these issues, there are deficits in fine motor control of saccades, smooth pursuits, and fixation such that these processes are more inaccurate and unsteady (Johnson et al. 2016). Autistic adults have also commonly reported visual hypersensitivities, particularly to bright lights and certain colors and patterns (Parmar et al. 2021). Some reported strategies to avoid these bothersome stimuli, such as avoiding places known to have irritating lighting or visual clutter, using tinted lenses, and even avoiding night driving due to the discomfort caused by bright headlights of oncoming traffic (Parmar et al. 2021).

In the U.S., approximately 30% of autistic people obtain a driver's license by age 21, less than half the rate in non-autistic peers (Curry et al. 2018). Autistic people were more likely to give a poor self-rating of their driving abilities than non-autistic peers, and reported more inappropriate driving behaviors and accidents (Daly et al. 2014). They were also more likely to self-restrict their driving, such as avoiding driving during rush hour, evening, and at night, and avoiding highway driving (Daly et al. 2014). Despite these self-reports, autistic participants' poor self-ratings of their driving abilities did not relate to their self-reports of inappropriate driving behaviors, which may demonstrate inaccurate self-perceptions of one's own driving ability in ASD (Daly et al. 2014). Moreover, parents of autistic teenagers reported high anxiety regarding the challenges their child may face in utilizing public transportation and school-facilitated transportation; they were also quite anxious about their child learning to drive and being able to develop the skills and processing abilities needed for safe driving

(Lindsay 2017).

There have been studies of autistic participants' ability to detect driving hazards when viewing pre-recorded videos, using eye tracking and button-press responses (Sheppard et al. 2010, Sheppard et al. 2017). Notably, the participants in these studies were non-drivers. Compared to non-autistic peers, autistic participants took longer to initially fixate hazards, and this effect increased with higher degrees of autistic traits, particularly for social hazards (Sheppard et al. 2010, Sheppard et al. 2017). Once the hazard was fixated, however, response time was comparable between ASD and non-ASD participants, suggesting a problem in orienting visual attention to hazards rather than processing and understanding their implications (Sheppard et al. 2017).

Other studies have similarly compared relevant driving skills of ASD and non-ASD participants, but with novice drivers. In a driving simulator study of hazard detection, Bishop et al. (2017) reported that novice ASD and non-ASD drivers had similar reaction times for both social hazards (e.g. a pedestrian walking into the road) and non-social hazards (e.g. another vehicle driving head-on into the participant's lane). However, within-group analyses showed that typically developing participants were significantly faster to react to social than non-social hazards, while ASD participants showed similar reaction times to both hazard types (Bishop et al. 2017).

Driving simulators have also been utilized to focus on more general aspects of ASD gaze behaviors when driving. Using eye tracking and physiologic measures, an early driving simulator study compared high-functioning autistic participants to neurotypical controls, with all participants being licensed drivers (Reimer et al. 2013). The results suggested that the ASD participants tended to shift their gaze towards visually simpler areas of the simulated roadway when cognitive load was higher (e.g. having to make a mock phone call to a doctor's office during the drive) (Reimer et al. 2013). Autistic participants' gaze was also generally directed at a higher area of the simulator screen, suggesting their focus was farther away at areas that may have been less visually complex than that of the foreground (Reimer et al. 2013). While looking at simpler areas of the roadway may help to prevent sensory overload by reducing the volume and complexity of information to be processed, such avoidant gaze behavior could certainly be dangerous if visual attention strays too far from the road and oncoming traffic where hazards could appear.

Worse executive function deficits, especially lower processing speed, have been associated with poorer driving simulator performance (such as deviating from the speed limit or poor lane position) in ASD participants, including both licensed and unlicensed young adults, versus matched controls (Patrick et al. 2020). Similarly, increased working memory demands – for example, having to recall road signs passed during the drive – also were markedly detrimental to the steering and braking performance of ASD participants with learner's permits (but not detrimental to neurotypical controls) in a driving simulator (Cox et al. 2016). Even without an explicit working memory task, deficits in working memory were associated with more abrupt braking in response to social ("behavioral prediction") hazards in ASD participants (Ross et al. 2019) and theory of mind deficits were associated with more frequent hard accelerations and decelerations as well as more collisions, among both ASD and non-ASD participants (Plunk et al. 2024).

While there is certainly a large body of literature on ASD, much of this has been focused on pediatric populations. There has been limited research on the driving performance and safety of autistic adults who are already licensed to drive, particularly in detecting and avoiding collisions with hazards. From those studies that have examined autistic participants' responses to driving hazards in pre-recorded videos (Sheppard et al. 2010, Sheppard et al. 2017) and those assessing driving performance using driving simulators (Reimer et al. 2013, Patrick et al. 2020, Cox et al. 2016, Bishop et al. 2017, Ross et al. 2019, Plunk et al. 2024), it would seem that ASD can sometimes make it more difficult for a driver to orient their visual attention to hazards, though importantly, ASD drivers do not always perform more poorly in driving simulator or driving hazard perception tasks than non-ASD peers. Prior findings regarding executive functions and theory of mind deficits suggest that higher levels of autistic traits as well as higher cognitive loads could each be factors that might reduce performance and safety for autistic drivers.

In this study, I used a driving simulator to investigate how ASD impacts licensed, current drivers' gaze behaviors and driving responses in the setting of pedestrian hazards posing potential collisions and compared these to the behaviors of non-autistic drivers. I was also interested in examining the relationship between autistic trait levels and collision avoidance measures across all drivers, and took a new approach by grouping drivers according to autistic trait level, rather than the dichotomous ASD versus non-ASD classification used in most prior studies (Daly et al. 2014, Sheppard et al. 2010, Sheppard et al. 2017, Bishop et al. 2017, Reimer et al. 2013, Patrick et al. 2020, Cox et al. 2016, Ross et al. 2019, Plunk et al. 2024). Another novel aspect of my approach was to examine the potential effects of a driver assistance system (i.e., a vibrotactile hazard warning system that provides directional hazard information) on pedestrian hazard detection and collision risks for autistic drivers. Similar advanced driver assistance systems have improved driving safety and performance in drivers with normal vision as well as those with vision impairments in driving simulator studies (Petermeijer et al. 2015, Hölzl et al. 2021, Xu et al. 2024), and have also improved self-perceptions of driving safety when used in real-world driving by drivers with vision impairments (Deffler et al. 2022, Xu et al. 2022, Xu et al. 2023, Wallace-Carrete et al. 2024). However, to the best of my knowledge, no studies have yet examined the impact of these systems on autistic drivers.

I hypothesized that drivers with higher levels of autistic traits would show longer times to orient to pedestrian hazards due to the social nature of the stimuli, but have similar response times once fixating on the hazard. I therefore expected that drivers with higher levels of autistic traits might benefit more from the hazard warning system compared to drivers with lower levels of autistic traits, as the directional warning system could help to orient their attention to the pedestrian hazards sooner, both by directing the driver to look more closely at one side of the roadway and by providing a general warning to slow down to avoid a collision with a hazard.

I did, however, anticipate two possible behavioral scenarios in drivers with higher levels of autistic traits. Given the vibrotactile stimulus of the warnings, drivers with autistic traits may find the stimulus uncomfortable or bothersome, and therefore might try to avoid receiving warnings by scanning the roadway more proactively to respond sooner without triggering the device. However, if drivers with higher autistic traits do not find the vibration irritating, it is possible they will become more lax in their scanning of the roadway and wait for the delivery of a warning to respond to a hazard, which could still allow for collision avoidance while also freeing up some cognitive resources to attend to other aspects of the driving task, such as speed maintenance or lane positioning. Both types of responses to the vibrotactile warning system have the potential to improve collision avoidance, though the former creates a more active strategy that could translate to real driving situations where such a driver assistance system is not available. I was also interested in collecting feedback from participants about their subjective workload and their thoughts on this mode of stimulus to deliver hazard warnings to help discern whether their behaviors and opinions aligned with my hypotheses.

If this hazard warning system improves responses to and avoidance of pedestrian hazards in autistic drivers, such devices may have a role in building confidence, easing anxiety, and improving driver safety in this population.

2. Methods

2.1. Participants

This study was conducted at the Schepens Eye Research Institute, part of Mass General Brigham (MGB) in Boston, Massachusetts, USA. The study followed protocols approved by the MGB institutional review board.

Inclusion criteria for participation in the study were as follows: (1) vision meeting the criteria for a regular driver's license in Massachusetts (acuity of 20/40 or better in each eye with habitual correction and horizontal visual field of >120 degrees), (2) possessing a driver's license and currently driving, (3) physical ability to operate standard vehicle controls in the driving simulator, (4) at least 18 years of age (with no upper age limit), and (5) able to give full informed consent. Additionally, participants self-reported whether they had a condition within the autism spectrum. Given that diagnosis labels and personal terminology can vary, the ASD group included participants who reported a diagnosis of autism, ASD, or Asperger's syndrome, recognizing that some participants may have received an Asperger's label before it was subsumed under ASD in the transition from DSM-IV to DSM-5 (Hosseini & Molla 2025). All participants provided written informed consent before completing any study procedures.

Participants were recruited via Rally, a public-facing research participation portal through the MGB network. Of the 37 recruited for the study, four were unable to complete the study due to motion discomfort associated with using the driving simulator, one had significant loss of eye-tracking data, and one was falling asleep repeatedly in the driving simulator. Thus, 31 participants have complete data and are included in the analysis.

Binocular single letter visual acuity and binocular contrast sensitivity were measured for each participant using FrACT software (Bach, 1996), while they wore their habitual refractive correction, if needed. The examiner also screened for peripheral visual field loss using confrontation fields. All recruited participants met the visual requirements for participation in the study.

Participants completed a questionnaire on their demographic information (age, gender, race/ethnicity), self-report of whether or not they had ASD, and their current driving habits, including weekly mileage, and driving situations they avoid. The examiner also completed the Montreal Cognitive Assessment (MoCA) on all participants to screen for and rule out mild cognitive impairment (Nasreddine et al. 2005).

2.2. Stratification by autistic trait level

Two self-report questionnaires, the Autism-spectrum Quotient (AQ-50) and Ritvo Autism and Asperger Diagnostic Scale revised and abridged version (RAADS-14) were administered to quantify participants' degree of autistic traits. The AQ-50 consists of 50 questions, found to differentiate well between participants with and without ASD – 79% of autistic participants were found to achieve the threshold score of at least 32 out of a maximum score of 50, while only 2% of non-autistic participants scored this high (Baron-Cohen et al. 2001). The RAADS-14 is a short questionnaire, taking 14 key questions from the original 80-question RAADS-R (Ritvo et al. 2011), and with both high sensitivity and specificity (97% and 95%, respectively) in differentiating autistic and non-autistic participants at a score of 14 or higher out of a maximum of 42 (Eriksson et al. 2013).

Although these questionnaires have been validated to differentiate between autistic and non-autistic persons (Lundqvist & Lindner 2017, Moseley et al. 2018), there are no guidelines in the literature on examining different degrees of autistic traits beyond ASD vs non-ASD. Each participants' scores for the AQ-50 and RAADS-14 were summed together to account for variability in scores between the two questionnaires, since they address different functional domains.

The summed autistic trait scores across participants had a median of 46, which is exactly the sum of the two questionnaires' thresholds to differentiate ASD vs non-ASD. Because there were some participants with self-reported ASD who had a summed score below 46, and some who reported not having ASD but had a summed score above 46, I was interested in a different stratification approach. The lowest third of summed scores all belonged to participants reporting no ASD diagnosis, so this group is termed *non-ASD*. The middle third of summed scores contains a mixture of those self-reporting ASD and those not, so to reflect the spectrum nature of our current understanding of autism, I termed this group as *low-ASD*, for an intermediate degree of autistic traits. The upper third of summed scores contained only participants self-reporting ASD, and was termed *high-ASD*. A similar attribute-based stratification strategy has been used previously with NEPSY-II (theory of mind) scores to examine gaze behavior in autistic and non-autistic teens and young adults (Plunk et al., 2024), which supports the present work's grouping of participants by social cognitive profile rather than diagnosis alone.

2.3. Driving simulator

A fixed-base, custom-built driving simulator was used in this study (Figure 1). Features included an adjustable driver's seat, a steering wheel, accelerator and brake pedals typical of a standard automatic transmission vehicle (Fanatec; Landshut, Germany), a computer, three curved monitors (Samsung C34F70, 3440x1440 pixels), the vibrotactile warning device, and an eye-tracking system (Tobii Eye Tracker 5, Sweden). The three monitors provided a 165° horizontal by 26.5° vertical field of view. During the simulated drives, fixed regions of the screens showed simulated rearview and sideview mirrors, as well as a digital speedometer. The eye-tracker was mounted on the bottom frame of the central monitor (the monitor on which pedestrian hazard events occurred) to record the participant's gaze positions on that screen at 120 Hz. The simulation software synchronized the eye-tracking data with driving performance data.

Figure 1.
The custom-built driving simulator and the virtual driving environment.

The simulation software and virtual environment were developed with Unity 3D (Unity, San Francisco, USA). This study used four experimental drives in a simulated city environment (see a screenshot in Figure 2). Each drive followed a different route in the city and lasted about 10-15 minutes (Kang et al. 2025). In each drive, participants drove on two-lane roads with parking lanes on each side and with both oncoming and passing traffic, such as cars and trucks. The roadway was surrounded by scenery of typical storefronts and businesses, trees, benches, parking meters, and other objects typically found on sidewalks. Pedestrians were distributed throughout the environment, and could be walking along sidewalks, standing in groups or solitarily, or crossing the roadway. These pedestrians had human-size models with varying appearance in terms of their age, gender, skin color, and clothing color.

Pre-recorded GPS audio cues were given to guide participants to drive along predetermined routes. The simulator software recorded performance data, such as the driver's speed, location, steering and pedal inputs. It simultaneously collected data on hazardous pedestrians, such as when and where these pedestrians began crossing the roadway and their trajectories across the roadway. These hazardous pedestrians were scripted events, and are further detailed in the following section.

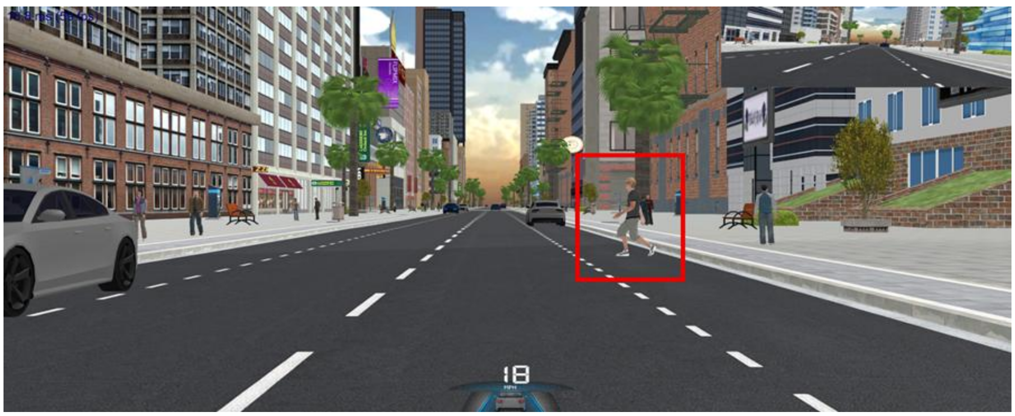

Figure 2.

An example of a pedestrian crossing event from the participant's perspective, as seen on the central monitor of the driving simulator. Pedestrian events were scripted and were never at risk of a collision from vehicles other than the participant's own. The pedestrian (highlighted by the red box) initially started walking out from behind an obstacle on the left sidewalk, such as a palm tree, and walked directly towards the roadway. The pedestrian continues straight across the road and is entering the driver's path, such that the driver must react (brake) to in order to avoid a collision. The pedestrian will continue across to the other side of the road without stopping and the driver may increase vehicle speed once they perceive the situation to be safe. The rear-view mirror is represented by the inset in the upper right corner of the screen shot and the digital speedometer (18 mph) is visible at the bottom center.

2.4. Pedestrian crossing hazard events

Each simulated drive scenario contained 10 scripted pedestrian hazard events, in which a pedestrian crossed from the side of the road and the driver had to use the brake to avoid a collision. Half of the crossings came from the right side and half from the left, in random order. These crossing events were designed such that they occurred on a straight section of road, were not too close to intersections or turns along the drive route, and were never at risk of a collision from vehicles other than the participant's own.

The pedestrian was initially positioned mid-way down the block behind some visual obstacle, such as a tree or phone booth, so that it was not yet visible to the driver. The pedestrian only began to move into the roadway ahead of the driver once the predicted time to the collision zone for the pedestrian at its walking speed and the driver at their current speed were equal; thus, a collision would have occurred unless the driver braked. This ensured that the crossing pedestrians always became visible to the driver between 10-15° eccentricity with respect to the car's heading.

Once the pedestrian started moving, it continued to walk straight across the sidewalk and road at a constant speed of 2.5 m/s without stopping. If the driver failed to avoid a collision during one of these pedestrian crossing events, the pedestrian model was programmed to disappear without additional visual or auditory effects to reduce any distress that might arise from a collision. An example of a pedestrian crossing event is shown in Figure 2.

2.5. Vibrotactile hazard warning device

The tactile warning device was custom-designed and consisted of a seat cover, measuring

44.4cm x 38.0cm x 3.5cm, with six vibration motors embedded within the foam cushion (three motors on the left side, three on the right) (Hölzl et al. 2021). When active, this seat cover would vibrate on either the left or right side to provide directional information to the driver regarding the position of an impending pedestrian hazard. A 500ms vibration (Summers et al. 1997) was given by the system when the predetermined warning threshold, based on the predicted time-to-collision (TTC), was exceeded.

TTC was calculated in the simulation software in real time based on the distance, velocity, and current trajectory of the pedestrian and the driver's vehicle, determining the time (in seconds) required to stop the vehicle before a collision if both continued at their current speeds (Hydén 1996). The threshold value for TTC varies depending on the scenario, and has ranged widely in prior studies (from 0.9 to 4 sec) (Mahmud et al. 2017). Lower TTCs provide smaller windows of time for which the driver can react to avoid a collision, and thus are more dangerous. A TTC of 3s was the threshold for a warning to be given in this study, ensuring a sense of urgency while still allowing sufficient time for drivers of all included neurotypes to respond to the warning and avoid a collision.

2.6. Quantifying perceived workload of the driving task

In order to compare the perceived workload of the driving task for the two warning conditions, participants were asked to complete the workload subscales of the NASA Task Load Index (NASA-TLX). These allow participants to provide a subjective yet quantitative measure of workload for the simulated driving task in the domains of mental, physical, and temporal load, the effort required, their frustration with the task, and their perceived performance (Hart &

Staveland 1988, Hart 2006). Participants were told the scale is from 0 on the left to 100 on the right (except for performance, which is reversed), with tick marks corresponding to increments of 5. They were asked to place a mark along the scale for each domain regarding their perception of the demand and difficulty of the task they just completed to provide a sense of the overall perceived workload for that task.

The subscale design was designed to reduce inter-rater variability, and can be combined with a weighting system that is specific to the task under study (Hart & Staveland 1988). A weighting system was not applied for this study, as the subscale data was more interesting for my purposes than the overall workload rating.

2.7. Study procedures

All participants who completed the study procedures did so in one visit, lasting about 2-3 hours, with breaks provided throughout. After providing informed consent, participants completed the questionnaire on demographics, ocular history, and driving history, as well as the MoCA and vision measures. Once eligibility was confirmed, participants went on to drive in the simulator. Before driving, eye-tracking was calibrated using Tobii's calibration software, then verified using custom-developed gaze validation software.

Participants first drove through an acclimatization drive, in which they started on a straight stretch of a rural road that led into a city environment, similar to that of the experimental scenarios, but without pedestrians or other vehicles. This allowed participants to practice following the GPS instructions and get a feel for the acceleration, braking, and steering of their virtual vehicle through stop signs and turns at intersections. There were additional practice drives before the experimental scenarios, adding other vehicles and pedestrians (including pedestrian crossing events) so that participants could practice responding to other traffic, crossing pedestrians, and crowds within the virtual environment. There was a posted speed limit of 30 mph (48.3 km/h), though the simulator had a speed cap implemented so participants could not exceed 35 mph (56.3 km/h).

Participants completed two drives with vibrotactile warnings and two without warnings, in a counterbalanced order. The first practice drive was without warnings and always completed immediately after the acclimatization drive. A second practice drive was completed with warnings, directly prior to the block of experimental drives with warnings. This second practice drive introduced the warning system, explained its use, and demonstrated the feeling of the vibratory warning before beginning the drive, so that participants knew what to expect.

Before each simulated drive, participants were asked to follow the normal rules of the road, avoid collisions, follow the GPS audio instructions, and to try to drive safely and similarly to how they would in the real world. They were also informed that other traffic and pedestrians may not always follow the rules of the road. Participants were informed of the 30 mph speed limit and of the built-in speed cap of 35 mph. When driving with warnings active, participants were also reminded prior to starting the drive that, like hazard systems used in real life, the device would only provide a warning if a situation started to become hazardous, but might not always work perfectly.

After the first drive block, participants took a break from the simulator and completed the NASA-TLX ratings. Participants also completed the AQ-50 and RAADS-14 during this break.

Upon completion of the second drive block, participants completed a second NASA-

TLX for that block (they were not able to see their first NASA-TLX to copy values across). Finally, participants completed one additional questionnaire (Appendix 1) to provide feedback on their experience with the vibrotactile warning system and the study overall.

2.8. Driving performance and gaze behavior data

The data collected by the driving simulator were processed in MATLAB (v2017a) (The MathWorks Inc. 2017) using software developed in-house (Swan et al. 2021) to examine measures including time to first fixation on the pedestrian, total fixation duration throughout the event window (defined as the period from the hazard's appearance in the driver's view to when it crossed the conflict area in the driver's lane), time to first brake, and number of collisions. Time to first fixation was measured from the time the pedestrian was first visible to the time the participant first made a fixation on it. Time to first brake was measured from the time the pedestrian was first visible to the time the participant first pressed the brake pedal. Collisions were defined as physical contact between the driver's virtual vehicle and a crossing pedestrian. The time at which a warning was given, or would have been given in drives without the warning system active, was also recorded for each pedestrian event where it was applicable.

The output of the MATLAB software also generated plots of gaze and pedestrian eccentricity for each pedestrian crossing event as a visual check of the data – for example, ensuring there was not excessive loss of eye-tracking data.

2.9. Statistical analysis

Statistical analyses were performed using R Statistical Software (v4.4.1) (R Core Team 2024).

A significance level of p=0.05 was applied for all statistical tests. Participant characteristics were summarized with descriptive analyses and a Kruskall-Wallis test was used to evaluate between-group differences. I analyzed each measure of response to the pedestrian hazards (time to first fixation on pedestrian, fixation duration, and time to first brake) using linear mixed-effects models (LMMs) (Bates et al., 2015). Before applying LMMs, each measure's data underwent Winsor transformation to remove extreme outliers and was checked for normality. Data not following a normal distribution underwent a reciprocal transformation, which was only necessary for time to first fixation. Residual diagnostics confirmed that the transformations normalized the residuals. All models included warning condition (without warnings or with warnings) and autistic trait group (non-ASD, low-ASD, or high-ASD) as main factors. Hazard event number and participant ID were also introduced as random factors to account for variance from individual differences and the scripted pedestrian scenarios.

Only safety-critical events – hazard events in which a warning was triggered (with-warnings condition), or would have been triggered when the warning device was not active (without-warnings condition) – were included in the analysis of gaze behaviors and hazard responses. Accordingly, the without-warnings condition included 152 (69.1%), 141 (70.5%), and 133 (66.5%) hazard events for non-, low-, and high-ASD, respectively. The with-warnings condition included 141 (64.1%), 138 (69%), and 124 (62%) hazard events, respectively. Thus, 829 critical events were included in the analysis, out of 1240 total events.

Correlation analysis was run for the response measures used in the LMMS, with summed autistic trait score as the effect, but was not significant for any of the three variables.

3. Results

3.1. Participant characteristics

The three trait-level groups did not differ in age, vision measures, or MoCA score, nor did the median number of days driven in a typical week, number of miles driven in a typical week, and total number of types of driving situations avoided differ significantly across the three groups (Table 1). As expected based on my grouping criteria, there were significant differences in scores on both the AQ-50 and RAADS-14; scores on each questionnaire were lowest in the non-ASD group and highest in the high-ASD group, and the same pattern was observed for the sum of their autistic trait scores (AQ-50, RAADS-14, and summed score all $p<0.001$; Table 1). Visual inspection of the data suggests that the high-ASD group avoided driving in more situations than the non-ASD and low-ASD groups (median: 3.5 vs 1 and 2 situations), and the interquartile range of the number of driving scenarios avoided increased with autistic trait category; however, the between-group differences in the total number of driving situations avoided were not statistically significant ($p=0.17$).

Table 1.

Participant characteristics by autistic trait level.

Characteristics	**Non-ASD** (n = 11)	**Low-ASD** (n = 10)	**High-ASD** (n = 10)
Age (years), median (IQR)	24 (22-28)	26 (22-46)	27 (21-30)
VA (logMAR), median (IQR)	-0.14 (-0.20 - -0.07)	-0.11 (-0.21 - 0.00)	-0.17 (-0.19 - -0.09)
CS (logCS), median (IQR)	1.92 (1.89-1.99)	1.96 (1.84-2.08)	2.03 (1.69-2.15)
MoCA score (out of 30), median (IQR)	28 (27-29)	29 (28-30)	30 (27-30)
AQ-50 score (out of 50), median (IQR)	15 (9-19)	25.5 (22-28)	33 (31-37)
RAADS-14 score (out of 42), median (IQR)	9 (4-11)	21.5 (20-24)	33 (32-34)
Summed autistic trait score (out of 92), median (IQR)	26 (12-31)	48 (37-53)	67 (61-71)
Years since licensure, median (IQR)	7 (6.0-8.5)	6.5 (5.0-13.3)	9 (5.0-12.0)
Number of days driven in a typical week, median (IQR)	3 (1.3-5.0)	4.5 (3.0-6.0)	3 (1.5-4.8)
Number of miles driven in a typical week, median (IQR)	30 (12.5-99.6)	52.5 (22.5-107.9)	42.5 (21.3-66.9)
Number of driving situations avoided, median (IQR)	1 (0.0-1.5)	2 (1.0-3.0)	3.5 (0.3-4.0)
Self-rated driving ability (1-10), median (IQR)	7 (7.0-8.5)	8 (7.0-8.8)	7 (6.3-8.0)

IQR = interquartile range, VA = visual acuity, MAR = minimum angle of resolution, CS = contrast sensitivity, MoCA = Montreal Cognitive Assessment, AQ-50 = Autism-spectrum Quotient, RAADS-14 = Ritvo Autism & Asperger Diagnostic Scale (revised and abridged version).

3.2. Fixation behavior during pedestrian hazard events

Without warnings, the non-ASD, low-ASD, and high-ASD groups did not significantly differ in their time to first fixation on pedestrian hazards (mean 0.87s, 1.01s, 0.93s respectively). However, when driving with warnings, the low-ASD group took significantly longer to fixate on the pedestrian hazards than the non-ASD group (mean 1.47s vs 0.92s; interaction p=0.042) and the high-ASD group (mean 1.47s vs 0.93s; interaction p=0.045; Figure 3 - left). There were similar patterns for the fixation duration measurement. Specifically, non-ASD, low-ASD, and high-ASD did not significantly differ when driving without warnings (mean 2.81s, 2.53s, 2.71s respectively). However, with warnings, the low-ASD group fixated the pedestrian for significantly less total time throughout the event window than the non-ASD group (mean 2.26s vs 2.85s; interaction p=0.016) and the high-ASD group (mean 2.26s vs 2.78s; interaction p=0.046; Figure 3 - right). When driving with warnings, the time to first fixation and fixation duration on pedestrians did not significantly differ between the non-ASD and high-ASD groups.

Although the average of each fixation measure did not differ between the high-ASD and non-ASD groups, a manual review of individual pedestrian hazard events across all participants revealed that certain participants, in the high-ASD group only, showed distinct and unique patterns during drives without warnings. For example, one participant (AQ-50 score 33, RAADS-14 score 27) mostly looked straight ahead toward the distant roadway, with occasional scans to the pedestrian, but seldom to other peripheral areas of the roadway (Figure 4A). Another high-ASD participant (AQ-50 score 36, RAADS-14 score 32) frequently shifted their fixation between the pedestrian and the straight-ahead roadway and its immediate surrounding environment (Figure 4B). A third participant (AQ-50 score 33, RAADS-14 score 33) in this group fixated almost exclusively on the hazardous pedestrians during each event, with hardly any scans to other areas of the roadway (Figure 4C). When hazard warnings were introduced, these three participants maintained these patterns. Only one high-ASD participant (AQ-50 score 32, RAADS-14 score 38) showed any obvious changes from drives without warnings to drives with warnings. When driving without warnings, this participant looked primarily straight ahead with occasional scans to the pedestrian hazards but hardly any glances to the other areas of the roadway, but when driving with warnings, there was more frequent fixation on the pedestrian hazards and more fixations to the other areas of the roadway, becoming more like the gaze behavior of the non-ASD and low-ASD participants.

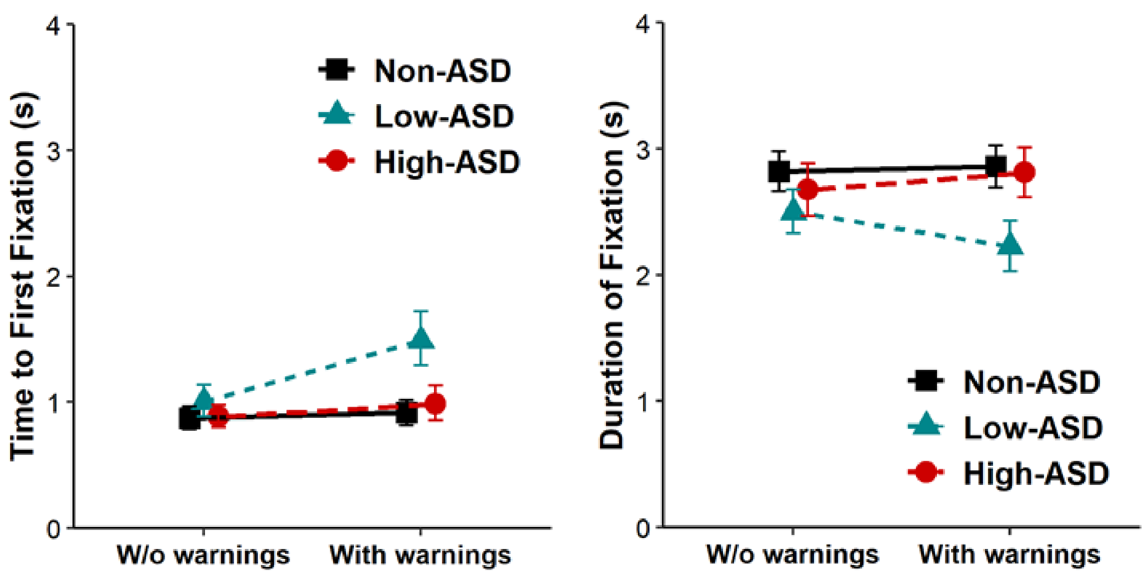

Figure 3.

Mean time taken to first fixate (left) and mean total fixation duration throughout the event window (right) on the pedestrian hazard by each group in the without-warnings versus with-warnings conditions. Errors bars represent standard error of the mean (SEM).

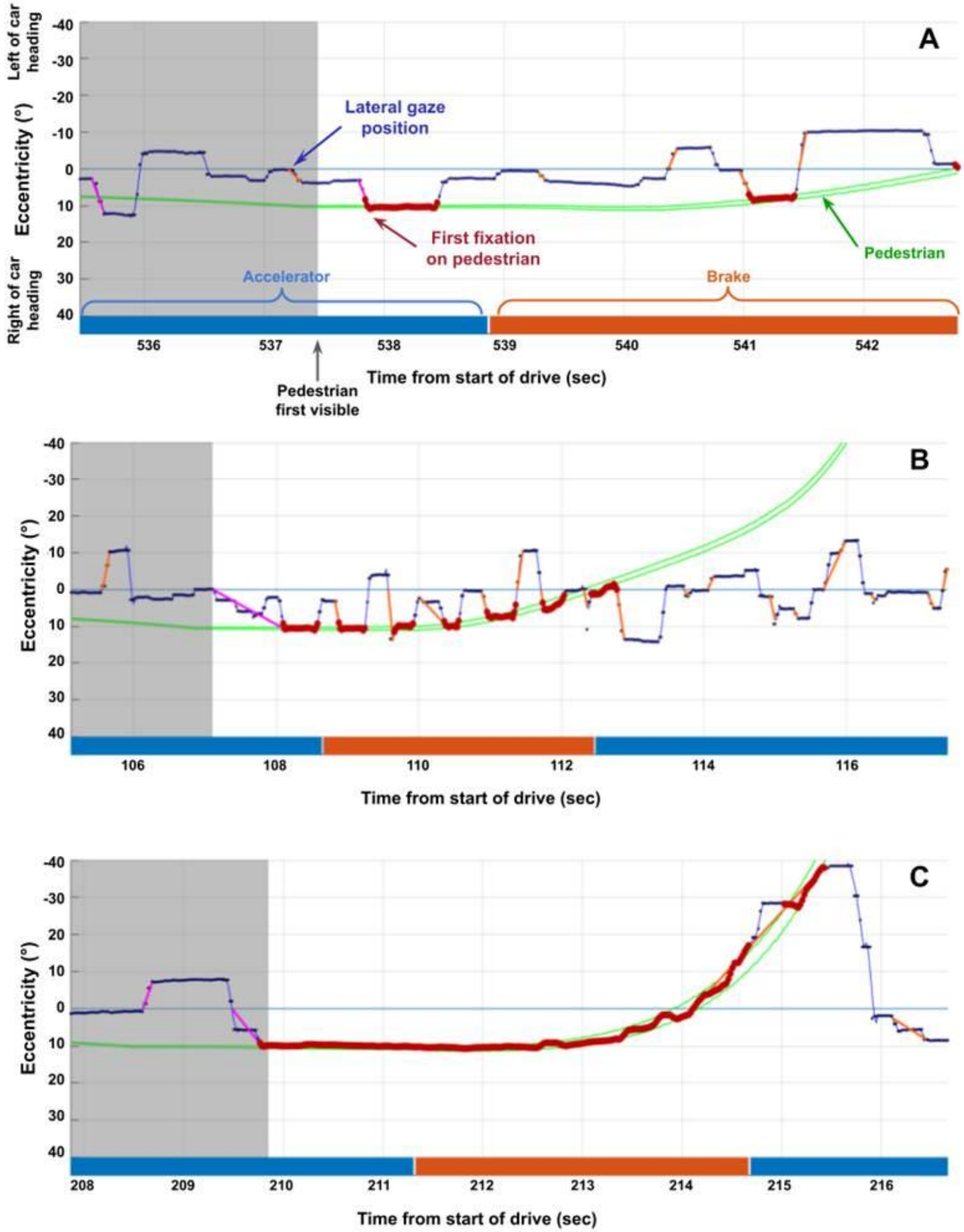
A
Left of car heading
Right of car heading
Eccentricity (°)
Lateral gaze position
First fixation on pedestrian
Pedestrian
Accelerator
Brake
Pedestrian first visible
Time from start of drive (sec)
B
Eccentricity (°)
Time from start of drive (sec)
C
Eccentricity (°)
Time from start of drive (sec)

Figure 4.

Sample event plots of high-ASD drivers. The x-axis shows the time from the start of the experimental drive (sec) and y-axis shows the eccentricity (degrees) from the heading of the participant's virtual car. The green line shows the eccentricity of the pedestrian as they walk across the road. The pedestrian is initially hidden from the driver's view by an obstacle, such as a tree, which is shown by the grey shading over the start of the event window. The driver's horizontal gaze position is shown with the dark blue line, and highlighted in red when overlapping with the eccentricity of the pedestrian. The bars at the bottom of each plot show the driver's inputs for the accelerator pedal (blue bar) and brake pedal (orange bar). A. This high-ASD driver fixates on the pedestrian hazard quickly, but only maintains fixation on the pedestrian for two short spans, and is otherwise looking mostly straight ahead or within 10 degrees eccentricity during the hazard event. B. Another high-ASD driver who also fixates on the pedestrian hazard quickly, but makes many changes in fixation between the pedestrian and areas of the road, both straight ahead and within about 10 degrees eccentricity, until the pedestrian has crossed the road and is out of the way. C. A third high-ASD driver, who happened to be looking towards the area in which the pedestrian was hidden, and fixates on the pedestrian immediately once it becomes visible. This driver "stares down" the pedestrian throughout the event window, maintaining fixation even for a short duration after the pedestrian has crossed in front of the vehicle.

3.3. Brake responses and collisions during pedestrian hazard events

Brake response times did not differ among the non-ASD, low-ASD, or high-ASD groups when driving without warnings (mean 1.74s, 1.73s, 1.79s respectively). I found a significant interaction between the low-ASD and high-ASD groups. Specifically, the brake response times of the high-ASD group did not differ between driving with and without warnings (mean 1.79s vs 1.76s respectively). However, the low-ASD group took significantly longer to initiate brake responses to the hazards when driving with warnings than when driving without warnings (mean 1.85s vs 1.73s, interaction p=0.001; Figure 5). The non-ASD group also took longer to brake when driving with warnings than without (1.86s vs 1.74s, interaction p=0.006).

Throughout the 1240 pedestrian hazard events in the full dataset, collisions with the pedestrian only occurred in four events, all of which were during drives without warnings: one collision occurred in the low-ASD group, and three occurred in the high-ASD group.

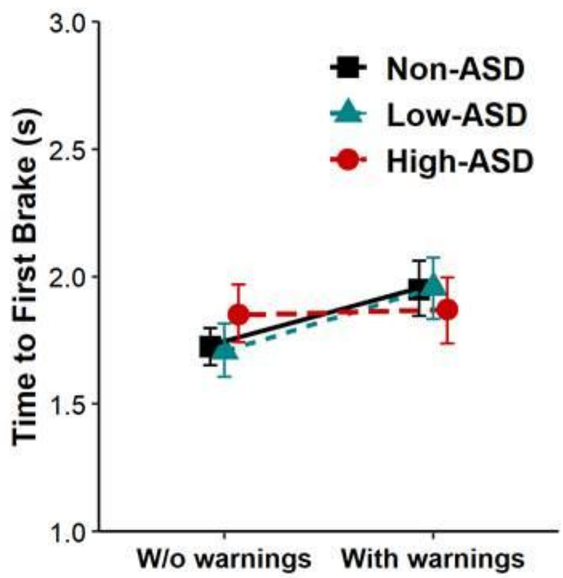

Figure 5.
Mean time taken to initiate a brake response to the pedestrian hazard by each group in the without-warnings versus with-warnings conditions. Error bars represent SEM.

3.4. Perceived workload while driving

Median group ratings for each NASA-TLX subscale of perceived workload were determined for both driving without warnings and driving with warnings (Appendix Table 1). The subscales of mental demand, physical demand, temporal demand, performance, and effort, and the total across subscales were not significantly different between groups or between warning conditions. However, there was a significant between-group difference for the frustration subscale when driving with warnings, in which the high-ASD group rated their frustration with completing the driving task during the experiment significantly higher than the other two groups (median: high-ASD 35 vs non-ASD 10, low-ASD 7.5; Kruskal-Wallis $p=0.007$; Figure 6). High-ASD participants also rated their frustration higher than the other two groups in drives without warnings, but this did not quite reach statistical significance (median: high-ASD 37.5 vs non-ASD 15, low-ASD 15; $p=0.066$; Figure 6).

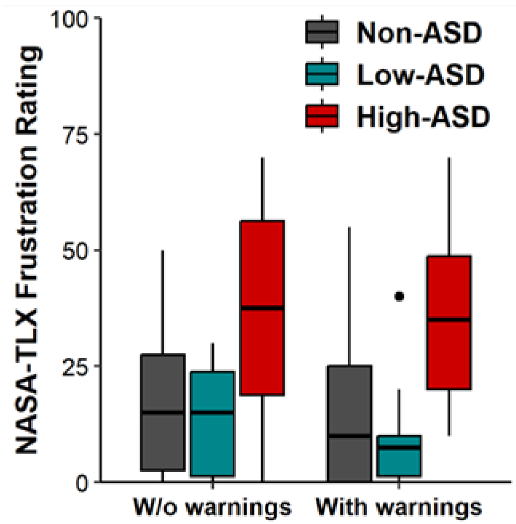

Figure 6.

Boxplots of ratings on the frustration subscale of the NASA-TLX for the three groups when completing the driving task without warnings and with warnings. Thick black line represents group median, box extent represents interquartile range (IQR). Upper ends of whiskers represent largest values within 1.5 times IQR above 75th percentile. Lower ends of whiskers represent smallest values within 1.5 times IQR below 25th percentile.

3.5. Subjective feedback on hazard warnings

Participants' subjective feedback on the vibrotactile hazard warning system used during the study are summarized in Appendix Table 2. Most participants across all three groups were satisfied with both the duration of the vibrations and the overall frequency of warnings received during each drive. Regarding the intensity of the vibration, 91% of non-ASD and 70% of low-ASD participants found it "ideal." However, opinions within the high-ASD group were more divided: 40% felt it was "too intense" and 50% found it "ideal."

When asked about how irritating the vibrations were, 73% of non-ASD participants responded “not at all,” compared to 30% of low-ASD and 40% of high-ASD participants. In contrast, 30% of high-ASD participants found the warnings “extremely” or “very” irritating, vs 0% of non-ASD and 10% of low-ASD participants ($p=0.08$).

Perceptions of the usefulness of the directional information provided by the directional vibrational warning varied. While 55% of non-ASD and 60% of high-ASD participants rated this feature as “extremely” or “very” useful, only 30% of low-ASD participants shared this view. Additionally, 50% of the low-ASD group found the directional warnings “slightly” or “not at all” useful, compared to 27% of non-ASD and 20% of high-ASD participants. Interestingly, follow-up responses revealed that most non-ASD and low-ASD participants reported they did not actually use the directional information provided by the warnings to identify hazards, while the majority of high-ASD participants reported that they did use it. Overall, more high-ASD participants found the hazard warning system useful (70%) than did non-ASD (54%) or low-ASD (50%) participants.

4. Discussion

Unlike many prior studies that used a binary comparison between participants with and without diagnoses of ASD (Sheppard et al. 2010, Sheppard et al. 2017, Reimer et al. 2013, Patrick et al. 2020), I stratified participants into low- and high-ASD groups based on their summed AQ-50 and RAADS-14 scores and compared them with a non-ASD trait-level group. While not the first to examine certain characteristics associated with autism (such as executive functions and theory of mind) in both ASD and non-ASD drivers (Patrick et al. 2020, Cox et al. 2016, Ross et al. 2019, Plunk et al. 2024), the autistic trait scores more broadly encompass the degree to which someone may struggle with any of the domains that can be affected, providing a more detailed representation of the spectrum of presentations of autism. I found that the three groups did not differ in their driving exposure (frequency or amount driven weekly).

Some prior studies utilizing driving simulators have shown that for novice drivers, participants with ASD exhibited poorer performance on a number of driving skills compared to neurotypical peers (Classen et al. 2013, Cox et al. 2016); others have shown comparable driving simulator performance between ASD and non-ASD novice drivers (Bishop et al. 2017, Ross et al. 2019, Plunk et al. 2024). Non-driver ASD participants also exhibited delayed first fixation times and overall reaction times to social hazards in a desktop-based driving hazard perception task with pre-recorded driving videos and button press responses (Sheppard et al. 2017). However, in driving simulator studies, reaction times of novice ASD drivers did not differ from those of matched non-ASD participants (Bishop et al. 2017, Ross et al. 2019). In the present study, comparing current, licensed drivers in drives without hazard warnings, I found no significant differences between the two ASD groups and the non-ASD group in terms of the time to first fixate on or to initiate a brake response to pedestrian hazards in driving scenarios. These differences between the present findings and prior studies (Classen et al. 2013, Cox et al. 2016, Sheppard et al. 2017) may be due to different participant characteristics and the driving task used. All participants in the present study had achieved driving licensure and had at least one year of post-licensure driving experience, similar to the recruitment criteria of Bishop et al. 2017, who also found no differences between ASD and non-ASD for time to react to social hazards. This is in contrast to recruitment of unlicensed or inexperienced ASD participants in other prior studies (Classen et al. 2013, Cox et al. 2016, Sheppard et al. 2017), which each reported various deficits of their ASD groups in orienting visual attention to appropriate areas of driving simulations or videos. The drivers in the present study had likely developed strategies to drive and compensate (when possible) for difficulties they might experience from their autism.

Considering differences in the driving task across studies, the present work's driving task and those used in similar driving simulator studies (Reimer et al. 2013, Classen et al. 2013, Cox et al. 2016, Bishop et al. 2017, Patrick et al. 2020, Ross et al. 2019, Plunk et al. 2024) were more representative of real-world driving than the hazard perception task used by Sheppard et al. (2017), where participants did not have to control vehicle speed or steering. However, the driving task in the present study was not overly taxing of cognitive resources, as evidenced by the relatively low perceived workload scores on the NASA-TLX (Appendix Table 1). Differences between ASD and non-ASD behaviors may emerge in driving tasks with higher cognitive loads, such as findings from studies incorporating working memory tasks (Cox et al. 2016) and increased attentional demands (Reimer et al. 2013), where ASD participants demonstrated reduced visual attention to the roadway, which has the potential to compromise hazard detection. Additionally, while some research has shown ASD individuals to have longer times or decreased preference to first fixate on social hazards (e.g. pedestrians) and attributed this to reduced prioritization of social stimuli (Fletcher-Watson et al. 2009, Freeth et al. 2010), the present study found no such deficit despite the use of pedestrian hazards. This discrepancy could again reflect the present work's cohort of experienced drivers with high-functioning/low support needs autism or the driving simulator, where pedestrian hazards may not fully replicate real-world social interactions or urgency, reducing the need for social cue prioritization.

Prior research evaluating neurotypical participants found different visual behaviors when hazards are present than without hazards. These studies showed prolonged fixation durations on hazards (versus other areas of the roadway) and narrowed visual search patterns (Chapman & Underwood 1998a, 1998b; Underwood et al. 2011), which can be affected by visual clutter and the cognitive load of the driving task (Lee et al. 2009). While my group-level analysis revealed no differences in total fixation duration within the event window between the ASD and non-ASD groups, some individual high-ASD participants exhibited distinct and unique gaze behavior patterns during the hazard events: some maintained continuous fixation on hazards (e.g. Figure 5C), while others alternated their visual attention between hazards and the environment (e.g. Figure 5B), and such distinctive individual gaze patterns were not present in the low-ASD group. This underscores the importance of individual variability in driving behavior of those with ASD, suggesting that subgroup analyses or personalized assessments may better capture their behavioral characteristics than when analyzed as a whole group contrasted against neurotypicals.

In terms of subgroup analyses in the current study, the trait-level groups demonstrated different behavioral responses to vibrotactile hazard warnings. The high-ASD group did not show significant changes in their gaze or braking behavior (i.e. fixation latency and duration to the pedestrian, time to brake in response to the pedestrian) when driving with warnings. Importantly though, their number of collisions with pedestrians decreased compared to their drives without warnings. This difference in collisions was greater for the high-ASD group than the other two groups (high-ASD 3 vs 0, low-ASD 1 vs 0, non-ASD 0 vs 0). The lack of changes in the high-ASD group for the parameters measured likely represents a stronger influence of cognitive inflexibility and repetitive behaviors, which are outlined as one of the symptom domains for ASD in the DSM-5, and have been shown to be associated with higher autistic trait scores (Zhou et al. 2024). Less cognitive flexibility and more difficulty with task-switching in this group may also be the source of higher frustration ratings in this group, as the driving task without pedestrians is rather monotonous, but the pedestrian hazards constantly interrupt the drive and force the participant to shift their behavior. Cognitive rigidity in this group is also supported by the unique and repetitive gaze behaviors shown by certain individuals in this group as discussed above.

In contrast, the low-ASD group demonstrated clear behavioral changes when driving with warnings: they took longer to fixate, spent less time fixating, and were slower to brake in response to the pedestrian than when they drove without warnings. Having fewer autistic traits, it may be that this group demonstrated more cognitive flexibility than the high-ASD group, such as a greater willingness to rely on the warning system to offload one aspect of the driving task to the device. The delayed visual orientation and braking to the pedestrian by low-ASD participants when driving with warnings suggests that they may have been waiting for the tactile cue to alert them to the hazard before taking action. While this shows more adaptability than the high-ASD group, it may also highlight a risk of over-reliance.

Lastly, the non-ASD group was also slower to brake when driving with warnings than without, but their gaze behavior did not change. This suggests they may have relied on the device to some extent for alerting them to crossing pedestrians, though this reliance influenced only their timing of action (braking) rather than relaxing their attention to the visual environment. Similar to the low-ASD group, non-ASD participants were slower to brake when driving with warnings, without clear evidence of reduced safety. However, their visual strategies differed. The non-ASD participants maintained their baseline gaze behavior (without warnings), likely treating warnings as supplementary reminders while preserving their usual level of visual monitoring. In contrast, the low-ASD group showed reduced visual engagement (later and shorter fixations on hazards), suggesting that they may rely more on automation for hazard detection, therefore investing less effort in active visual monitoring.

4.1. Limitations

This study represents my initial efforts in exploring driving performance in the autistic population. As such, several limitations should be considered when interpreting the results. The requirement to be a licensed and current driver made recruitment somewhat challenging (particularly in Boston where many people utilize public transit), resulting in a relatively small sample size in each group. Moreover, ASD confirmation and classification were based solely on self-report and questionnaire results. Validation by an independent clinician could offer an additional assessment of participants' current presentation of autism, providing more detailed data to aid in the interpretation of results. Additionally, the participants in the present ASD cohort likely only reflect the high-functioning/low support needs portion of the much larger autistic community; however, this sample is representative of current drivers with ASD. Finally, only one type of hazard was implemented (a pedestrian crossing midway down a block) as well as only one type of advanced driver assistance system (vibrotactile pedestrian hazard warning system).

4.2. Future directions

Future research is needed to understand how different presentations of autism affect visual behaviors and driving safety performance both in simulated driving and real-world, on-road conditions (Chee et al. 2017, Cox et al. 2020). In the present study, I found distinctive gaze patterns for some individuals in only the high-ASD group. However, with the current sample size, it is difficult to discern whether these patterns represent group-level differences or individual variability; with a larger sample, clearer group patterns may emerge. If such patterns were confirmed, the relationship between gaze behavior and hazard responses could be examined more directly, particularly in more cognitively demanding driving situations. Identification of fixational patterns that are associated with poorer hazard response performance may be useful in providing feedback to novice drivers in customized driver training programs to help improve their safety.

Interviews of specialized driving instructors have emphasized that novice ASD teen drivers are all unique, and that training should be very individualized to target each individual's challenges and strengths (Myers et al. 2021). Several studies have emphasized individuality in driver training programs for young autistic people and those with intellectual disabilities, findings that adjusting programs to work with each participant's strengths and address their weaknesses with direct, individualized feedback generally yields the best success and enjoyment Myers et al. 2021, Baker-Ericzén et al. 2021, Bian et al. 2013, Wade et al. 2016, Bian et al. 2019, Randall et al. 2021).

Future work in this area might consider utilizing a hazard warning device as a more integrated method to provide live feedback to autistic people learning to drive. Integration of a hazard warning system with training programs such as those utilized in the aforementioned studies may help to demonstrate safe versus unsafe driving in real time, and can help novice autistic drivers to learn what speeds and distances are safe to prevent collisions. It is also important to study the effects of driver assistance systems in diverse populations as they continue to grow in availability and popularity among standard vehicles. While these systems have the potential to increase safety in many populations, there is also a risk of over-reliance on this technology that could lead to poorer driver safety in the event these systems fail.

Additional considerations for future work might include a larger sample and clinical confirmation of ASD diagnoses to better support the stratification method. Future studies in the driving simulator could implement a wider range of hazard types, such as motorcycles, other traffic, or unexpected objects posing obstacles in the roadway to assess how hazard detection and collision avoidance, as well as responses to hazard warnings, might differ. Other types of hazard warnings (e.g. heads-up displays or auditory warnings) and other types of advanced driver assistive systems (e.g. lane-keep assist) should also be considered for study with the autistic driving population, as many of these features are increasingly commonplace in real-world vehicles.

4.3. Conclusions

To my knowledge, this was the first study exploring the effects of autistic trait levels on gaze fixation behaviors and pedestrian hazard responses in a population of licensed drivers in a driving simulator. I grouped participants by their amount of autistic traits rather than by diagnosis alone, and found distinctions between the low-ASD and high-ASD group, which may not have been detected had a binary classification of non-ASD vs ASD been used. The inclusion of licensed, active drivers with ASD also provides new insights, as their driving behavior and hazard responses may differ from those of unlicensed or naive driver populations that have been previously studied. I also explored the potential effects of implementing an advanced driver assistance system on ASD drivers, with both objective and subjective metrics. Introducing hazard warnings in this tactile stimulus did not increase the perceived workload or negatively affect the driving performance of low-ASD participants. While drivers in the high-ASD group were less likely to adjust their behavior in response to the warning system and may have felt frustrated or irritated while using it, they benefited the most in terms of collision avoidance.

As we continue to learn more about autism and its prevalence increases, it will be important to understand potential challenges to safety and independence that face this population and what resources will be the most useful and effective to support safe driving. The potential benefits and limitations of in-vehicle advanced driver assistance systems should continue to be evaluated while accounting for the individual's presentation of autism.

4.4. Acknowledgements

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Appendix 1.

Exit questionnaire for feedback on the driving simulator and vibrotactile hazard warning system.

1. **How would you assess the <u>intensity</u> of the vibrational warning?**
   ___Too high ___Somewhat high ___Ideal ___Somewhat low ___Too low

2. **How would you assess the <u>length</u> of the vibrational warning?**
___Too long ___Somewhat long ___Ideal ___Somewhat short ___Too short

3. **How irritating were the warnings from the assistance device?**
___Extremely ___Very ___Moderately ___Slightly ___Not at all

4. **The number of times a vibrational warning was given was…**
___Too often ___Somewhat too often ___About right ___Somewhat little ___Too little

5. **The timing of the vibrational warning was…**
___Too early ___Somewhat early ___Ideal ___ Somewhat late ___ Too late

6. **Is there anything you would like to improve or change about the vibrational warning design you just experienced? Any comments?**

____

____

____

7. **From your understanding, in what situations was a warning given?**

____

____

8. Did you change your driving behavior because of the warning?

___To a great extent ___Somewhat ___Not Sure ___Very little ___Not at all

9. In what way(s) was your driving behavior influenced by the assistive device?

____

____

____

10. The vibrational warning system you tried provided information about the side from which the hazard was approaching. How useful did you find this directional information?

___Extremely useful ___Very useful ___Moderately useful ___Slightly useful

___Not at all

11. Did you actually use the directional information from the warnings to identify the hazards?

___ Yes ___ No ___ Not sure **If so, how?______**

____

____

12. Any other comments about the directional warning information design?

____

____

____

13. Overall, how helpful did you find the assistance device warnings?

___Extremely ___Very ___Moderately ___Slightly ___Not at all

14. Other than the warning design you just experienced in this study, is there any other type of warning design you would prefer while driving? If so, please specify:

____

____

15. Additional feedback?

____

____

____

Appendix Table 1.

Median (interquartile range) of each NASA-TLX subscale (rated from 0-100) and total across subscales (0-600) for each group and warning condition.

NASA-TLX subscale, median (IQR)	**Non-ASD** (n = 11)		**Low-ASD** (n = 10)		**High-ASD** (n = 10)	
	Without warnings	With warnings	Without warnings	With warnings	Without warnings	With warnings
Mental demand	25 (15.0-52.5)	30 (20.0-40.0)	40 (17.5-73.8)	35 (26.3-63.8)	55 (18.8-60.0)	50 (45.0-58.8)
Physical demand	30 (0.0-30.0)	10 (0.0-27.5)	25 (11.3-33.8)	20 (8.8-46.3)	30 (20.0-38.8)	30 (21.3-35.0)
Temporal demand	10 (0.0-17.5)	10 (0.0-22.5)	7.5 (0.0-20.0)	7.5 (1.3-35.0)	17.5 (11.3-30.0)	22.5 (16.3-28.8)
Performance	90 (80.0-90.0)	90 (75.0-92.5)	92.5 (82.5-98.8)	95 (90.0-98.8)	82.5 (76.3-90.0)	82.5 (80.0-88.8)
Effort	20 (12.5-40.0)	25 (12.5-45.0)	17.5 (0.0-28.8)	25 (20.0-37.5)	27.5 (25.0-48.8)	45 (21.3-55.0)
Frustration	15 (2.5-27.5)	10 (0.0-25.0)	15 (1.3-23.8)	7.5 (1.3-10.0)	37.5 (18.8-56.3)	35 (20.0-48.8)
Total across subscales	220 (127.5 - 232.0)	150 (137.5 - 230.0)	210 (153.8 - 243.8)	182.5 (158.8 - 280.0)	265 (195.0 - 306.3)	290 (222.5 - 320.0)

Appendix Table 2.

Participant feedback on the vibrotactile warning device and its usefulness during the simulated drives. P-values are across group Kruskal-Wallis testing.

Item	Rating	Non-ASD (n = 11)	Low-ASD (n = 10)	High-ASD (n = 10)	p-value
Intensity of vibration	Somewhat high / too high	9%	30%	40%	0.53
	Ideal	91%	70%	50%	
	Somewhat low / too low	0%	0%	10%	
Duration of vibration	Somewhat long / too long	27%	20%	20%	0.75
	Ideal	73%	70%	80%	
	Somewhat short / too short	0%	10%	0%	
Irritation with vibration	Extremely / very	0%	10%	30%	0.08
	Moderately / somewhat	27%	60%	30%	
	Not at all	73%	30%	40%	
Frequency of vibration	Somewhat often / too often	18%	0%	30%	0.35
	About right	55%	80%	60%	
	Somewhat little / too little	30%	20%	10%	
Impact of warnings on driving behavior	To a great extent / somewhat	36%	50%	50%	0.64
	Not sure	0%	0%	10%	
	Very little / not at all	64%	50%	40%	

Usefulness of directional information	Extremely / very	55%	30%	60%	0.23
	Moderately	18%	20%	20%	
	Slightly / not at all	27%	50%	20%	
Overall usefulness of warning system	Extremely / very	27%	30%	20%	0.81
	Moderately	27%	20%	50%	
	Slightly / not at all	45%	50%	30%	