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Automated Driving Systems' Communication of Intent With Shared Road Users

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16.Abstract

This project explored shared road users' potential needs for information about Automated Driving Systems' (ADS) intent and developed preliminary laboratory testing procedures for assessing external human-machine interface (eHMI) designs for communicating the intent of ADS-equipped vehicles. In Study 1, researchers interviewed driving instructors to determine the most important visual and auditory cues predicting driver actions in specific traffic scenarios. In Study 2, drivers, pedestrians, and bicyclists participated in field studies on public roadways while verbally commenting about the actions and anticipated actions of nearby vehicles. Study 3 introduced a preliminary laboratory method to assess prototype eHMI designs. All trials used a single unsignalized crosswalk, only one approaching vehicle, and no other pedestrians present. Results show that participants generally recognized that an eHMI indicated the vehicle was self-driving, and if the vehicle yielded, participants indicated that they perceived the vehicle had recognized their presence, even before the meanings of the interfaces had been explained to them. Results showed that the preliminary lab method showed promise in potentially differentiating between different eHMIs for the single specific scenario involving a relatively simple crosswalk case; however, the generalizability of findings is not claimed.

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Executive Summary

This research contributes to understanding the potential safety impact of interactions between vehicles equipped with Automated Driving Systems (ADS) and shared road users.[1] Throughout this report, the term "ADS vehicle" refers to a vehicle equipped with an ADS and has ADS engaged.

While ADSs have the potential to provide safety benefits, they also can change the driving environment in certain ways, including in the way human drivers and other road users communicate in the current traffic environment. Less formal communications occur between drivers that often involve taking turns, granting permission, and acknowledgments of presence. Direct observation of drivers may also allow other road users to anticipate another driver's level of awareness of objects in the roadway or anticipate the next maneuver. Some of this type of information exchange may be affected with the introduction of high levels of automated control, where a person is either not present or not directly involved in the dynamic driving task (DDT).

The project described in this report included three related studies:

- Study 1: Structured Interviews of Driver Evaluation Experts
- Study 2: Field Observations of Cues Used by Drivers, Pedestrians, and Bicyclists to Predict Intent of Drivers
- Study 3: Testing External Signaling System Concepts

Study 1: Structured Interviews of Driver Evaluation Experts

The goals of Study 1 were to identify and characterize the various signals and cues normally exchanged among road users under manual control conditions. With this information we might establish an understanding about how automation could affect the ability of road users to anticipate and interact with driving automation systems and perhaps identify what information might be replaced by new vehicle-signaling systems and/or maneuvering behaviors for vehicles equipped with ADSs.

To understand the nature of communication between road users, 10 experts in driving evaluation and training were recruited to provide feedback during a structured interview in which they were asked to characterize all communication that might occur between a driver and another road user in nine roadway scenarios. For each signal or cue they reported, the interviewer asked the interviewee to judge the relative prevalence of the cue and the relative difficulty in understanding it in daylight and darkness.

Participants identified 19 specific cues. Researchers broadly categorized each cue or signal source as

- an observed behavior,
- an observed signal state,
- an observed movement of a vehicle,
- or a direct communication of intent (a verbal message).

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[1] ADS refers to the SAE International definition of driving automation, specifically levels 3- to 5 where the system monitors the driving environment under certain or all driving circumstances. www.sae.org/standards/content/j3016_202104/

Cue and signal descriptions were also condensed into one of 18 thumbnail descriptions that identified whether the cue:

a) referred to a driver/vehicle or another road user,
b) was an explicit (i.e., an overt attempt to communicate) or implicit (i.e., inferred by the observer) cue, and
c) the modality (i.e., visual or audible) of the cue.

Survey responses that referred to drivers and vehicles were analyzed separately from those that referred to other road users (who presumably will not be displaced by automation).

Experts identified driver behavioral cues in more than half of the parking lot, four-way-stop, and pulling-into-traffic scenarios. They mentioned more vehicle-movement cues around congested pedestrian areas, crosswalks, and bicyclists, suggesting a vulnerable-user perspective in which vehicle movement might be perceived as the most significant threat. For higher-speed roadway scenarios (e.g., merges, lane changes), experts identified use of explicit signals (signal lamps, horn) as often as vehicle movement and driver behavior. Direct verbal exchanges were mentioned only in congested pedestrian areas and crosswalk scenarios, where speed is low and proximity to other road users is small—conditions conducive to verbal communication.

Mention of some types of explicit and implicit cues also varied with scenario. There were twice as many explicit cues versus implicit cues mentioned in a four-way-stop scenario. A scenario involving vehicles pulling into traffic produced more reports of implicit driver behavior cues, possibly because explicit gestures may be less effective when drivers are facing the same direction. Reports of implicit cues were also proportionally higher in freeway merge conditions and high-speed lane changes.

Participants rated cues with respect to their commonality and detectability. Rated detection difficulty of cues was systematically higher in darkness than in daylight. In particular, experts rated visual cues related to vehicle movement or driver behavior as more difficult to detect in darkness.

Participants who mentioned cues that were associated with other road users (i.e., non-drivers) largely focused on implicit behavioral cues such as body movement and gaze direction, although explicit use of gestures was also noted. In the case of bicycles, participants mentioned movement of the bicycle as a cue. As with the cues associated with drivers, the rated detection difficulty of cues associated with non-drivers' behavior was systematically higher in darkness than in daylight.

Scenarios that are most dominated by behavioral cues produced by drivers are likely to be most affected by conditions in which a driver is no longer present in the vehicle, or in circumstances where an individual in the vehicle is mistaken for being the driver. These scenarios include parking lot, four-way-stop, pulling-into-traffic, and congested pedestrian area scenarios: primarily low-speed areas where road users are present in relatively close proximity. Other scenarios in which there is prominent mention of cues related to vehicle movements may also be affected by automation, but this is less certain since it is currently unclear how ADS vehicle movements will differ from driver-controlled vehicle movements.

Study 2: Field Observations of Cues Used by Drivers, Pedestrians, and Bicyclists to Predict Intent of Drivers

The objective of Study 2 was to determine the key pieces of information that other road users need from vehicles to be able to identify their intent. This study focused on identifying the communication cues that pedestrians, bicyclists, and drivers use to predict the actions of other vehicles (and intent of their drivers) in many situations where traffic interactions take place.

Forty participants were recruited and trained to perform think-aloud commentary procedures while engaged in travel through intersections, merge lanes, parking lots, and other locations where interactions between road users occur. Participants included shared road user subgroups of bicyclists (n=12), pedestrians (n=16), and automobile drivers (n =12). Each participant was equipped with video and audio recording cameras that captured video data in the general direction where the participant was looking. Researchers instructed participants to report on their perceptions of vehicles and drivers, and to talk through their decision-making process with regard to choosing when and how to proceed through traffic. The emphasis was on reporting all of the cues from other vehicles and drivers that they use for making these decisions.

Data collection took place over two sessions. A researcher supervised the first session, and the second session was conducted as naturalistic, unsupervised travel. In the first session (supervised phase), the participant interacted with other traffic in a set of predefined scenarios at specific locations along a predefined route. The included traffic scenarios (such as four-way stop sign controlled intersections) where road user to road user communication of intent is useful to avoid or resolve conflicts. In the second session of data collection (naturalistic, unsupervised phase), participants recorded one hour of video commentary data as they traveled by the mode specified in their subgroup (bicyclist, pedestrian, automobile) anywhere that they choose to go on public roads.

Video and audio data recorded during both sessions of data collection were reviewed and coded to produce summary tables of the frequency of different intent cues reported by participants in each type of traffic scenario. Researchers categorized the cues mentioned into three broad categories: driver-related cues, vehicle-movement cues, and vehicle-signaling systems cues. These categories were defined as follows:

- Driver-related: any cues that pertain specifically to the driver of the vehicle (e.g., eye contact, gaze direction, use of gestures).
- Vehicle movement: any cues that pertain to how the vehicle is moving or not moving (e.g., approach rate, lane changes, drifting, stopped, vehicle noise, such as engine revving, vehicle's position in the travel lane).
- Vehicle-signaling systems: any cues that pertain to signaling systems already in place in the vehicle (e.g., turn signals, brake lights, hazard lights).

The results of this study showed that within all three groups of shared road users and during a majority of the traffic scenarios, participants relied most on vehicle-movement cues. However, driver cues are used frequently, and more so by pedestrians and bicyclists, especially in close situations where there are immediate safety consequences.

Study 3: Testing External Signaling System Concepts

The purpose of Study 3 was to develop a preliminary laboratory-based protocol for assessing shared-road users' understanding of novel external signaling systems for ADS vehicles. The goal was to create and make use of high-quality video stimuli to simulate early prototype designs for external human-machine interfaces (eHMI). Six different visual eHMI interfaces were developed for this study. The eHMIs were based on existing concepts presented by automotive technology developers and researchers. Because the primary purpose of this study was to exercise and assess the preliminary laboratory research method itself, the eHMI set includes a range of communication approaches. The eHMIs are described below and shown in Figure E1.

1. *ADS beacon*: A green light on the front of the vehicle where the hood meets the windshield. The light is on when the vehicle is in automated mode. It is off when it is in manual mode. The image below shows the ADS beacon in use, from a frame of an actual video used in the study.
2. *Light bar*: A light bar spanning the top of the windshield. Different patterns of light indicate whether the vehicle is in motion, yielding, or preparing to resume motion. "In motion" is represented by four light segments steady in the center of the display. "Yielding" is represented by two pairs of light segments symmetrically bouncing from the center to the outside of the display and back again. "Preparing to resume motion" is not used in this study, but it is represented by the same display as "moving" but with the lights flashing rather than steady.
3. *"I see you" eyes*: This display uses a pair of large eyes on the vehicle's grill to indicate the vehicle's awareness of a pedestrian. The eyes look straight ahead until a pedestrian is detected, then look in the direction of the pedestrian to simulate eye contact of a driver. The eyes also look in the direction of an upcoming signaled turn.
4. *Yielding text*: The word "Yielding" is presented in the vehicle's grill to indicate that it is yielding to a pedestrian. If the vehicle is not signaling that it will yield, the display is blank.
5. *Pedestrian WALK/DON'T WALK symbols*: WALK or DON'T WALK icon is presented on vehicle grill to indicate whether or not the vehicle is yielding to pedestrian. Icons are comparable to pedestrian crossing signals.
6. *Headlamp flash*: Vehicle quickly flashes its headlamps twice, as drivers sometimes do to signal intent to yield to pedestrian.

Figure E1. The eHMIs used in Study 3: 1) ADS beacon, 2) light bar, 3) "I see you" eyes, 4) "Yielding" text, 5) WALK/DON'T WALK icons, 6) headlamp flash

Researchers recorded videos of an approaching vehicle from the perspective of a pedestrian at a crosswalk. The setting for these videos was a crosswalk at a four-way intersection in a residential area with a 25-mph speed limit, with the research vehicle approaching from the pedestrian's left. The research vehicle was the only approaching vehicle in the videos.

Thirty research participants playing the role of a pedestrian waiting to cross the street watched videos of an approaching vehicle projected onto a wall. The eHMIs were digitally added to the exterior of the vehicle, and the vehicle took different actions in different videos (e.g., yield before crosswalk, drive through crosswalk, turn off road before reaching crosswalk). There were 29 unique trials in this study, each one a combination of an eHMI and a vehicle action. These trials included control trials where no eHMI was present. Ten of the trials were presented to participants before the meanings of the interfaces were explained to determine how intuitive the interfaces were. The researcher then explained the intended meaning of each interface. The session continued with the full set of 29 unique trials for a total of 39 trials in the study. For each trial, participants answered three questions about the vehicle at three time points during the vehicle's approach. The questions were:

1. Is the vehicle in self-driving mode, or is there a driver in control?
2. Is the [VEHICLE/DRIVER] aware of your presence?
3. Is the [VEHICLE/DRIVER] going to yield to you or turn before the crosswalk, or is it going to continue through the crosswalk without yielding or turning?

For questions 2 and 3, the experimenter said "vehicle" if the participant believed that the vehicle was in self-driving mode, or "driver" if the participant believed that there was a driver in control. The driver was not visible in the videos, so participants could not see if a driver was present or in control of the vehicle. After participants answered each question, they also rated their confidence in their answer on a scale from 0 (no confidence) to 10 (complete confidence). Participants also answered additional qualitative questions about the perceived meanings of the interfaces, preferred interfaces, and problems or potential improvements for the interfaces. These questions provided additional context to the findings from the set of trials and helped to identify potential benefits and limitations of interfaces.

Results show that participants generally recognized that the presence of an eHMI indicated that the vehicle was self-driving, and if the vehicle yielded, participants indicated that the vehicle recognized their presence, even before the meanings of the interfaces had been explained. Five of the six eHMIs also helped participants recognize that the vehicle would yield (i.e., come to a stop prior to entering the crosswalk) under naïve conditions (i.e., before the intended meanings of the interfaces were explained to them), relative to a control trial with no eHMI. The one eHMI that did not help participants recognize the vehicle's intent to yield was a beacon that only indicated that the vehicle was in self-driving mode but provided no information about vehicle intent. Training on the meaning of the interfaces further enhanced comprehension of all eHMIs. Overall, under both naïve and informed conditions, the eHMIs assessed in this experiment led to improved comprehension of the vehicle's status and intentions relative to a no-interface baseline condition. Participants' preferred interface overall was one that displayed pedestrian walk and don't walk icons on the front grill of the vehicle. Participants liked that this interface was familiar from pedestrian crossing signals and was clear in its meaning. This finding is supported by data from video trials showing that participants clearly understood the vehicle's self-driving status and intentions across a range of scenarios. The beacon interface was unpopular among participants because it did not clearly communicate vehicle intent. The light bar interface, which used varying light patterns to indicate vehicle status and intent, was unpopular among participants because it was considered to be unintuitive and confusing, even after the meaning of the patterns was explained to participants.

While the study method was largely successful in differentiating between interfaces with regard to the three questions participants answered during each video, it was limited in terms of scenarios used. All trials were set at a single crosswalk and one approaching vehicle (the research vehicle) with no traffic control devices on its approach to the crosswalk. Therefore, the generalizability of these results to other settings and scenarios is unknown. An additional limitation of the method revealed in the data was participants' limited use of the lower portion of the 0 to 10 confidence rating scale. Participants overwhelmingly rated their confidence 5 or higher, even when the trial video gave them no indication of what the correct answer should be. Such overconfidence biases have been documented in decision-making research literature (e.g., Moore & Healy, 2008). One potential way to address this overconfidence in future research is to provide participants with three distinct response options (i.e., yes, no, don't know) rather than binary options with confidence scales, and to provide instructions that clearly and objectively delineate the different response options.

Conclusions

The first two research studies conducted for this project provided insights about the information that the ADS vehicle should communicate to shared road users, while the third study developed and exercised a preliminary lab-based protocol for evaluating early eHMI prototype designs for ADS vehicles for one specific scenario. The findings of Study 1 and Study 2 show that pedestrians, bicyclists, and drivers most often use implicit cues provided by vehicle movements and vehicle position on the roadway to predict intent. However, they also frequently look for, expect to see, and rely upon cues provided directly by the driver such as head pose, eye contact, posture, and gestures. The use of these driver-related cues depends on both the traffic scenario and shared road-user type. Driver-related cues were used mostly when vehicles were in close proximity to the shared road user. An eHMI might help support shared road users' expectations and help them to predict the vehicle's movements just as driver-related cues are currently used.

Study 3 involved the development and evaluation of preliminary methods to assess the effectiveness of visual communication from an approaching ADS vehicle to pedestrians in one specific scenario. Presentation of eHMI designs as video overlays was an effective way to visualize interface designs within projected, high-fidelity dynamic visual scenes. This method allowed participants to view the vehicle and eHMIs at a realistic scale and allowed the precise repeatability of the stimuli for all participants. The stop-motion video segments allowed researchers to assess participants' understanding of the eHMI when the vehicle was at different distances.

Results of Study 3 also showed that the method demonstrated success in being able to differentiate between various concept eHMIs for the single, simple scenario considered and vehicle approach actions across the three key questions. Results show that eHMIs that clearly and intuitively indicate intended vehicle action or suggested pedestrian action resulted in the highest comprehension levels and highest levels of satisfaction. Interfaces that were unfamiliar and unintuitive were unpopular, even after the meanings of the interfaces were explained. A beacon interface that indicated that the vehicle was in self-driving mode was effective in communicating that fact but was not effective at communicating vehicle intention.

Surprisingly, confidence ratings in this Study 3 were bimodal, with participants rarely rating their confidence below 5. The reasons for this outcome are unclear, but future applications of this method should consider approaches to ensure appropriate ratings. One potential way to address this overconfidence in future research is to provide participants with three distinct response options (i.e., yes, no, don't know) rather than binary options with confidence scales, and to provide instructions that clearly and objectively delineate the different response options.

1 Introduction

1.1 Background

Drivers and shared-road users (including other drivers, pedestrians, and pedalcyclists) interact in many ways and influence each other's behavior. For example, even a pedestrian's facial expressions can have an influence on drivers' behaviors when approaching crosswalks (Gueguen et al., 2016). Wilde (1976) has pointed out that road users' interactions are influenced by two types of norms: social/informal and legal/formal. Communication of intent is particularly important when planned maneuvers deviate from legal norms but conform to informal norms, and safety problems may result for maneuvers that deviate from informal norms but conform to formal norms. That is, crashes are avoided when shared-road users are able to correctly predict what type of norms others are using. Driving automation systems have the potential to change the driving environment in many ways, particularly in the way drivers and other road users communicate with each other and how that applies to interactions between the ADS and other road users.

In many driving situations, drivers make implicit predictions about the future movement of other vehicles based on a variety of contextual cues. Some of these cues are clearly visible. For example, as a driver in a vehicle ahead brakes on approach to an intersection with a green signal light, a following driver might presume that the vehicle will turn, regardless of whether the turn is signaled. If the lead vehicle was operated with ADS engaged, it is unlikely that a following driver would have much difficulty reacting in the same manner, given that the brake lights and vehicle kinematic cues would be similar. In other cases, road users may make their judgments about other drivers based on the lookout behavior of the person driving the vehicle (i.e., head pose, gaze direction, and eye contact). Thus, at a 4-way, stop-controlled intersection, drivers may signal using hand gestures to indicate whether they are yielding the right-of-way. Similarly, pedestrians are often advised to maintain some level of eye contact with an approaching driver to confirm that they are seen by the driver and granted by some visible indication the right-of-way. In these situations, vehicle automation may leave road users uncertain about whether to proceed or yield because the occupants of the ADS vehicle may not be driving the vehicle, and therefore not provide eye contact or other intentional means of communication with shared road users.

Other cases in which the behavior of an ADS departs from ordinary drivers' behaviors may stem from differences in the way each senses the surrounding world. ADS sense the world using different types of radar, lidar, cameras, connected-vehicle data sources, and GPS, to name a few. A human driver senses the world largely by overt looking behavior, necessitated by the limitations of the human visual system. Thus, most humans assume that if an observer makes no glances, or even head turns, in their direction, they will not be seen. Thus, observed postural and gaze behavior of other drivers may be interpreted by other drivers as a prelude to a lane change or merge, seen as indicative of some level of driver confusion, or even as evidence of a distracted driver interacting with a hand-held device. Making use of these postural cues has been the basis of development of improved predictions of a driver's future intent. For example, researchers have examined drivers' gaze and head position as predictors of intent to change lanes (Doshi & Trivedi, 2009; Morris et al., 2011; Ohn-Bar & Trivedi, 2016). Indeed, a driver's looking behavior is a key component in the assessment of driver distraction (AMT, 2013). Because an ADS does not exhibit distracted driving behaviors and gathers information revealing few observable clues, other road users will likely have limited insight into what the ADS is ‘attending’ to. That is, the ADS’s distribution of attention is hidden from other road users.

It is unclear how much other road users rely on this information. The yielding behavior described earlier may vary across locales to the degree that interactions among drivers occur. In some locales, drivers might simply adhere to arrival-time rules at intersections and avoid exchanging glances with others; in other places, custom may dictate that some form of wave or acknowledgment occurs. A road user’s reliance on driver lookout behavior may be far more limited in certain traffic scenarios where a clear view of the driver is not available. When a shared road user encounters an ADS, there may be a need for the shared road user to recognize the vehicle as being under automated control so that reliance on driver lookout behavior can be reduced and attention can be shifted to other cues from the ADS itself.

Some automobile manufacturers have addressed ADS communication of attention and intent through novel interface approaches. Two examples are recently produced concept vehicles from Nissan and Mercedes.

- Nissan IDS Concept: Note the lights along the car perimeter that signal the detection of bikes and pedestrians as well as the text displays of intention (“Stopping,” “After You”) just after video time 1:12. www.motorauthority.com/news/1043116_nissan-ids-concept-hints-at-next-gen-leaf-live-photos-video and www.youtube.com/watch?v=tdaiKOveFbk
- Mercedes F105 Concept: Note the signaling of a stop (possibly before parking), provision of a projected crosswalk, tracking grill lights that show detection of shared road users, and possibly audio cues to the pedestrian. www.youtube.com/watch?v=_cVN1yMJgWs

These examples show that ADS vehicles may use many new forms of displays to provide information to shared road users. The new concepts for external signaling systems are quite different from the small, well-defined set of traditional signaling systems (brake lights, including the center high-mounted stop lamp (CHMSL), backup lights, horn, and turn signals). Some novel interfaces are likely incompatible with current Federal Motor Vehicle Safety Standards. How ADS users and other shared road users will interact through use of new external displays is generally unknown. The safety challenge is in deriving general principles and methods that promote good design and provide an objective and practical means of evaluating externally facing displays and other means of communication.

Another related, but subtler, safety concern with increasing use of automation is the unanticipated changes that may occur in driving safety culture when drivers are not fully engaged with the driving task, including the social, communicative aspects of it. The anonymity of the ADS user may increase as he or she disengages from the external environment and reduces direct eye contact and other forms of intentional communication with shared road users. This disengagement, and the increased perceptions of anonymity that may result, may reduce road users’ sense of shared responsibility for maintaining safety (Jenness, 2007). However, as the ADS user recedes from public contact, the ADS, with its friendly external displays may become the social actor itself (or the ADS user’s avatar) for dealing with shared road users. There is much evidence in the human-computer interaction literature that humans generally have no trouble engaging, even on an emotional level, with robots (e.g., Nass & Brave, 2005).

1.2 Objectives

The high-level objectives of this research program are to address the following questions:

1. What are the key pieces of information that the ADS would likely need to communicate to other road users?
2. How does intent communication between vehicles with ADS and pedestrians compare to the communication between drivers and pedestrians, and how might the difference in the communication affect road safety?
3. What are some means for measuring communication effectiveness (under a multiple of environmental conditions for a wide range of shared users)?
4. What are the appropriate metrics for measuring effectiveness of communication between ADS and shared road users?

2 Study 1 – Structured Interviews of Driver Evaluation Experts

2.1 Purpose

The main objective of this study is to identify driver behaviors important for signaling driver intent but might not be present in an ADS vehicle. Many of these cues are associated with the looking behavior of the observed driver, the management of the vehicle movement along the roadway, and use of existing signaling systems to convey secondary meanings.

In the Phase 1 literature review effort, the literature on the prediction of driver intent from gaze and postural cues was reviewed to obtain some initial guidance about conceivable cues that road users may be sensitized to. While head pose and posture provided significant information about driver intent, other cues, such as eye movements, appeared to provide less clear support for intent prediction.

In the present study, opinions and judgments were directly solicited from driving skill evaluation professionals (e.g., driving instructors and registered occupational therapists) about such cues in a variety of roadway scenarios. A structured interview was created in which professionals were asked to identify and describe a possible cue, evaluate how rare/common that cue might be observed in the scenario, and how difficult it would be to clearly observe and interpret that cue. The results of this study would be to identify cues that are most commonly observed and to evaluate how easily they can be detected.

2.2 Method

2.2.1 Structured Interview Overview

The structured interview was based on a series of scenario descriptions in which participants were read scenario descriptions and invited to describe as many signals/signs that they could imagine using in the given context. For each example, they were asked to evaluate both the prevalence of the sign in daylight and in darkness, and the relative difficulty of using that sign. This latter evaluation was requested to ensure that participants directly considered the availability of the cue under different lighting conditions. In darkness, the visibility of a driver within a vehicle is likely to be significantly diminished compared to conditions in daylight.

Each structured interview was conducted as a one-hour telephone conversation that was transcribed by the interviewer. Interviewers read the description of each scenario and recorded each participant's detailed description of a particular signal that might be driver-generated in the given context and might not be present if the vehicle was driverless. The interviewer would pursue further clarifications to ensure that coherent commentaries would be available.

Participants were made aware of the purpose of the interview: to obtain "…professional opinions about the relative importance of gestures and indirect cues from other drivers and other road users in supporting safe driving." Further examples of the meaning of gestures and cues was given to ensure participants understood what information was being sought.

The scenarios discussed in the interview included scenarios divided into two broad groups: urban and freeway environments. A listing of the scenarios is shown in *Table 1*. For each cue that a participant associated with a scenario, their verbal description was transcribed, and a rating of ease of detection and prevalence of the cue was made for observation in darkness and in daylight.

Table 1. Scenarios discussed in the structured interview

Urban Scenario Environments
Parking Lots—Vehicle Entering or Leaving
Intersections—4-Way Stops
Pulling Out Into Traffic
Around Congested Pedestrian Traffic
Around Crosswalks
Around Bicyclists
Freeway Environments
Merge Coordination
Lane Changes at Low Speed
Lane Changes at High Speed
Other
Suggested Scenarios From Participants

2.2.2 Participants

Ten participants were recruited for the interviews; 5 of the participants were driver education professionals recruited from the local commercial driving schools; 5 of the participants were occupational therapists with specialized training in driving assessment, recruited through professional groups. The pool of participants included 2 males and 8 females distributed as follows: among the driver education professionals, there was 1 male and 4 females; among the occupational therapists, there was 1 male and 4 females.

2.2.3 Response Processing and Categorization

Since respondents described a wide variety of cues, each cue was categorized along several dimensions to permit pooling results for summarization. Descriptions were coded into four attribute categories— a) the entity that the cue referenced (i.e., driver/non-driver), b) whether the cue was explicit or implicit, c) the modality of the cue (visual/auditory), and d) a thumbnail standardized description of the cue (i.e., categorization).

Because the focus of this effort is obtaining a better understanding about what cues road users receive from vehicle drivers that might be lost with vehicle automation, care was taken to distinguish when the interviewees identified cues of other non-driver road users such as pedestrian and cyclists. Indeed, it was difficult for participants to confine their comments exclusively to drivers. Efforts to steer responses were not successful and abandoned since it seemed to reduce the overall response volume from a participant. Instead, responses were tagged with respect to target of the response as “vehicle” (which included the driver) or “other” (i.e., not the vehicle or driver). While not the specific focus of this study, information about non-driver cues is of general interest and was retained. Identification of such behaviors might be helpful in predicting the movements of other road users. They are reported separately below.

The study also distinguished whether the cue was intentionally produced to explicitly communicate with another road user, or if it was based on an inference made by the observer but not intentionally produced to communicate with other road users.

The modality of the cue was identified with the understanding that modality may be sensitive to the environmental conditions. The most obvious case is that visual cues are likely to be more difficult to see in darkness; auditory cues may be less sensitive to light level, but possibly less usable in noisy urban environments.

Cue descriptions were also reduced to thumbnail descriptions. This was done iteratively as each participant's responses were added to the dataset. In some cases, particular cues were uniquely applicable to non-drivers. For example, only the full body movements (e.g., walking, running) of pedestrians and cyclists are visible to observers. Drivers are normally seated, and their bodies are hidden within their vehicles. The complete set of thumbnail descriptions and notes are provided in Table 2. The set of cues fall into four high-level categories: observed activity of a person, observed states of vehicle signaling devices, observed movements of the vehicle on the roadway, and explicit verbal communication between road users.

Four examples of the coding conventions applied to the structured interview responses are shown in Table 3. The table contains the cue description (in italics) provided by a participant for a particular scenario, the source of the cue (i.e., the referent), whether the cue is implicit or explicit, the modality of the cue, and the thumbnail description associated with the description. All participant responses were coded using this framework.

Table 2. Thumbnail descriptions cues derived from the full text descriptions of participants

Cue Source	**Thumbnail Description**	**Implicit/ Explicit**	**Notes**
Observed Behavior of Road User	Body Movement	Implicit	Applied to descriptions of movement of pedestrians and cyclists. Some examples include stepping into street, change in walking speed, and foot movements.
	Body Posture	Implicit	Applied to descriptions of leaning, straightening, or turning of the torso toward a specific direction
	Head Posture	Implicit	Applied to descriptions of head pose, such as head turning or movements, and mirror checks.
	Gaze Direction	Both	Applied to descriptions that specifically reference where a driver or pedestrian may be looking. In some cases, there may be little semantic difference between head posture cues and gaze direction cues other than how the movement was originally characterized by the participant.
	Presence in Vehicle	Implicit	Applied to descriptions in which the presence of a driver within a vehicle was identified as a cue that the vehicle may begin a maneuver (e.g., in parking lots).
	Hand Position on Wheel	Implicit	Applied to reports of anticipated turn maneuvers of a driver (e.g., in parking lots).
	Gesture (B) Gesture (M) Gesture (P) Gesture (D)	Explicit	Applied to descriptions of explicit gestures such as a hand wave or head nod produced by a bicyclist (B), motorcyclist (M), pedestrian (P), or a driver (D).
Observed State of Signaling Devices	Headlamp Flash	Explicit	Applied to descriptions of use of headlamps to communicate with other road users. For example, granting permission to merge in front, reminding another driver to turn on their headlamps, signaling a pedestrian to cross.
	Signal Lamps	Explicit	Applied to descriptions of turn signal and hazard lamp use to indicate to other road users an intent to change lanes, merge, or to "go around" a stopped vehicle.
	Horn	Explicit	Applied to descriptions of the use of the horn to grant permission to another driver to go at a four-way stop or to ask permission to merge.
Observed Movement of Vehicle	Vehicle Movement	Implicit	Applied to descriptions of vehicle motions that are interpreted as signs that a vehicle is about to change lanes, pull out, initiate a turn, or pull into traffic.
	Vehicle Movement and Signal Lamps	Both	Applied to descriptions of a vehicle stopping motion by brake application—in most cases the vehicle's stop lamp will also be actuated during the maneuver.
	Vehicle Position	Implicit	Applied to descriptions where the vehicle location in the roadway is identified as a cue to an anticipated maneuver. For example, proximity to a crosswalk may be an indication of a driver's intention to stop, or a bicycle's lateral position on the road may be read as an indication of a left turn.
Direct Communication of Intent	Verbal (B) Verbal (D)	Explicit	Applied to descriptions where a verbal message is relayed to another road user by either a bicyclist (B), pedestrian (P), or driver (D).
Other	Unspecific	Both	Applied to descriptions in which participant did not clearly identify a cue. For example, *"Drivers entering a roadway need to know when to go and when not to"; "Experienced drivers can just sense when another driver wants to change lanes"*

Table 3. Example coding conventions applied to textual descriptions used in the study

Scenario	Description	Referent	Implicit/ Explicit	Modality	Description
Freeway Merge	*Drivers make head movements as they check their mirrors, which can be a cue that they are preparing to merge, or it can be a cue to merging drivers that a driver already on the road is checking their mirrors and sees them coming in*	Vehicle	Implicit	Visual	Head Posture
Pulling into Traffic	*"…sometimes drivers preparing to enter the road have a hunched body with their dominant hand on the top of the steering wheel"*	Vehicle	Implicit	Visual	Body Posture
Pulling into Traffic	*Drivers intending to pull into traffic may have increased eye movement as they check mirrors. Where are they looking?*	Vehicle	Implicit	Visual	Gaze Direction
Pulling into Traffic	*Drivers use turn signal to indicate that they intend to pull away from curb and to indicate that they intend to pull out from driveway*	Vehicle	Explicit	Visual	Signal Lamps
Freeway Merge	*Drivers flash their headlights saying, "it's okay to come on in"*	Vehicle	Explicit	Visual	Headlamps Flash
Crosswalks	*Pedestrians may step down and up from the curb or demonstrate a reversal in step as they prepare to enter the crosswalk*	Other	Implicit	Visual	Body Movement
Four-Way Stops	*Drivers use car horn: toots at you to go*	Vehicle	Explicit	Audible	Horn
Crosswalks	*Drivers wave their hands to pedestrian to say "go ahead."*	Vehicle	Explicit	Visual	Gesture (D)

2.3 Results

Results were tabulated separately for cues associated with vehicles and cues generated by other road users (i.e., pedestrians and cyclists). While the primary focus of this report is on cues that would be absent with automation—those associated with a vehicle—the latter data will also be presented later. Counts of responses across participants, segregated by referent is shown in Figure 1. In this study, participants 1- to 5 were driver education professionals (DE), and subjects 6- to 10 were occupational therapists (OTs). The figure suggests that the driving instructors were more heterogeneous in the number of cues reported and in how these cues were distributed between referent objects. Overall, most of the reported cues were about the characteristics of a vehicle or driver—on average across participants, 22 percent of the responses were associated with "Other" road users, and 78 percent of the responses were about vehicles and drivers.

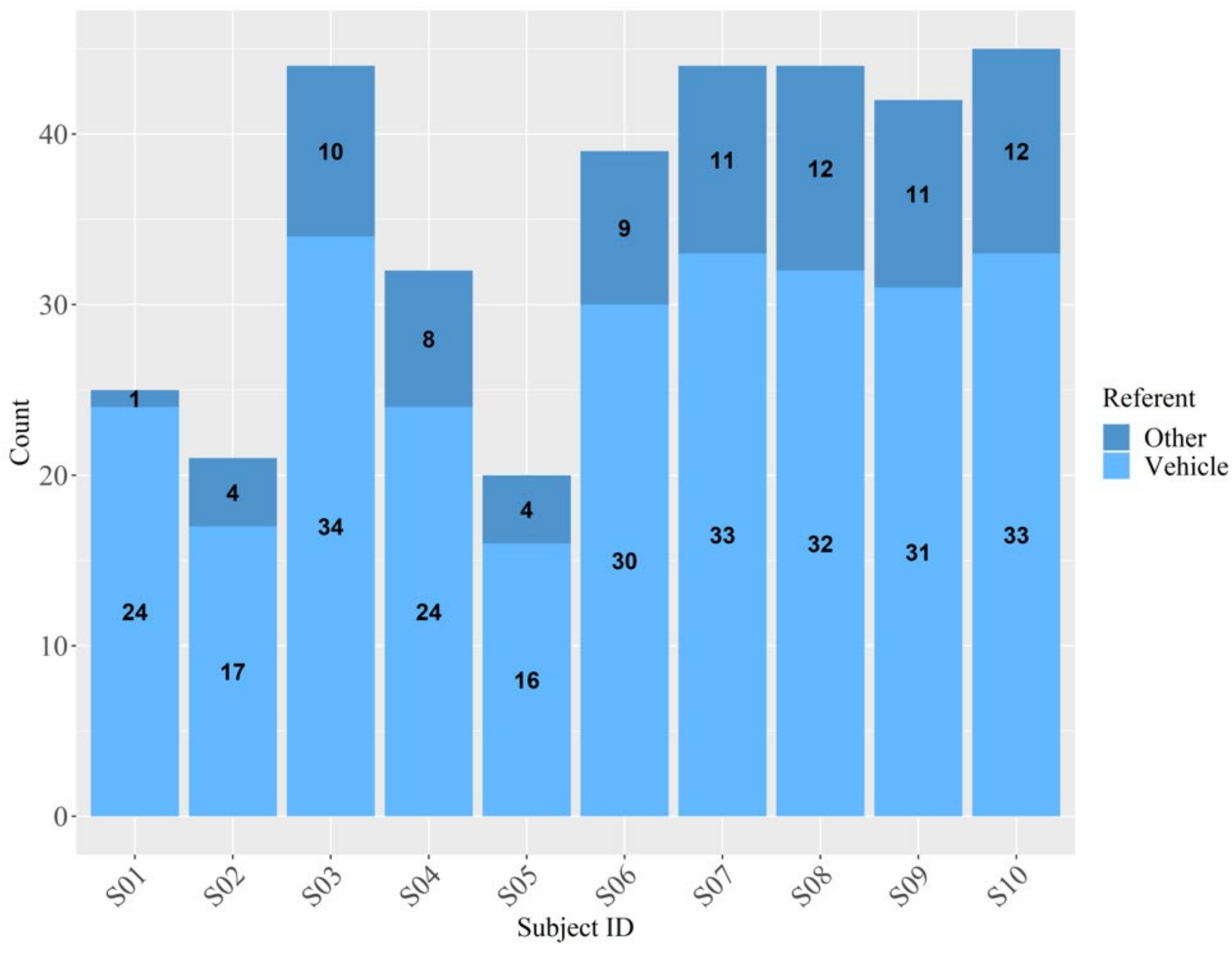


Figure 1. Total count of cues generated by each study participant (subject), partitioned into cues about the vehicle (light blue) and cues about other road users (dark blue)

2.3.1 Cues About Drivers and Vehicles

This initial analysis focuses on participant responses that described cues produced by drivers or vehicles. Many of these cues are interpreted by observers using knowledge about driver motivation, environmental context, and an estimation about a driver's level of awareness of the traffic environment. For example, if a driver is not observed to glance in the direction of an approaching vehicle, it might be assumed that the driver is unaware of that vehicle; conversely, a glance in the direction of an approaching vehicle may be taken as evidence of awareness.

2.3.2 Implicit and Explicit Cues by Participants and Scenario

Across participants, there was significant variation in the percent of cues identified that were explicit versus implicit. Each participant's breakdown of explicit versus implicit cues for descriptions that referenced vehicles is shown in Figure 2. Percentages averaged across participants were nearly even: 50.3 percent of the cues were explicit (with 49.7% of the cues implicit). The standard deviation, 25.8 (and Figure 2), indicates that there was high variability among the participants.

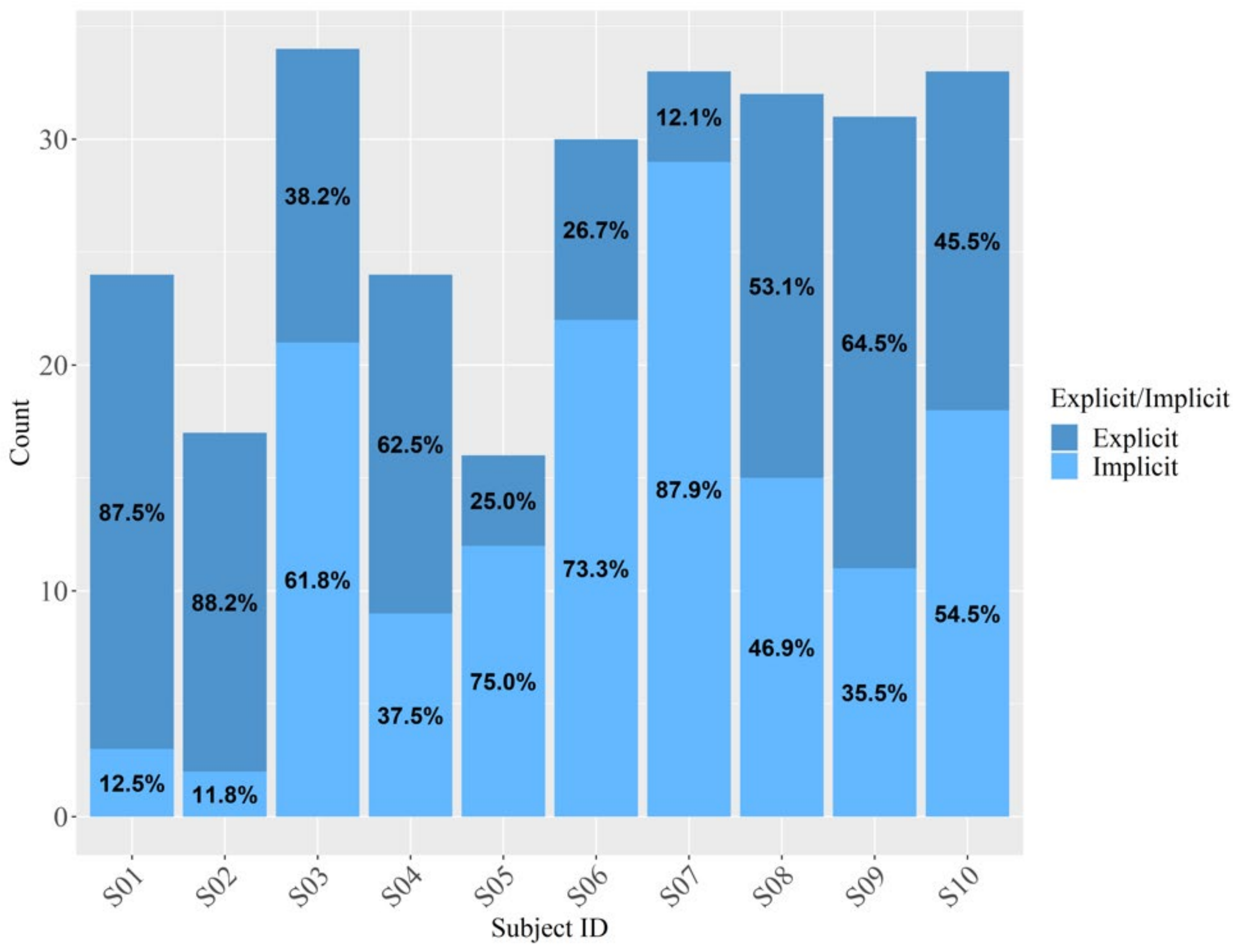


Figure 2. Distribution of cue descriptions that were explicit or implicit, by participant

2.3.3 Scenario and Cue Description

Data were collapsed by participant such that multiple cue/scenario combinations were only counted once per driver. For example, if a participant described three cues that all involved gaze direction observed in a parking lot, this was counted as one cue for that driver. The association of cue with each scenario is shown in Figure 3. Note that the maximum height of any cue type is five (within occupation), corresponding to the number of participants in the DE and OT groups. Overall, the emphasis on observing driver activity and gestures dominates parking lot, four-way-stop, and pulling-into-traffic scenarios. Gestures are less frequently mentioned in freeway merges and high-speed lane changes, where the time to catch the eye of another road user may be too short for it to be practical. There also appears to be more cues involving observation of gaze, head, and body posture among the OT group than the DE group. Notably, there is little mention around crosswalks and bicycle scenarios.

Both groups generated similar quantities of cues for the scenarios; the parking lot and pulling-into-traffic scenarios produced the greatest number of cues for each group. Counts of cues and the average number of participant cues are shown in Figure 4 for each scenario. The mean number of cues produced by the OTs was about 3.5 across scenarios; this was about one greater than the mean number (M = 2.5) of cues provided by the DE group ($t(90) = -3.32$, $p < 0.01$).

Differences in the distribution of cue sources by scenario can be seen in Figure 4. Within each scenario, the proportion of cue sources is shown within each of the stacked bars. This provides a general idea about how many variations of cue in each category were mentioned by participants during the structured interview. Each cue category is the sum of the cues pictured in Figure 3, collapsed over participant groups. This figure shows that driver behavioral cues make up more than half of the cues mentioned in parking lot, four-way-stop, and pulling-into-traffic scenarios. Mention of vehicle-movement cues were larger around congested pedestrian areas, crosswalks, and around bicyclists. This suggests that the participants may have looked at the scenario from the perspective of a vulnerable road user who would perhaps place greater importance on the movement of a nearby vehicle as a potential threat. Use of signals (i.e., headlamps, signal lamps, and horn) were identified about as often as the behavior of drivers, the motion of vehicles in freeway contexts including merges, and lane changes in high- and low-speed situations. Direct verbal communication with other road users was only identified for congested pedestrian areas and crosswalks, where the low speed and likely proximity to other road users is small and most conducive to verbal communication.

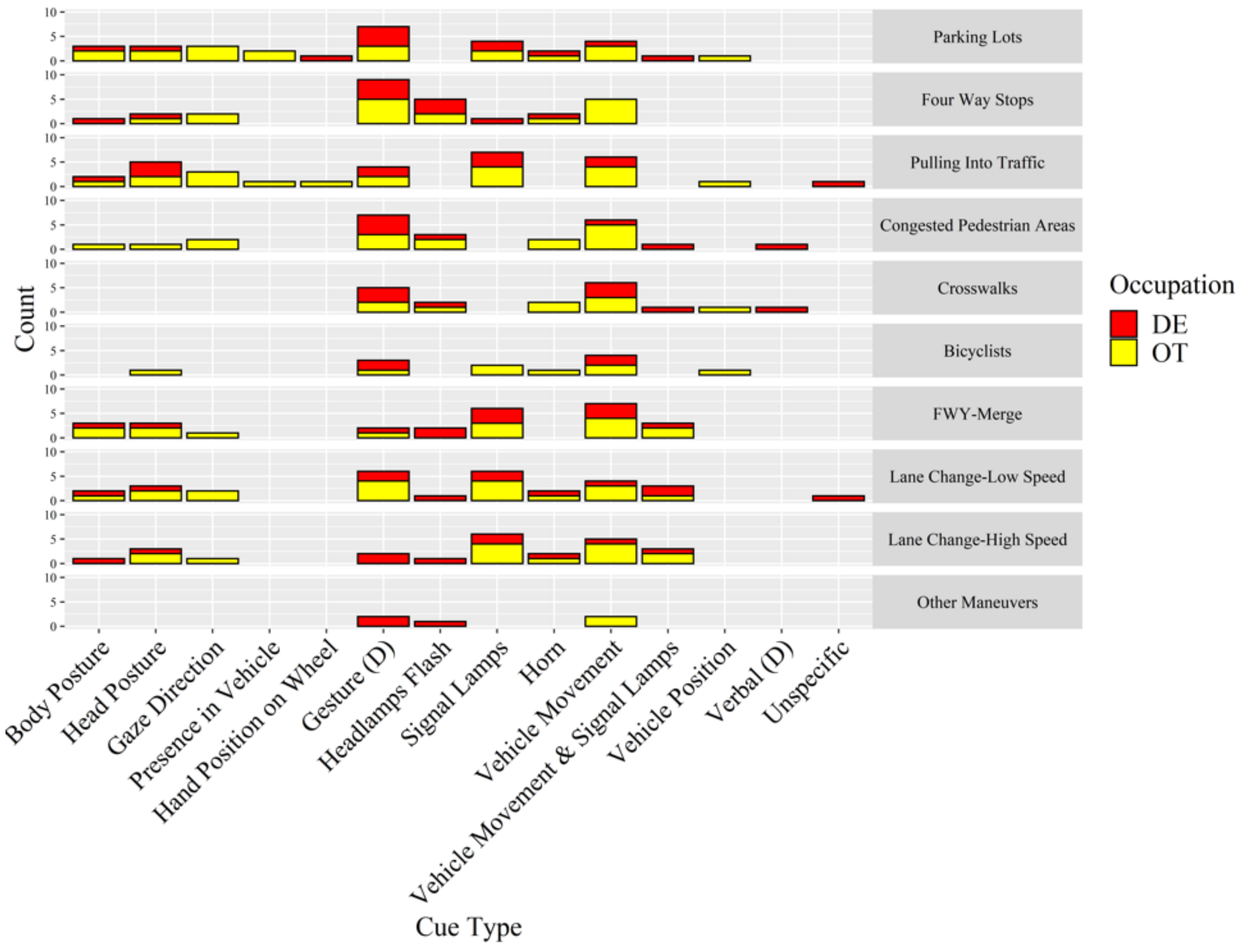


Figure 3. Driver cues generated by participants arranged by scenario (at left) for driver education professionals (DE) and occupational therapists (OT)

Table 4. Total and average number of cues generated by participants for each scenario

	Total		**Average by Participant**	
Scenario	**DE**	**OT**	**DE**	**OT**
Parking Lots	17	24	3.4	4.8
Four-Way Stops	15	18	3.0	3.6
Pulling Into Traffic	16	23	3.2	4.6
Congested Pedestrian Areas	11	20	2.2	4.0
Crosswalks	10	12	2.0	3.0
Bicyclists	4	9	1.0	1.8
Freeway-Merge	13	17	2.6	3.4
Lane Change-Low Speed	13	20	2.6	4.0
Lane Change-High Speed	12	14	2.4	2.8
Other Maneuvers	4	2	2.0	1.0

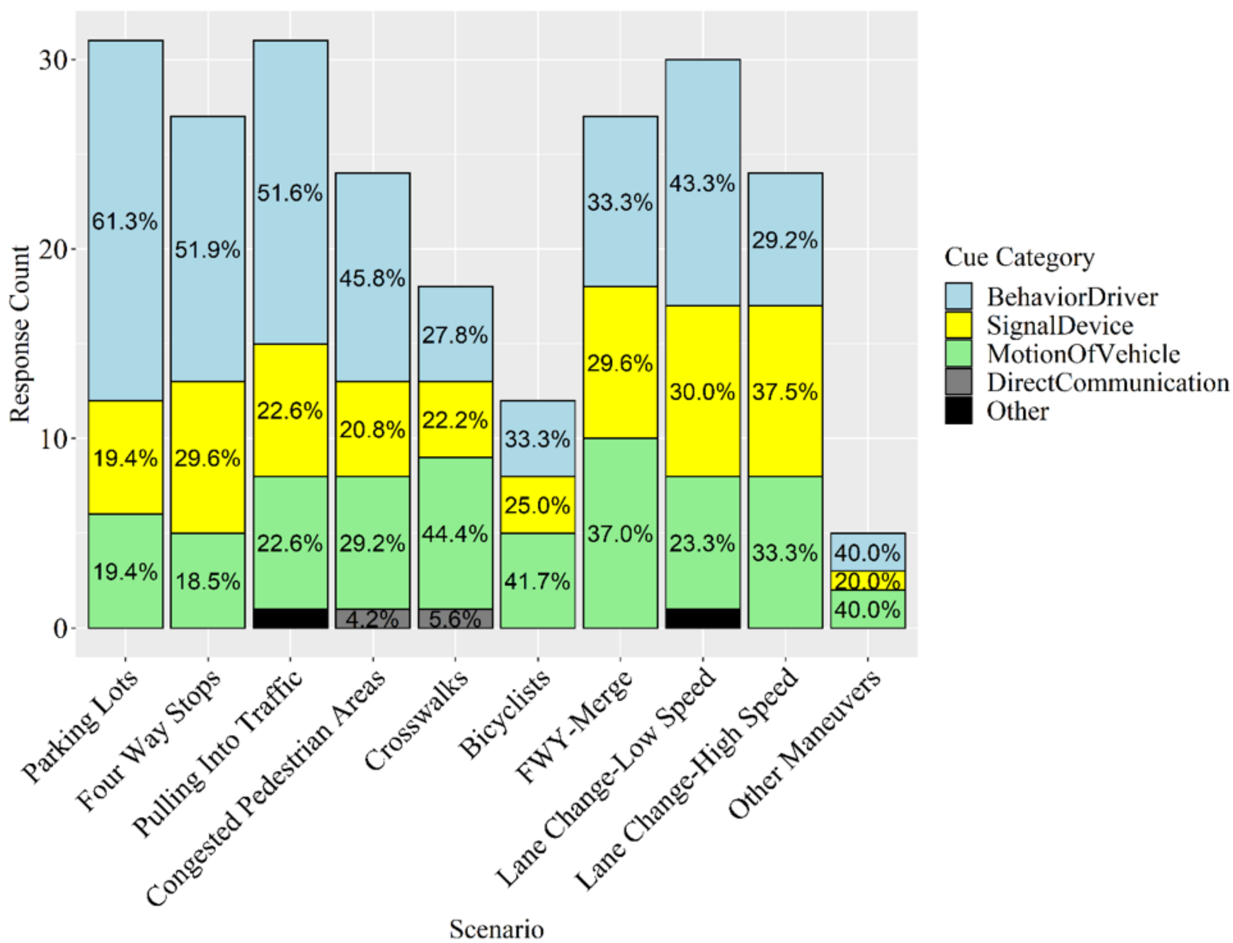


Figure 4. Distribution of cue sources by scenarios, collapsed over participant groups

2.3.4 Explicit and Implicit Cues by Scenario

Figure 5 shows the mean number of implicit and explicit cues reported by participants in each of the scenarios. Nearly twice the number of explicit cues were reported for four-way-stop scenarios. This is largely comprised of gestures made by drivers, use of the horn, or headlamp flashes. Such cues are likely to be most effective when traffic is stopped, and the vehicles involved are in relatively close proximity to each other (and road users) so that gestures may be easily seen. Scenarios involving vehicles pulling into traffic produced a comparatively large number of reports of implicit cues, although use of signal lamps was greatest for this scenario (see Figure 3). Explicit cues, like gestures from the driver, may be less effective because, in many cases, the driver of the vehicle pulling into traffic may be facing away from other conflicting vehicles. For example, when pulling into traffic from a parking space, a driver is facing the same direction as the approaching traffic. Consequently, only the back of the driver's head may visible. It would be difficult for the driver pulling into traffic to direct gestures at traffic approaching from behind. Reports of implicit cues like body movements or vehicle motions dominate this scenario. Likewise, participants reported more implicit cues for freeway-based merges and high-speed, lane-change scenarios. This is likely a consequence of the high-speed driving environment, where the traffic stream faces the same direction (precluding the use of gestures) and, because the high speed allows little time for two-way interactions. Instead, mostly implicit cues are reported that are based on vehicle movement or position in the road or body posture/movement and gaze direction of the driver.

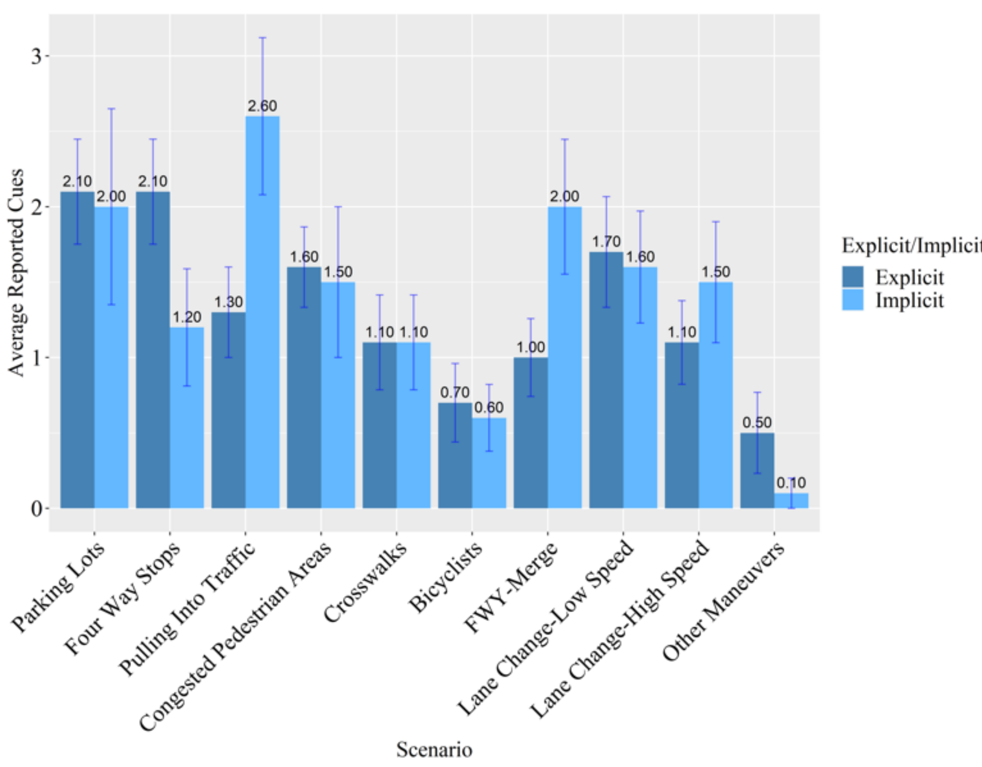


Figure 5. Average number of explicit driver/vehicle cues identified by the ten participants for each scenario

2.3.5 Visual and Audible Cues by Scenario

In general, the overwhelming majority of reported cues relied on driver vision. This is not surprising since the audible cues could only be generated through a verbal exchange or through use of the vehicle horn. Verbal exchanges are only practical where vehicles are stopped and in close proximity to a prospective listener (e.g., around crosswalks and pedestrian areas). Reported cues based on the use of the vehicle horn were also quite limited. The combined average number of audible cues by scenario is shown in Figure 6. No audible cues were identified for scenarios involving pulling into traffic or freeway merges.

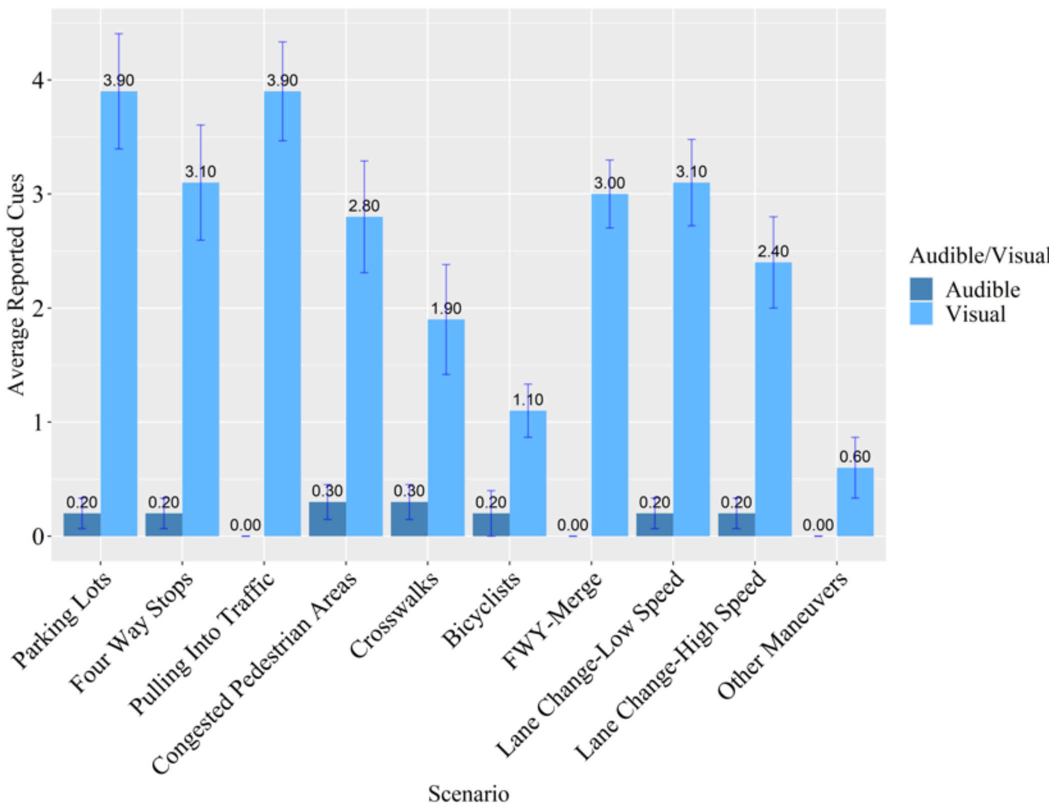


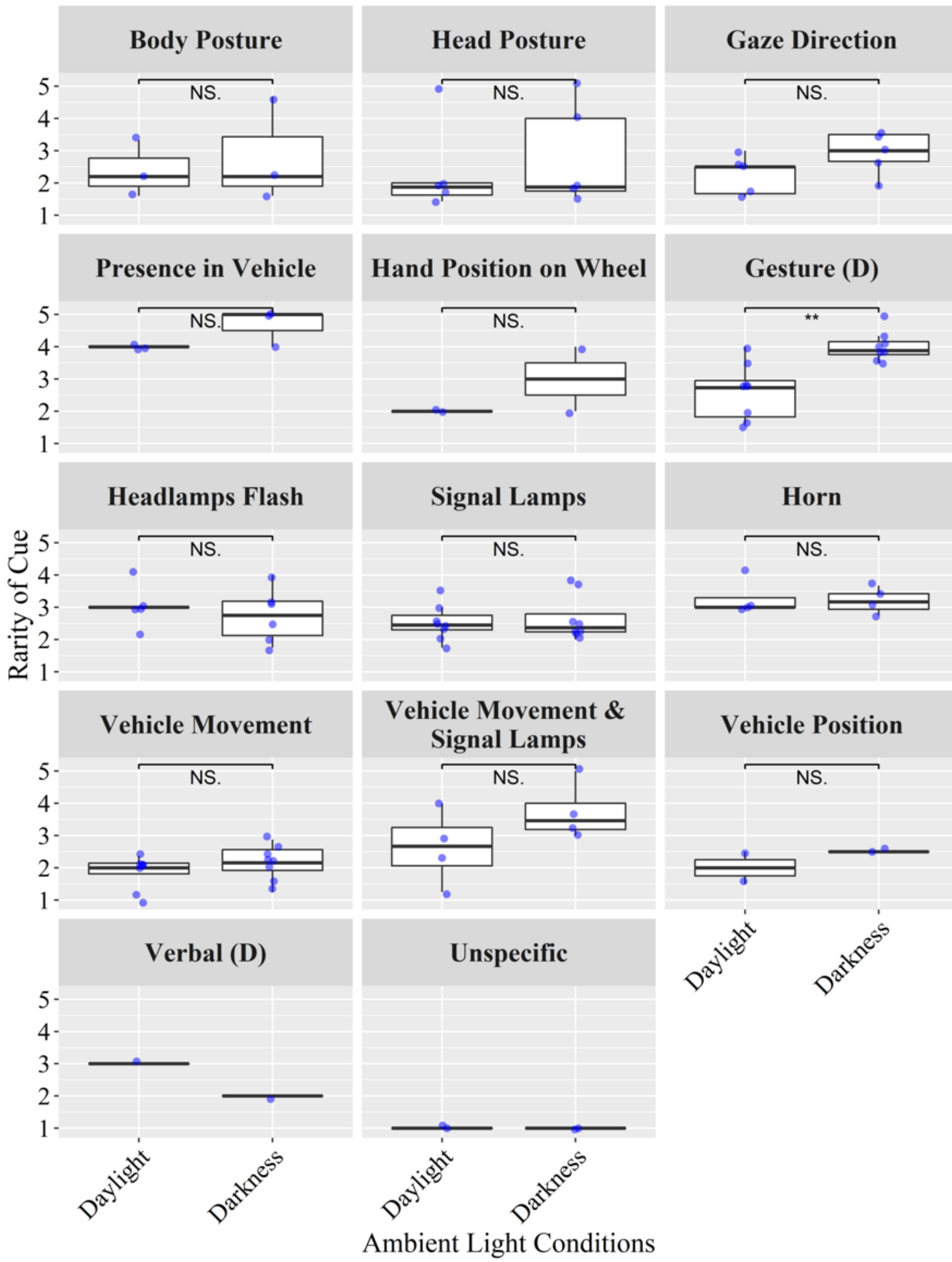
Figure 6. Average audible/visual cues reported by participants for each scenario where the referent was a vehicle or driver

2.3.6 Judgments of Cue Rarity and Difficulty of Detection Under Ambient Light Conditions

A key question related to a road user's reliance on non-standard cues is the judged prevalence of the cue and the ease with which it can be understood and acted on. Participants used a five-point scale to judge how common-to-rare (0-5) and easy-to-difficult (0-5) an identified cue might be in a particular scenario and under different ambient light conditions. Light condition was included because many cues become less salient in darkness, through the glare of headlamps or from within the darkened vehicle interior (e.g., driver gaze direction). Cue judgments made by participants were averaged within participant for each cue category, collapsing over scenarios. For each cue, comparisons were made between ambient light conditions for judgments of common/rareness of the cue and the ease/difficulty detecting the cue.

Figure 7 compares the daylight and darkness viewing conditions associated with how common or rare a given cue is. Only one cue was judged as rarer in darkness compared to daylight: driver gestures. All other comparisons were nonsignificant. It seems plausible that road users might have lower expectations that drivers would communicate using hand waves or head nods in darkness because of the limited visibility of such gestures to others.

A mixed model analysis in which "participant" was modeled as a random effect indicated main effects of both light condition and cue type on rareness ratings ($F_{(1, 97.2)} = 11.5$, $p < 0.01$; $F_{(13, 102.0)} = 5.8$, $p < 0.01$) . The rareness of cues in darkness was rated about 0.5 points higher (rarer) than the cue in daylight ($t = 3.4$, $df = 97.2$, $p < .01$). Differences among the different cues are generally clear from Figure 7, with some clear differences related to light level for some cues. Cues rated most rare based on least square means included presence in a vehicle (mean 4.1), driver gestures (3.3), and use of horn (3.3). Rareness estimates are provided in Table 5.



Blue points indicate average subject rating collapsed over scenarios
Significance levels are indicated as follows: "*" = .01; "**" = .05; "***" = .001; NS = not significant
Median indicated by thick horizontal line; 25 and 75 percentile intervals indicated by upper/lower box boundaries

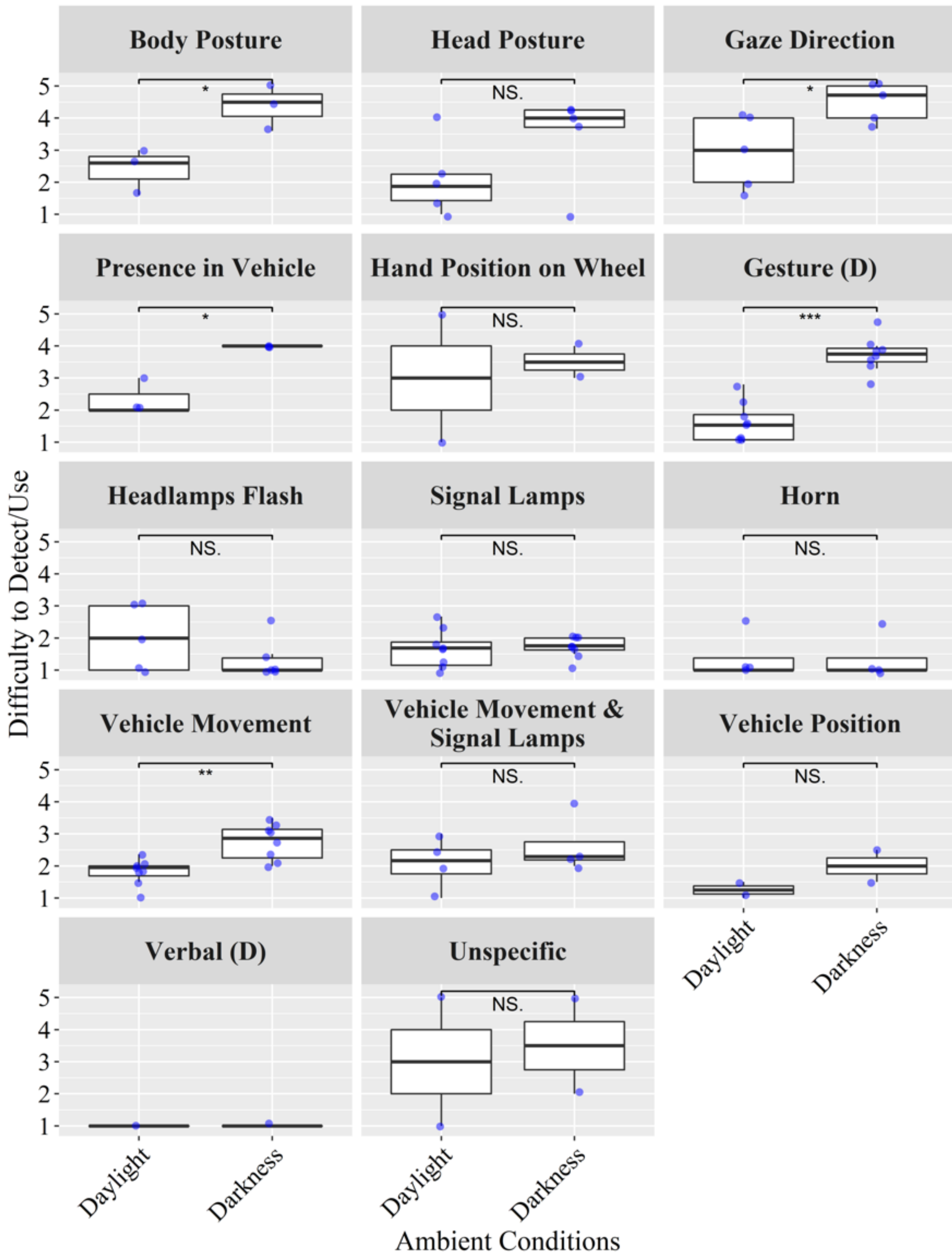
Figure 7. Rated rareness of cue occurrence in daylight and dark viewing conditions

Table 5. Least square means of rated rareness of different cues produced by drivers/vehicles (cues are ordered from least rare to most rare based on rating)

Cue Type	Rated Rareness
Vehicle Movement	1.953
Vehicle Position	2.269
Signal Lamps	2.519
Gaze Direction	2.575
Head Posture	2.605
Hand Position on Wheel	2.653
Body Posture	2.709
Headlamps Flash	2.850
Verbal (D)	2.878
Vehicle Movement & Signal Lamps	3.256
Horn	3.301
Gesture (D)	3.308

Figure 8 compares the rated difficulty of detecting each of the identified cues in daylight and darkness. Not surprising, visual cues that depend most on ambient light levels are judged more difficult to detect in darkness. Body posture, head posture, gaze direction, presence in vehicle, and driver gestures are all rated as more difficult to detect in darkness. The other driver behavioral cue—hand position on wheel—was mentioned by only 2 participants. Consequently, the small number of observations limited the power of the comparison. Detection difficulty of flashing headlamps, signal lamps, and use of the horn were rated as similar in both daylight and darkness. Vehicle movement was rated as more difficult to detect in darkness than in daylight. Notably, vehicle movement and signal lamps (i.e., cues present during vehicle braking) were not rated very different in difficulty for daylight and darkness, likely because the automatic illumination of stop lamps makes this maneuver conspicuous in both conditions.

A mixed model analysis in which "participant" was modeled as a random effect indicated main effects of both light condition ($F_{(1,84.5)} = 24.3$, $p < 0.01$), cue type ($F_{(13, 88.3)} = 8.0$, $p < 0.01$), and an interaction between light level and cue on rated detection difficulty ($F_{(13, 84.5)} = 3.1$, $p < 0.01$). The interaction effect is not a surprise as is clearly illustrated in Figure 8. Cues involving observation of driver behavior and vehicle movements are clearly more difficult to detect in darkness than other cues like headlamp flashes or use of the horn.



Blue points indicate average subject rating collapsed over scenarios
Significance levels are indicated as follows: "*" = .01; "**" = .05; "***" = .001; NS = not significant
Median indicated by thick horizontal line; 25 and 75 percentile intervals indicated by upper/lower box boundaries

Figure 8. Rated difficulty of cue detection in daylight and dark viewing conditions

2.3.7 Cues Associated With Other Road Users

As previously mentioned, many of the reported cues were about other non-motorized road users and were separated from the previous analyses because they would perhaps be less directly affected by the transition to vehicle automation. It is possible that automation could indirectly reduce the use of explicit cues that bicyclists and pedestrians might normally produce in the presence of drivers. The absence of a driver or other person who might be the target of an explicit attempt to communicate may discourage explicit communication entirely. If there is no one present to wave to, waving may seem unnecessary. Thus, gestures made by vulnerable road users to ADS vehicles could decline without confirmation that the message sent was received by the ADS vehicle. Consequently, it seems reasonable to examine the signals generated by other road users, apart from drivers and vehicles, because these cues may also be affected by vehicle automation.

2.3.8 Other Road-User Cue Types by Scenario

As in the vehicle/driver analyses, data were collapsed by participant such that multiple cue/scenario combinations were counted once per driver. Most responses were associated with cues and interactions with pedestrians and bicyclists around the roadway. Not surprisingly, only scenarios that explicitly mentioned these road users—congested pedestrian areas, crosswalks, and bicyclists—elicited mentions of these other road users. The association of cue with each scenario is shown in Figure 9. As before, the maximum height of any cue type is 5, corresponding to the number of participants in the DE and OT groups. In one case, a pedestrian's use of signal lamps was mentioned for crosswalks; otherwise, most cues were either implicit judgments of body/gaze behavior or vehicle movements (i.e., a bicycle), or explicit use of gestures.

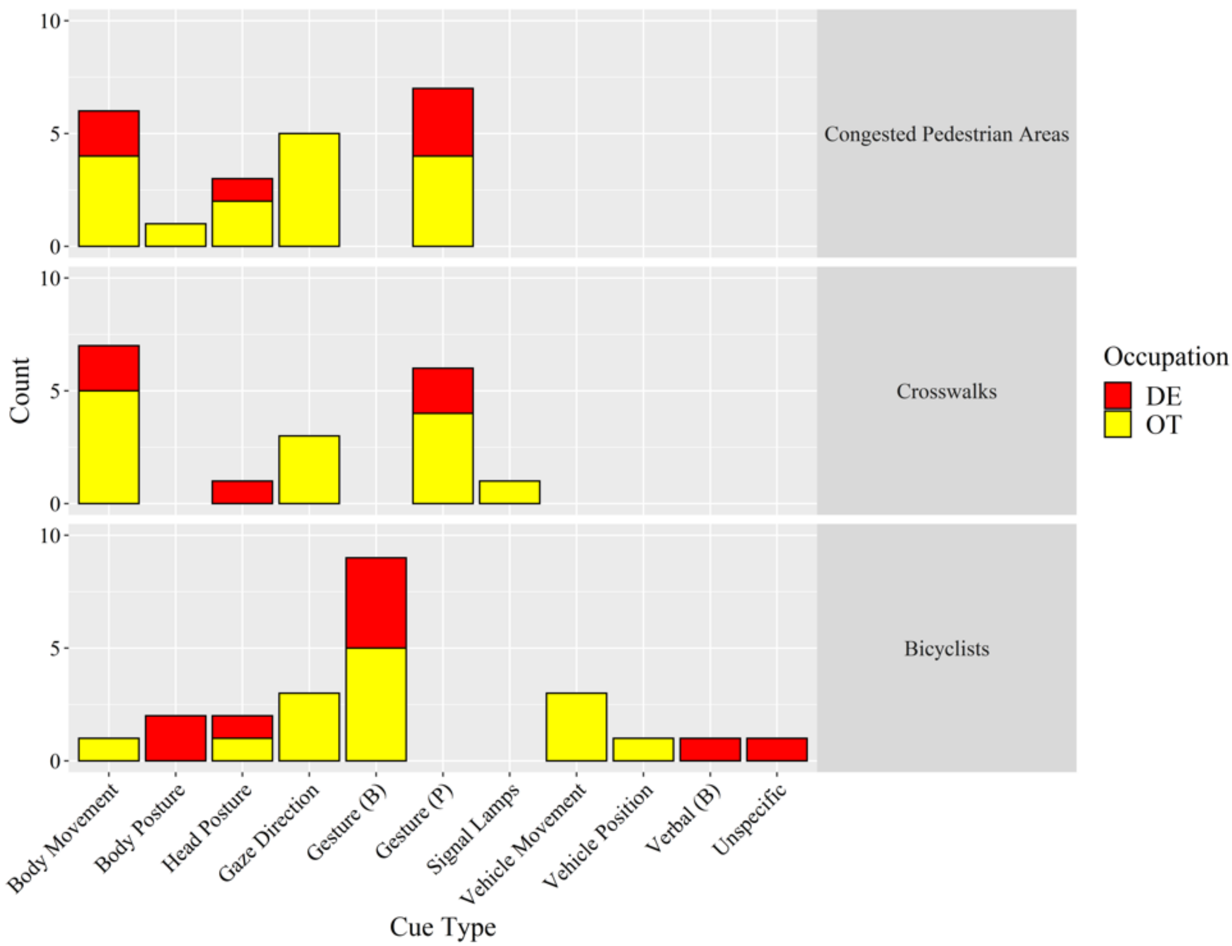


Figure 9. Reported cues about pedestrians and bicyclists by scenario for driver education professionals (DE) and occupational therapist (OT)

The distribution of cue sources by scenario is shown in Figure 10. Given these scenarios, participants mostly focused on behavioral cues produced by pedestrians or bicyclists. In the bicycle scenario, 4 participants described movements of the bicycle as providing a cue about what maneuver the bicyclist was contemplating. Example cues mentioned were changes in bicycle speed or position in the roadway. Most of the cues, however, were associated with explicit gestures, or implicit gaze direction and body posture.

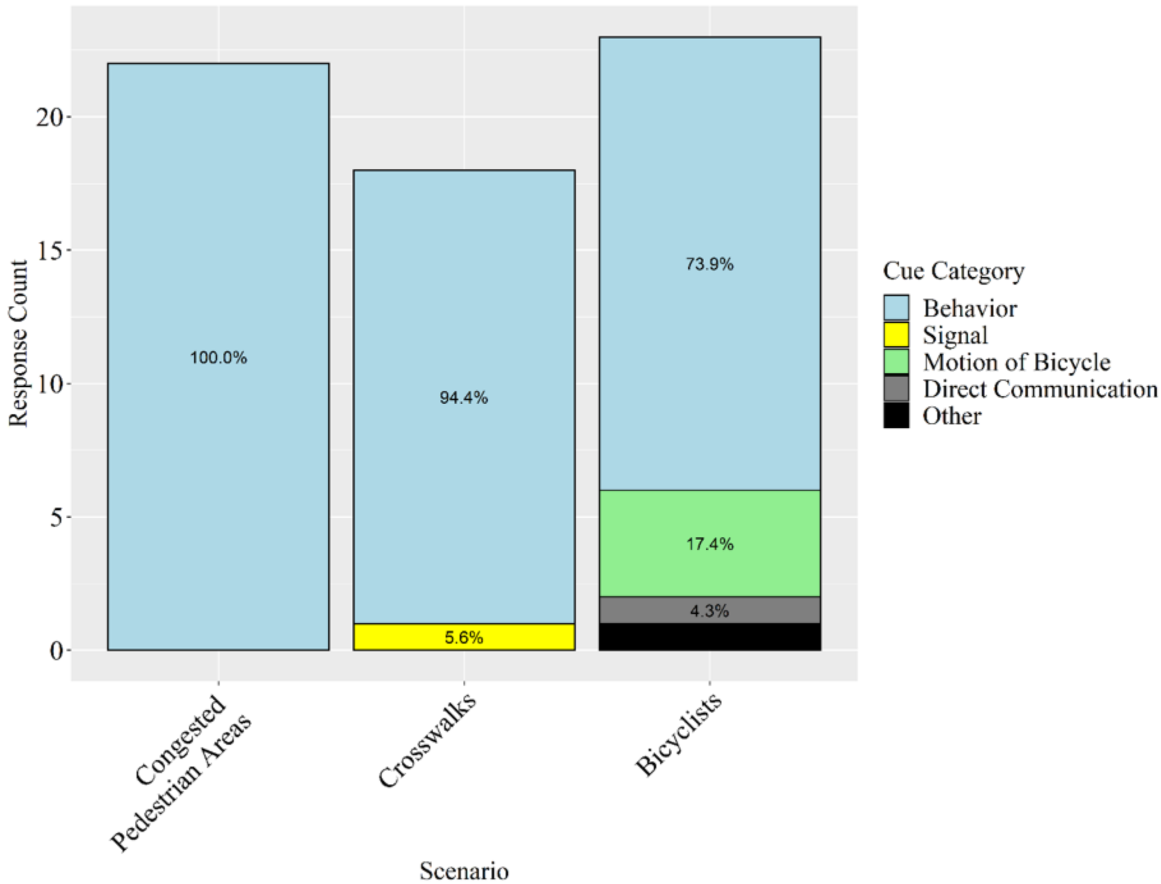


Figure 10. Distribution of cue sources by scenarios, collapsed over participant groups

2.3.9 Explicit and Implicit Cues by Scenario

Figure 11 shows the average number of implicit and explicit cues reported by participants in each of the scenarios where non-driver/vehicle cues were identified. In most cases, the explicit cues were gestural exchanges, deliberate eye contact, or verbal exchanges.

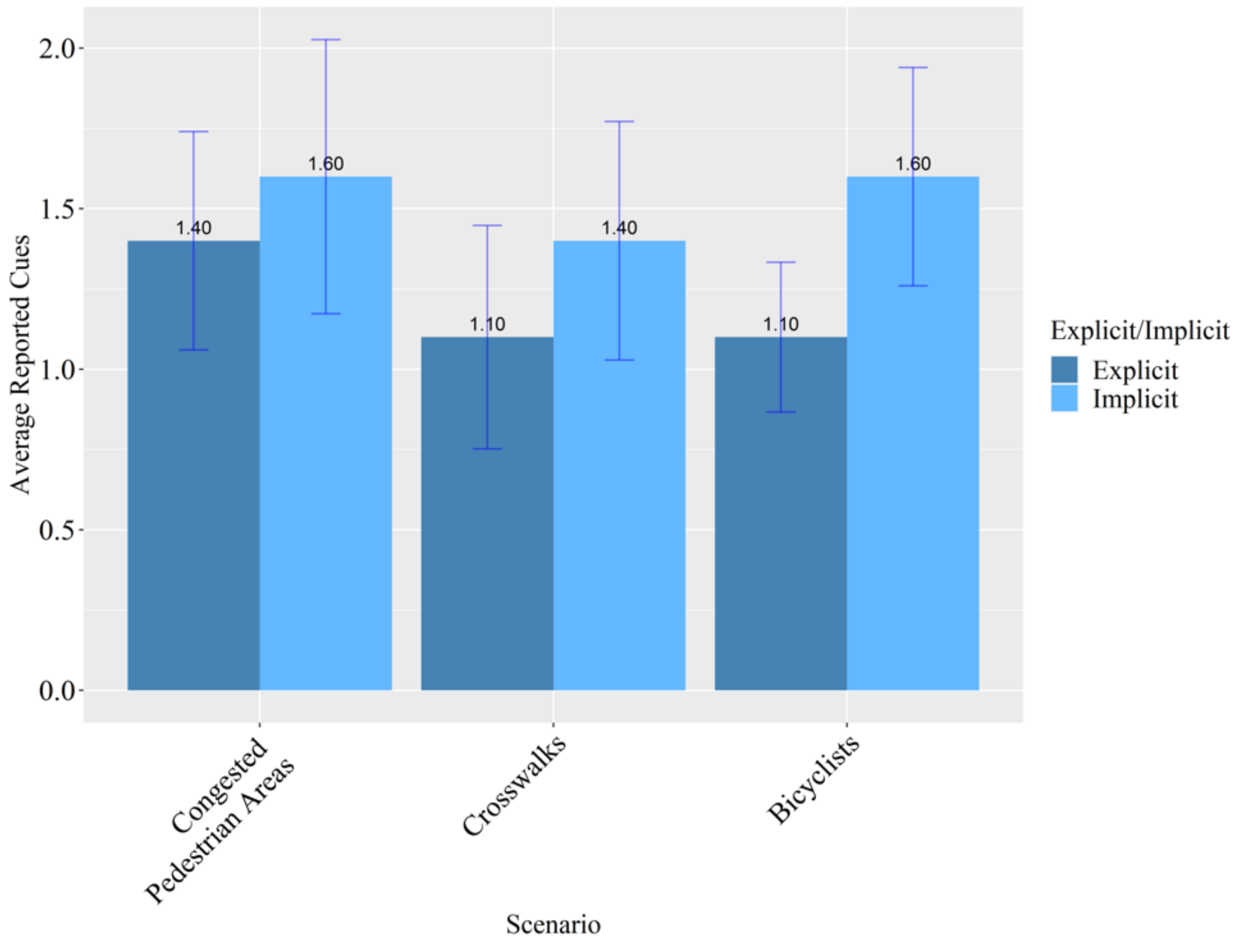


Figure 11. Average number of explicit pedestrian/bicyclist cues identified by the ten participants for scenarios in which these other road users were referenced

2.3.10 Visual and Audible Cues by Scenario

In general, pedestrians and bicyclists have little means at their disposal to generate anything other than visual cues that indicate their future intention. The one audible cue mentioned was characterized as a verbal exchange in which "bicyclists yell to drivers when they want the drivers to pass them (and yell at drivers if the drivers won't pass them)."

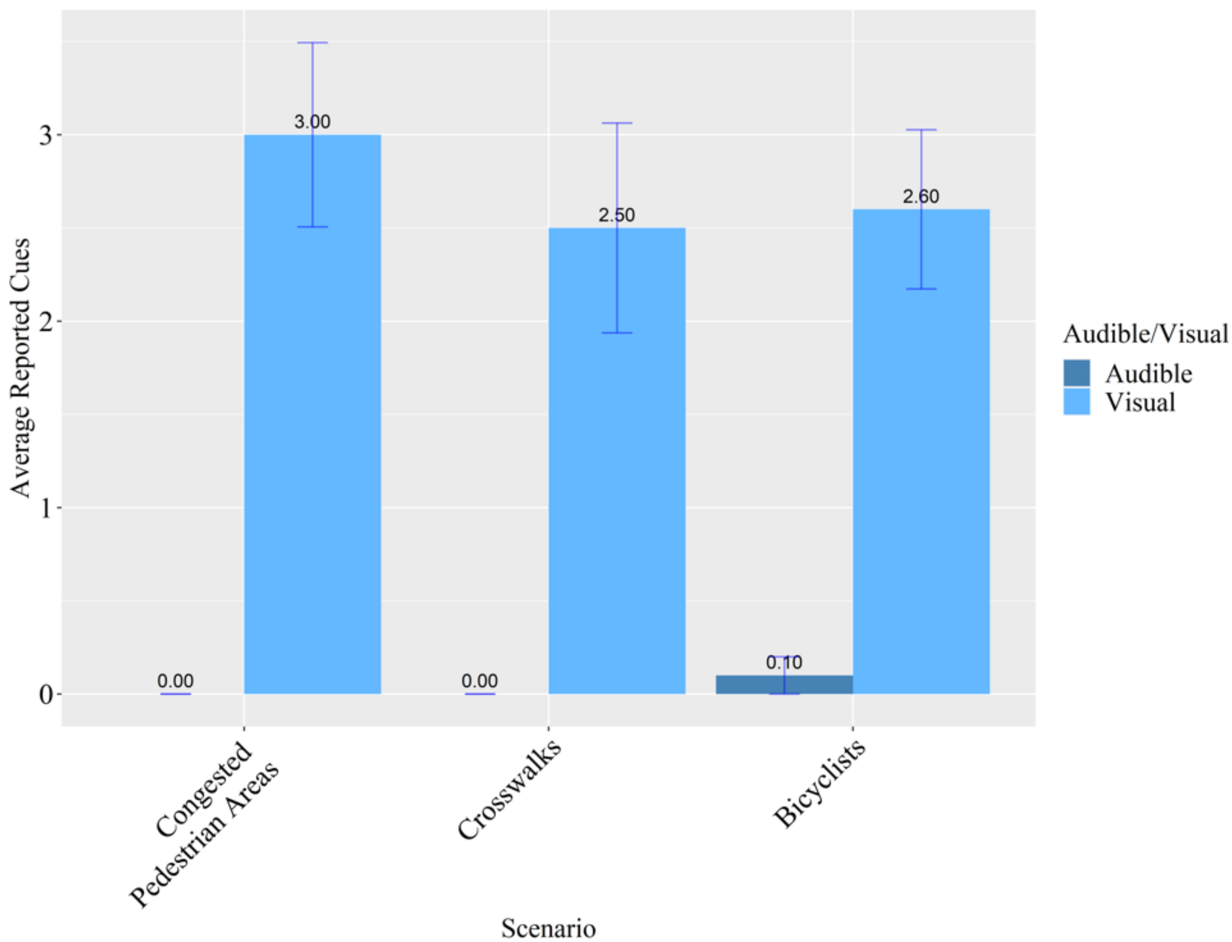


Figure 12. Average audible/visual cues reported by participants for each scenario where the referent was a pedestrian or bicyclist

2.3.11 Judgment of Cue Rarity and Difficulty of Detection Under Ambient Light Conditions

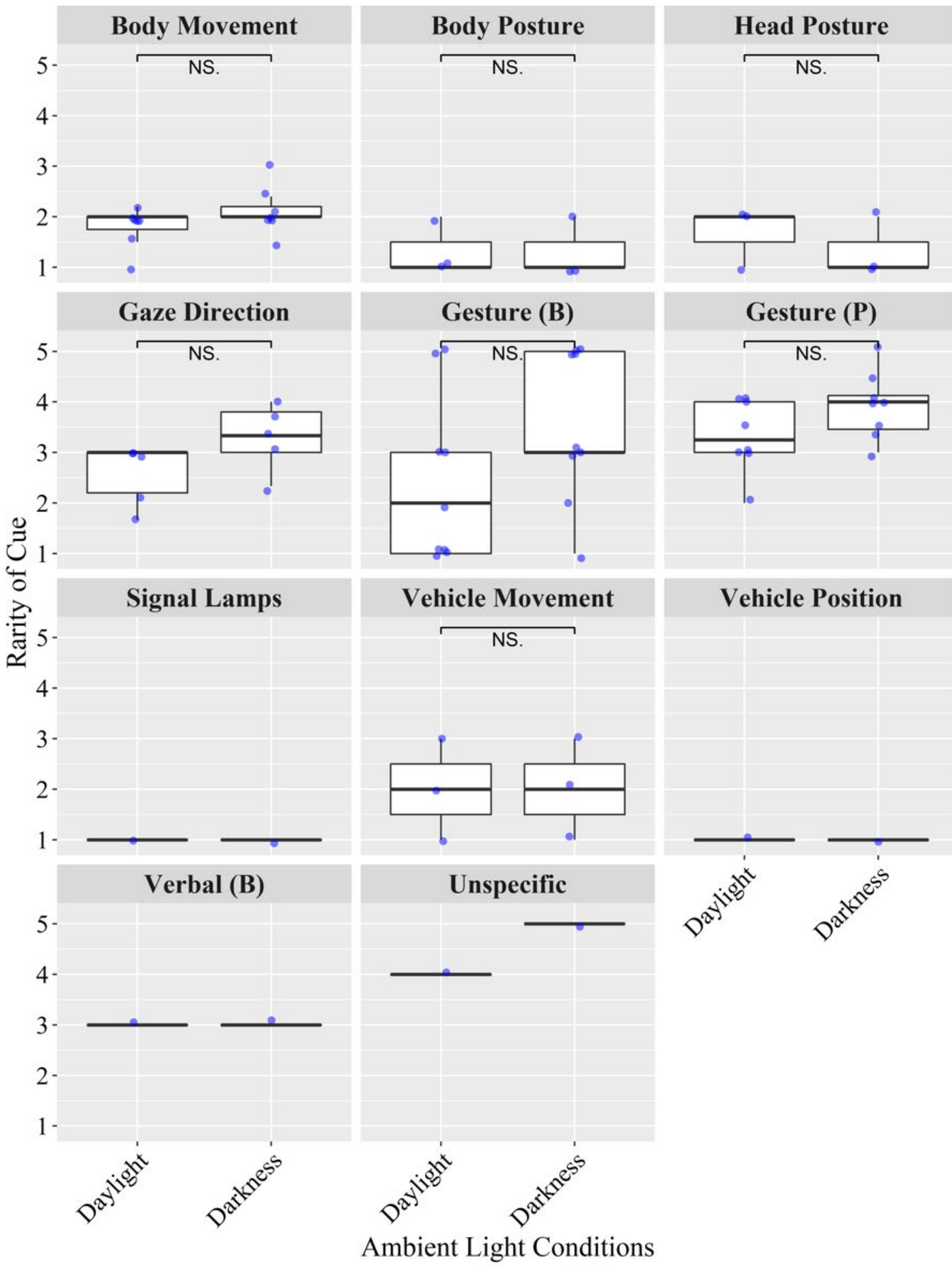
The analysis of cues observed among pedestrian and bicyclists contained fewer overall observations than those of the cues associated with drivers. For example, eight participants reported at least one pedestrian gesture, seven described the body movements of either pedestrians or bicyclists, and five mentioned gaze direction. The number of participants identifying each cue type is indicated by the number of blue points in Figure 13.

As in the analysis of driver cues, a mixed model analysis was conducted in which participant was modeled as a random factor. Main effects of both ambient light condition ($F_{(1, 60.0)} = 6.3$, $p < 0.05$) and cue type were observed ($F_{(10, 67.8)} = 7.3$, $p < 0.01$). The rareness of cues in darkness was rated about 0.5 points higher (more rare) than the cue in daylight ($t(60) = 2.51$, $p = 0.01$). Table 6 shows the rated rareness of each cue ordered by increasing rareness. Note that some of the ratings (e.g., signal lamps, verbal cues from bicyclists, bicycle position) were made by only one participant and caution should be exercised not to over interpret these averages.

Table 6. Least square means of rated rareness of different cues produced by pedestrians/bicyclists (cues are ordered from least rare to most rare based on rating)

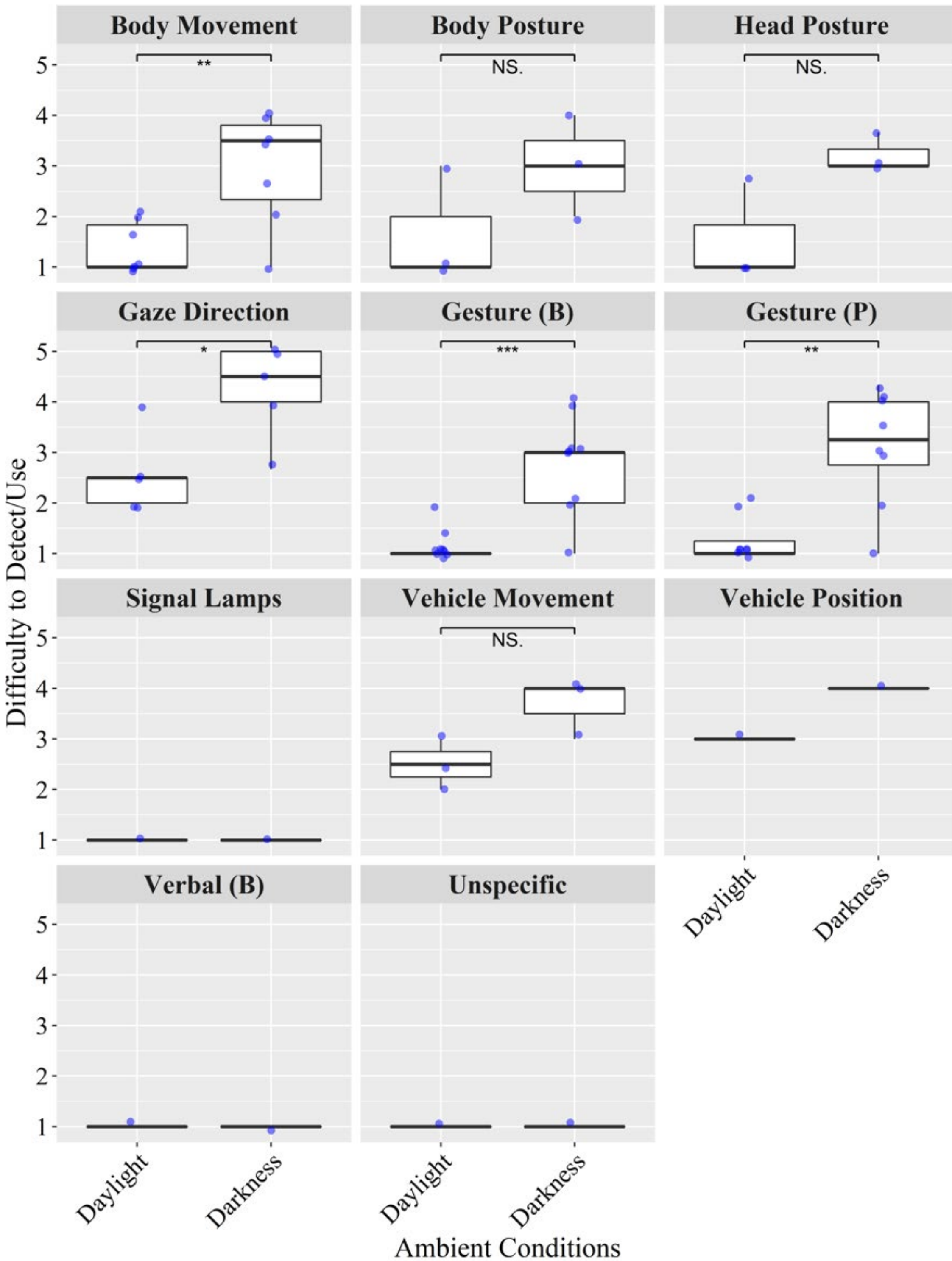
Cue Type	Rated Rareness
Vehicle Position	0.794
Signal Lamps	1.012
Body Posture	1.535
Head Posture	1.598
Body Movement	1.890
Vehicle Movement	1.962
Gaze Direction	2.872
Gesture (B)	2.997
Verbal (B)	3.333
Gesture (P)	3.634

Figure 14 compares the rated difficulty of detecting each of the identified cues in daylight and darkness. Since most cues produced by pedestrians and cyclists are visual cues, it is not surprising to observe the obvious effect of ambient light level on rated difficulty of detection. Daylight/Darkness comparisons of body movement, gaze direction, and gestures of both bicyclists and pedestrians show elevated detection difficulties in darkness. Note that many of the other cues show similar effects, but there are insufficient observations to establish reliability.



Blue points indicate average subject rating collapsed over scenarios
Significance levels are indicated as follows: "*" = .01; "**" = .05; "***" = .001; NS = not significant
Median indicated by thick horizontal line; 25th and 75th percentile intervals indicated by upper/lower box boundaries

Figure 13. Rated rareness of cue occurrence in daylight and dark viewing conditions



Blue points indicate average subject rating collapsed over scenarios
Significance levels are indicated as follows: "*" = .01; "**" = .05; "***" = .001; NS = not significant
Median indicated by thick horizontal line; 25th and 75th percentile intervals indicated by upper/lower box boundaries

Figure 14. Rated difficulty of cue detection in daylight and dark viewing conditions

2.4 Discussion of Study 1

Overall, the results obtained in this survey suggest that participants seemed to generate cues in a manner that varied with the traffic environment. Thus, mention of cues that involved use of explicit gestures were most likely to be offered in low-speed environments where the availability of time, close spatial proximity, and perhaps viewing angle are conducive to such an interaction. In high-speed scenarios—for example, freeway merging and high-speed lane changes—traffic is generally flowing in one direction within travel lanes. This generally restricts the view of other drivers to that which can be seen from behind. High travel speed is also likely to reduce the available time to understand the cue. Participants appeared to recognize this constraint by offering fewer examples of gestures and producing proportionally more cues related to signaling and vehicle motion (see Figure 4).

The results also suggest that different cue categories are judged to be more difficult to use in darkness. This is particularly evident for cues that require judgment of vehicle movements and driver behavioral cues. If vehicle automation provides no substitute for such cues, the resulting situation may be somewhat analogous to anticipating a vehicle's movements in darkness.

An initial implication for vehicle automation suggests that all cues that rely on either the explicit gestures of a driver or the implicit behavior of a driver (e.g., head movement, gaze direction) are absent in an ADS vehicle because the driver is no longer present to produce such cues. The change should have the greatest impact where mention of behavioral cues was prominent. In this study, proportionally more behavioral cues were reported for parking lot, four-way-stop, pulling into traffic, and congested pedestrian area scenarios. If the frequency of mention reflects the level of reliance on these cues, then efforts to address the possible loss of this information should focus on these scenarios.

Less clear is how vehicle automation will affect the use of vehicle motion as a cue used to anticipate a vehicle's maneuver. For some scenarios, participants described the vehicle's movement as part of a two-way negotiation. That is, a vehicle trying to pull into traffic may begin by nudging toward the traffic flow waiting for a sign from other road users that grants permission to enter traffic. For example, participants described the following cues observed while a vehicle is pulling into traffic:

> *Drivers wanting to exit a driveway or shopping center will inch forward; this is a cue to drivers already on the road that they want to come out.*
>
> *Drivers that want to enter the roadway often start to inch forward. When a vehicle positioned somewhere where roadway entry is possible (like at the end of a driveway or along the curb with a driver behind the wheel), look at the vehicle's tires for movement and position angle for evidence that they are inching forward, and clues as to the direction they intend to go.*
>
> *For cars leaving driveway, look at where front of vehicle [is] pointed and direction tires are rolling as a cue if the driver is getting ready to pull out and where he wants to go.*

It is unclear how this exchange could occur with an ADS vehicle. A consummately patient ADS vehicle may simply wait until a good merge opportunity arises and refrain from any "nudging" behavior whatsoever. On the other hand, automation may be required to make allowances for this kind of behavior among human drivers if the automation must share the road with these drivers.

Similarly, lane change cues were often described as an initial wandering in the lane or vehicle deceleration:

> *When drivers intend to change lanes, their vehicle changes position within the lane (it tends to drift left or right). People tend to just grab a small opening to change lanes, so they are getting primed to move quickly.*
>
> *Look at the position of vehicle in other lane; if it is drifting toward your lane, that might be a cue that the other driver is changing lanes.*
>
> *If the driver in the lane is slowing down, that might be a cue that he is letting the other vehicle go ahead.*
>
> *At high speeds, drivers are more likely to just go when they want to change lanes and see an opportunity, so drivers just have to be ready to react to a quick movement from another vehicle. Things are happening so fast in these situations that drivers are less likely to try eye contact and hand signals, and other drivers aren't able to detect head movements at these speeds, so really have to look at the vehicles themselves and the movements they are making.*

It may be that such movements could be considered a form of negotiation that may be either accepted (i.e., the other driver opens a gap) or rejected (i.e., the gap is closed). It is unclear how vehicle automation will alter these movement interactions.

There is normally wide variation in human driving style; there is also great flexibility in how such movements are interpreted and acted on by other road users. Each party to this communication is likely aware of this variation, since both presumably know something about human limitations, and perhaps make allowances for it. With the introduction of automation, it is possible that such style variation will be reduced. Whether drivers respond to this change by reducing their allowances is uncertain.

3 Study 2: Field Observations of Cues Used by Drivers, Pedestrians, and Bicyclists to Predict Intent of Drivers

3.1 Purpose

The objective of Study 2 was to identify the cues currently used by drivers, pedestrians, and bicyclists to determine the intent of other drivers in situations where traffic interactions occur.

Participants performed verbal commentary procedures while engaged in travel through intersections, merge lanes, parking lots, and other situations. Commentary drives is a technique that has been used widely in both research and driver training but rarely applied to pedestrians (Arikawa et al., 2007) and bicyclists. Participants included subgroups of automobile drivers, pedestrians, and bicyclists. For each participant, data collection took place over two sessions including a supervised session on a prescribed route where a researcher communicated with the participant, and a naturalistic, unsupervised session where the participant traveled independently on a nonprescribed route without any communication with researchers.

3.2 Data Collection

3.2.1 Participants

Forty people participated in Study 2, including 23 women and 17 men. The participants represented three groups of road users, including 12 people who frequently drive an automobile, 16 people who frequently travel as pedestrians, and 12 people who frequently travel by bicycle. All participants were between the ages of 18 and 56 and were native English speakers. Potential participants in the driver group were screened by the contractor's corporate background screening unit to ensure that their driving records were in good standing. It was important to represent as many different pedestrian experiences and practices as possible; therefore, we did not have specific screening criteria for how often participants should walk. The only requirement was that they had to be able to travel with or without accommodation for up to 2.5 miles. Two participants completed the study using motorized wheelchairs. With respect to bicyclists, we attempted to recruit participants who indicated they were comfortable riding in the road along with motorized traffic since the data collection route would have them traveling on local roads.

Participants were recruited via notices on the contractor's corporate intranet site, recruitment postcards left at various local establishments, and by word-of-mouth. None of the contractor's employees whose jobs involve transportation research were permitted to participate. Participants were compensated $50 for the first session and $75 for the second session. The contractor's Institutional Review Board (IRB) for the protection of human research participants reviewed and approved the study protocols.

3.2.2 Apparatus

Drivers

Participating drivers wore a head-mounted GoPro video camera that captured their approximate field of view and participants drove their personal vehicle.

Pedestrians

Participating pedestrians wore a head-mounted GoPro video camera that captured their approximate field of view. During the supervised data collection session, the accompanying researcher wore a chest-mounted GoPro video camera to capture a view of the participant within the environment. Participants wore a headset connected to a wireless phone that was used to communicate with the researcher when on different sides of the street. The cell phone was not used during the unsupervised data collection session.

Bicyclists

Two GoPro video cameras were mounted on the participant's bicycle, one was pointed in the forward direction and one was pointed in the reverse direction, capturing approaching traffic. During the supervised data collection session only, a cellphone was also mounted to the participant's bicycle with its face camera facing the forward direction. During the supervised data collection session, a researcher remotely viewed the forward roadway and communicated with the participant through a cellphone application that provided a live video phone call. The participant wore a Bluetooth earpiece and microphone to hear and speak to the researcher. The cellphone was not used during the unsupervised data collection session.

3.2.3 General Procedures

Data collection included a supervised scripted phase and a naturalistic unsupervised phase. In the first (supervised) session the participant interacted with other traffic in a set of predefined scenarios at specific locations that were chosen ahead of time. The traffic scenarios included in the study were chosen based on data regarding common crash scenarios and based on choosing traffic situations where communication of intent between road users is used to avoid or resolve conflicts. During both sessions, participants were instructed to provide verbal commentary as they interacted with the different traffic scenarios. Participants were told to focus on what they thought drivers intended to do and why. Specifically, they were instructed to focus on the cues—what they saw and heard—that helped them to make decisions. Participants were provided with video examples illustrating the verbal commentary procedure, and they took part in a practice trial prior to the start of the actual data collection route.

When not accompanying the participant, researchers observed the interactions and maintained communication with the participant through a hands-free cellphone. For example, some participants needed additional prompting to do more talking aloud, or to focus their comments on the cues that they used to determine the intent of nearby drivers. Researchers also made notes during the session to document the types of interactions observed and insights about the cues available for communicating intent. The first phase of data collection was approximately one hour.

In the second phase of data collection (naturalistic, unsupervised phase), participants collected an hour of additional video commentary data as they traveled anywhere that they chose to go on public roads. They were instructed to not use video data collection equipment in certain sensitive or prohibited areas, such as some government facilities or private property. The purpose of this phase of data collection was to expand the range of scenarios and interactions observed between shared road users. Additionally, the study of naturalistic behavior might include naturally occurring situations (e.g., jaywalking, hurrying, different weather conditions) that were not included in the scripted session.

3.2.4 Specific Procedures

Drivers

The driving route designed for the first session of data collection involved driving on both local roads and highways (see Figure 15) and was about one hour of drive time. The following driving scenarios were included in the route: merges, lane changes, navigating roundabouts or traffic circles, stop signs, right/left turns, U-turns, navigating parking lots, and periods of driving straight. In total, there were 16 planned scenario locations where the participant was prompted to engage in verbal commentary. Any additional verbal commentary made while the participant was driving the route outside of the 16 planned locations was also recorded and analyzed. A researcher was present with the participant throughout the entire drive, providing turn-by-turn instructions, recording notes or remarks made, and was able to ask the participant follow-up questions when necessary. During the session, participants drove their own vehicles. Driving sessions were scheduled during busier time periods when more vehicles would be traveling on the road, including morning and afternoon rush hours and lunch hours (11:45 a.m. – 1:30 p.m.).

The second data collection session was unsupervised. Participants were instructed to drive for at least one hour in a location of their choosing. In most situations, participants chose to drive for their daily commute to or from work. When selecting a route, participants were instructed to select a drive that had a variety of driving maneuvers, including stop signs, traffic signals, lane merges, turns, and so forth. Additionally, participants were told to restrict their second drive to mostly daylight hours (6 a.m. – 8 p.m.) and to try to drive during heavier traffic volume time periods. Prior to conducting their drive, participants were provided with instructions reminding them on proper verbal commentary procedures.

Figure 15. Session 1 driving route

Pedestrians

The walking route designed for the first session of data collection involved signalized intersections, controlled intersections with stop signs, mid-block crossings, crossings with pedestrian-activated traffic control devices (HAWK beacons), driveways, entrances and exits to retail establishments, and parking lots (see Figure 16). The entire route was a distance of 2.5 miles. In total, there were eighteen planned scenario locations where the participant was prompted to engage in verbal commentary. Any additional verbal commentary made while the participant was walking the route outside of the planned locations was also recorded and analyzed. A researcher was present with the participant throughout the walk. At times, the participant was separated from the researcher by a short distance, for example at the opposite end of the crossing. During these times, communication between the researcher and participant was maintained through use of a hands-free cellphone. The researcher provided turn-by-turn instructions, recorded notes or remarks made, and asked the participant follow-up questions when necessary. Walking sessions were scheduled during busier time periods when more vehicles would be traveling on the road, including morning and afternoon rush hours and lunch hours (11:45 a.m. – 1:30 p.m.).

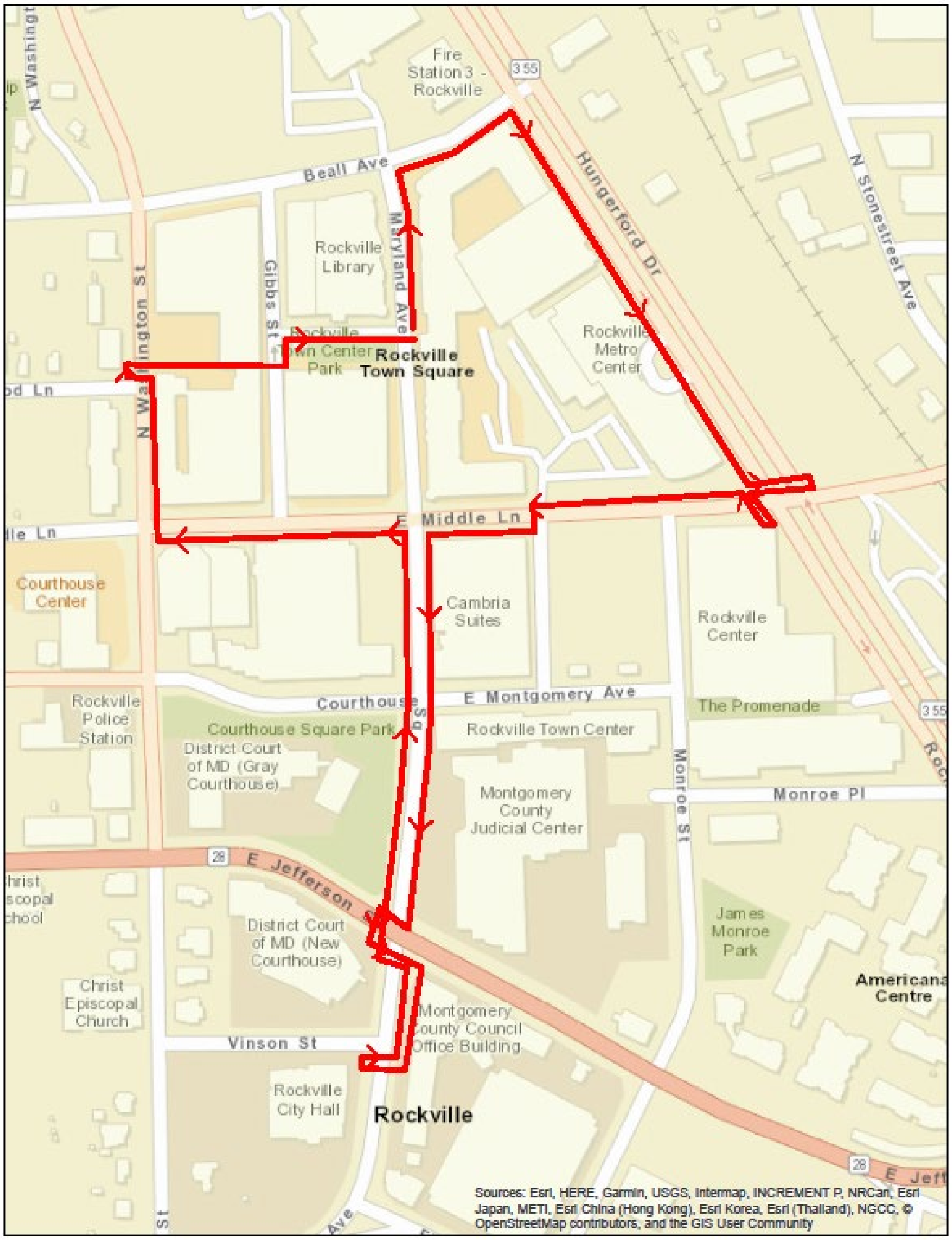


Figure 16. Session 1 pedestrian route

In the second unscripted and unsupervised session, participants were instructed to walk for at least one hour in a location of their choosing. When selecting a route, participants were instructed to select a busy urban or suburban route where there is frequent vehicle traffic. They were also asked to select a route with intersections and street crossings. Participants were told to restrict their walking to daylight hours (6 a.m. – 8 p.m.) and to try to walk during time periods with heavier traffic volume. Prior to conducting their walk, participants were reminded how to engage in proper verbal commentary procedures.

Bicyclists

The riding route designed for the first session of data collection involved signalized intersections, controlled intersections with stop signs, mid-block crossings, right and left turns, driveways, entrances and exits to retail establishments, and bike paths (see *Figure **17***). The participant completed the route twice, one time in each direction. In total, there were fifteen planned scenario locations where the bicyclist may have interacted with other traffic. Additional verbal commentary made while the participant was riding the route outside of the planned locations was also recorded and analyzed. The researcher provided turn-by-turn instructions to the participant, but the participant was also provided with the route prior to the data collection session. Sessions were scheduled during busier time periods when more vehicles would be traveling on the road, including morning and afternoon rush hours and lunch hours (11:45 a.m. – 1:30 p.m.). During the session, the participant rode his/her own bike.

During the unsupervised session, participants rode their bikes for at least one hour in locations of their choosing. Recruited participants indicated in the screener that they frequently ride in the street and with traffic but were not specifically instructed to avoid riding on sidewalks during data collection. They were simply told to ride as they normally would. The researcher told the participants to ride only during daylight hours and suggested that they choose a busy urban or suburban route where there is frequent vehicle traffic, intersections, and street crossings. The researcher also reminded participants about proper verbal commentary procedures for the study. For the unsupervised ride, two cameras were mounted to the participant's bicycle, one faced forward, capturing the roadway ahead, and the other faced backward, capturing the roadway behind and to the left of the rider.

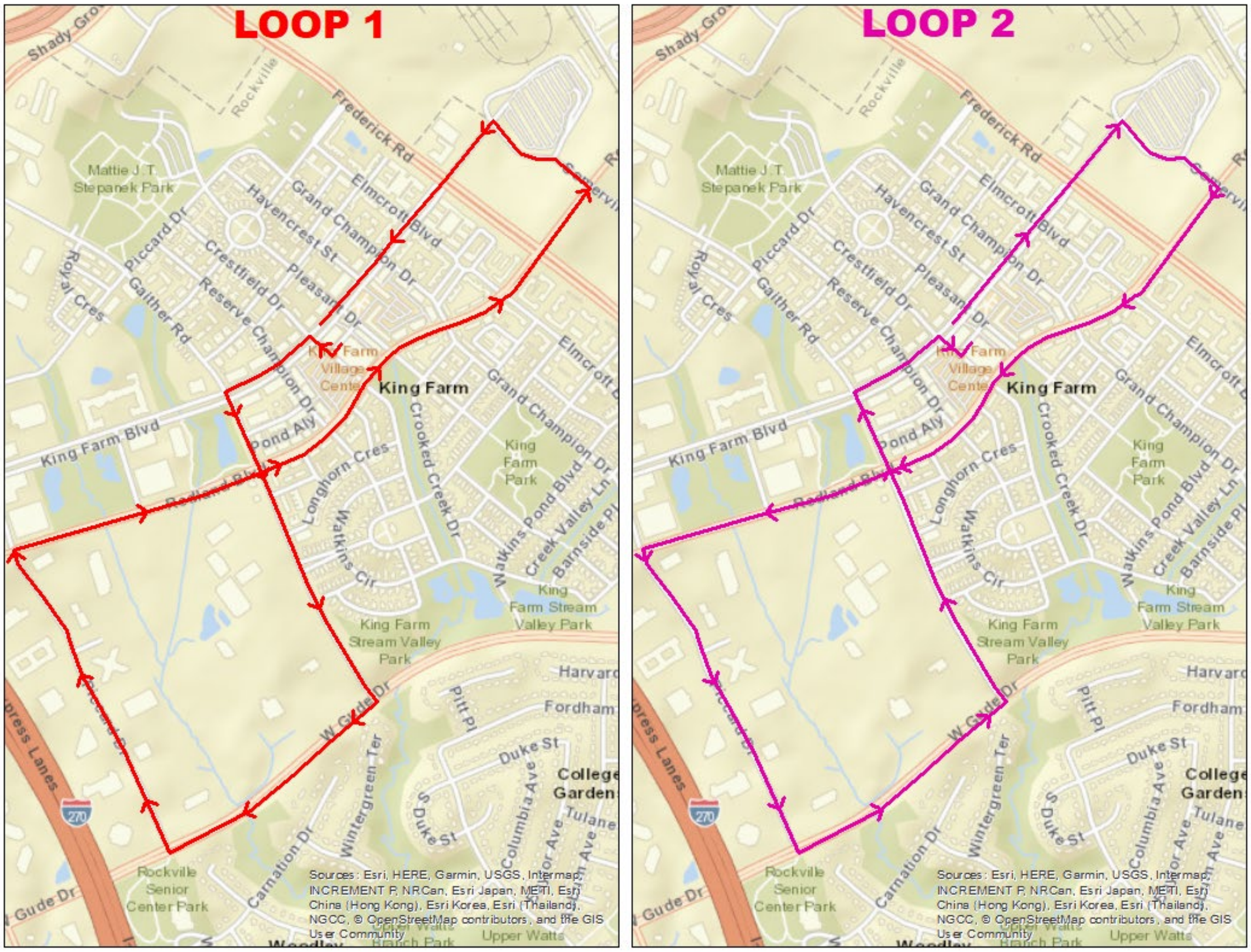


Figure 17. Session 1 bicycle route

3.3 Data Reduction

3.3.1 Video Review

Researchers reviewed video and audio from all data collection sessions using Morae Manager software and coded participants' comments, classifying the cues that they mentioned when referring to other vehicles' and drivers' actions or intent (intent cues). It is important to note that researchers coded what the participants <u>*said*</u> they were paying attention to with respect to traffic and the roadway, not what the participant was actually doing or what was happening during the scenario. Based on preliminary reviews of the data, researchers developed slightly different coding schemes for drivers, pedestrians, and bicyclists to fit the unique circumstances of each of these groups. However, for all three groups of participants, the cues mentioned were categorized into three broad categories: driver-related cues, vehicle-movement cues, and vehicle-signaling systems cues. These categories are defined as follows:

- Driver-related—any cues that pertain specifically to the driver of the vehicle (e.g., eye contact, gaze direction, use of gestures).

- Vehicle movement—any cues that pertain to how the vehicle is moving or not moving (e.g., approach rate, lane changes, drifting, stopped, vehicle noise, such as engine revving, position in lane).
- Vehicle-signaling systems—any cues that pertain to signaling systems already in place in the vehicle (e.g., turn signals, brake lights, hazard lights).

In addition to the cues mentioned by participants regarding the intent of other drivers and vehicles, video coders also noted cases where formal traffic rules were followed or not followed by the participant (e.g., jaywalking in the case of pedestrian participants) as well as any uncertainty expressed by the participant. Researchers also coded the different traffic scenarios the participant experienced when mentioning the different cues that he/she was using to determine driver intent. Traffic scenarios consist of roadway situations like signalized intersections, mid-block crossing, U-turns, parking lots, stop signs, and so forth.

Two researchers reviewed each session, one serving as the primary coder and the second as the quality control reviewer. In rare cases where there were coding discrepancies, a third reviewer was consulted, and the three reviewers together reviewed and discussed the event to reach a consensus. Specific coding and data reduction procedures for the three participant groups are discussed below.

3.3.2 Drivers

Table 7 defines the coded cues that were mentioned by the driver participants and Table 8 lists the traffic scenarios they encountered.

Table 7. Cues used by driver participants

Driver-related cues	Gesture	Participant felt the driver performed a gesture, such as a wave, nod, beckon, thumbs up, etc., to signal intent or communicate.
	Emotional projection	Participant assigned an emotion to the driver.
	Head posture/gaze direction	Participant noted something about where the driver was looking or the position of the driver's head.
	Eye contact	Participant specifically indicated that eye contact was made, or that he/she was looking for eye contact with another driver.
	Distracted	Participant felt that the driver was distracted by something or someone.
	Presence of driver in vehicle	Participant noted the physical presence of a person in the driver's seat.
	*Verbal communication	Participant indicated that he/she had or was looking for dialog with the driver.
Vehicle-movement cues	Slowing down	Participant indicated the vehicle was slowing down.
	Speeding up	Participant indicated the vehicle was speeding up.
	Approach rate	Participant commented on vehicle speed; typically, this was in comparison to other traffic.
	Position in lane	Participant indicated something about the vehicle's position in the lane; this might include driving in a

Vehicle-movement cues (cont.)		turn-only lane or the physical location of the vehicle toward one side of the lane over the other.
	Distance away	Participant mentioned the distance away of an approaching vehicle as a cue.
	Tailgating	Participant commented that a vehicle was either following at a close distance to his/her vehicle or another vehicle.
	Swerving/drifting in lane	Participant noted that a vehicle was swerving or drifting in a lane.
	Vehicle creeping	Participant described a vehicle inching forward, usually from a stopped position.
	Arrival order (at stop sign)	Participant indicated that order of arrival dictated which vehicle gets to proceed first; this typically occurred at stop signs.
	Position in lane during turn	Participant commented about a vehicle staying within its lane during a turn.
	Traffic volume	Participant commented on either low- or high-traffic volume.
	Lane change	Participant noted that a vehicle made a lane change.
Vehicle-signaling systems	Headlamp flash	Participant indicated the driver flashed the vehicle headlamps.
	Horn	Participant noted that a horn was used.
	Turn signal	Participant mentioned that the driver either used or did not use a turn signal when making a maneuver.
	Backup lights	Participant commented on the illumination of the backup lights.
	Brake lights	Participant noted the illumination of the brake lights.
	Hazard lights	Participant mentioned driver use of the hazard lights.
	Headlamp use	Participant mentioned use or nonuse of the headlamp.
Miscellaneous	General uncertainty	Participant expressed uncertainty about what a vehicle/driver intended to do.
	Violation of expectations/traffic laws	Participant expressed surprise with respect to another vehicle on the roadway, violation of informal norms, or indicated that a vehicle violated a traffic law.

**Researchers planned to code for this cue but participants did not mention it.*

Table 8. Traffic scenarios encountered by driver participants

Driving straight	Participant was driving straight when the comment was made.
Intersection	Participant was at an intersection when the comment was made.
Lane change/merge	Participant was engaged in a lane change or merge when the comment was made.
Parking lot	Participant was driving in a parking lot when the comment was made.
Stop sign	Participant was at a stop sign when the comment was made.
Traffic circle	Participant was navigating a traffic circle when the comment was made.
Turn	Participant was engaged in a left or right turn when the comment was made.
U-turn	Participant was engaged in a U-turn when the comment was made.

3.3.3 Pedestrians

Table 9 defines the coded cues mentioned by the pedestrian participants, and Table 10 shows the traffic scenarios encountered pedestrians.

Table 9. Cues used by pedestrian participants

Driver-related cues	Gesture - driver initiated	Participant felt the driver performed a gesture (e.g., wave, nod, beckon, thumbs up) to signal intent or communicate.
	Emotional projection	Participant assigned an emotion to the driver.
	Head posture/gaze direction	Participant noted something about where the driver was looking or the position of the driver's head.
	Eye contact	Participant specifically indicated that eye contact was made or that he/she was looking for eye contact.
	Distracted	Participant felt that the driver was distracted by something or someone.
	Presence of driver in vehicle	Participant noted the physical presence of a person in the driver's seat.
	Verbal communication	Participant indicated that he/she had or was looking for dialog with the driver.
Vehicle-movement cues	Slowing down	Participant indicated the vehicle was slowing down.
	Speeding up	Participant indicated the vehicle was speeding up.
	Approach rate	Participant commented on vehicle speed; typically, this was in comparison to other traffic.
	Direction of travel/orientation of tires	Participant commented about a vehicle's direction of travel; for example, going straight versus turning, or specifically the orientation of the vehicle's tires.
	Vehicle came to complete stop	Participant noted that the vehicle came to a complete stop.

Vehicle-movement cues (cont.)	Position in lane	Participant indicated something about the vehicle's position in the lane; this might include driving in a turn-only lane or the physical location of the vehicle toward one side of the lane over the other.
	Distance away	Participant mentioned the distance away of an approaching vehicle as a cue.
	Distance from crosswalk	Participant noted the distance a vehicle came to a stop from a crosswalk.
	Lane change	Participant noted that a vehicle made a lane change.
	Vehicle creeping	Participant described a vehicle inching forward, usually from a stopped position.
	Traffic volume	Participant commented on either low or high traffic volume.
	Vehicle noise	Participant commented on noises made by the vehicle, such as the engine accelerating or decelerating, brakes squealing, etc.
Vehicle-signaling systems	Headlamp flash	Participant indicated the driver flashed the vehicle headlamps.
	Horn	Participant noted that a horn was used.
	Turn signal	Participant mentioned that the driver either used or did not use a turn signal when making a maneuver.
	Backup lights	Participant commented on the illumination of the backup lights.
	*Brake lights	Participant noted the illumination of the brake lights.
	*Hazard lights	Participant mentioned driver use of the hazard lights.
Other cues used	Other pedestrians	Participant mentioned the presence of other pedestrians as a cue that was safe to walk.
	Used crosswalk signal	Participant explicitly stated that he/she used the crosswalk signal as a cue that it was safe to cross.
Pedestrian-initiated actions	Gesture – pedestrian initiated	Participant initiated a gesture, such as a wave, nod, beckon, thumbs up, etc., to signal intent or communicate with a vehicle driver.
	Improper cross	Participant choose to engage in an improper cross, either jaywalking or crossing against the traffic signal.
Miscellaneous	General uncertainty	Participant expressed uncertainty about what a vehicle/driver intended to do.
	Violation of expectations/traffic laws	Participant expressed surprise with respect to another vehicle on the roadway or indicated that a vehicle violated a traffic law.

** Researchers planned to code for this cue, but participants did not mention it.*

Table 10. Traffic scenarios encountered by participants

Driveway	Participant was crossing a driveway when the comment was made.
HAWK signal	Participant was at a crossing with a HAWK signal when the comment was made.
Intersection – traffic signal	Participant was at an intersection controlled by a traffic signal when the comment was made.
Intersection – stop sign	Participant was at an intersection controlled by a stop sign when the comment was made.
Mid-block crossing	Participant was engaged in a mid-block crossing when the comment was made.
Parking lot	Participant was traveling through a parking lot when the comment was made.

3.3.4 Bicyclists

Table 11 defines the cues mentioned by bicyclist participants and Table 12 displays the traffic contexts encountered by bicyclists.

Table 11. Cues used by bicyclist participants

Driver-related cues	Gesture - driver initiated	Participant felt the driver performed a gesture (e.g., wave, nod, beckon, thumbs up) to signal intent or communicate.
	Emotional projection	Participant assigned an emotion to the driver.
	Head posture/gaze direction	Participant noted something about where the driver was looking or the position of the driver's head.
	Eye contact	Participant specifically indicated that eye contact was made or that he/she was looking for eye contact.
	Distracted	Participant felt that the driver was distracted by something or someone.
	Presence of driver in vehicle	Participant noted the physical presence of a person in the driver's seat.
	Verbal communication	Participant indicated that he/she had or was looking for dialog with the driver.
Vehicle-movement cues	Slowing down	Participant indicated the vehicle was slowing down.
	Speeding up	Participant indicated the vehicle was speeding up.
	Approach rate	Participant commented on vehicle speed; typically, this was in comparison to other traffic.
	Direction of travel/orientation of tires	Participant commented about a vehicle's direction of travel; for example, going straight or turning, or specifically the orientation of the vehicle's tires.
	Vehicle came to complete stop	Participant noted that the vehicle came to a complete stop.

Vehicle-movement cues (cont.)	Position in lane	Participant indicated something about the vehicle's position in the lane; this might include driving in a turn-only lane or the physical location of the vehicle toward one side of the lane over the other.
	Distance away	Participant mentioned the distance away of an approaching vehicle as a cue.
	Distance – behind	Participant mentioned the distance of a vehicle behind his/her bicycle.
	Distance – next to	Participant mentioned the distance of a vehicle next to his/her bicycle.
	Distance – in front	Participant mentioned the distance of a vehicle in front of his/her bicycle.
	Lane change	Participant noted that a vehicle made a lane change.
	Vehicle creeping	Participant described a vehicle inching forward usually from a stopped position.
	Traffic volume	Participant commented on either low or high traffic volume.
	Vehicle noise	Participant commented on noises made by the vehicle (e.g., the engine accelerating or decelerating, brakes squealing)
	Vehicle door opening	Participant noted the vehicle door and whether or not it was ajar, usually in a situation when the participant was passing parked vehicles.
	Vehicle crossed over double yellow line	Participant noted that a vehicle crossed over to the other side of the road, usually in a situation where the vehicle was passing the participant.
Vehicle-signaling systems	Headlamp flash	Participant indicated the driver flashed the vehicle headlamps.
	Horn	Participant noted that a horn was used.
	Turn signal	Participant mentioned that the driver either used or did not use a turn signal when making a maneuver.
	Backup lights	Participant commented on the illumination of the backup lights.
	Brake lights	Participant noted the illumination of the brake lights.
	Hazard lights	Participant mentioned driver use of the hazard lights.
Bicyclist initiated actions	Gesture – bicyclist initiated	Participant initiated a gesture (e.g., wave, nod, beckon, thumbs up) to signal intent or communicate with a vehicle driver.
	Bicyclist signaled	Participant used standardized hand signals to communicate intent to a vehicle driver.
	Biking on sidewalk	Participant choose to bike on the sidewalk instead of in the street with traffic.
	Used crosswalk	Participant choose to navigate an intersection by using the pedestrian crosswalk.
	Bicyclist disobeyed traffic signal	Participant crossed against a traffic signal.

Miscellaneous	General uncertainty	Participant expressed uncertainty about what a vehicle/driver intended to do.
	Violation of expectations/traffic laws	Participant expressed surprise with respect to another vehicle on the roadway or indicated that a vehicle violated a traffic law.

Table 12. Traffic contexts encountered by bicyclists

Bicyclist changed lanes	Participant was engaged in a lane change when the comment was made.
Biking straight	Participant was biking straight when the comment was made.
Driveway	Participant was crossing or passing a driveway when the comment was made.
Left turn at intersection with light	Participant was making a left turn at an intersection controlled by a traffic signal when the comment was made.
Left turn at intersection with Stop Sign	Participant was making a left turn at an intersection controlled by a stop sign when the comment was made.
Parking lot	Participant was traveling through a parking lot when the comment was made.
Right turn at intersection with light	Participant was making a right turn at an intersection controlled by a traffic signal when the comment was made.
Right turn at intersection with stop sign	Participant was making a right turn at an intersection controlled by a stop sign when the comment was made.
Straight at intersection with light	Participant was proceeding straight at an intersection controlled by a traffic signal when the comment was made.
Straight at intersection with stop sign	Participant was proceeding straight at an intersection controlled by a stop sign when the comment was made.
Straight at intersection with no control	Participant was proceeding straight at an intersection without a traffic control device.
U-turn	Participant was engaged in a U-turn when comment was made.

3.4 Results

3.4.1 Comparison of Cues Used by Drivers, Pedestrians, and Bicyclists

Figure 18 represents the proportion of cues used in both sessions by the three participant subgroups (drivers, pedestrians, and bicyclists). The three groups were similar, with most participants focusing on vehicle-movement cues (drivers 70%, pedestrians 74%, and bicyclists 72%). However, participants in both the pedestrian and bicyclist groups tended to rely on driver-related cues (pedestrians 17% and bicyclists 18%) more than vehicle-signaling systems (pedestrians 9% and bicyclists 10%). This pattern was not shared by drivers. Instead, drivers mentioned using vehicle signaling system cues 23 percent of the time and driver-related cues 7 percent of the time.

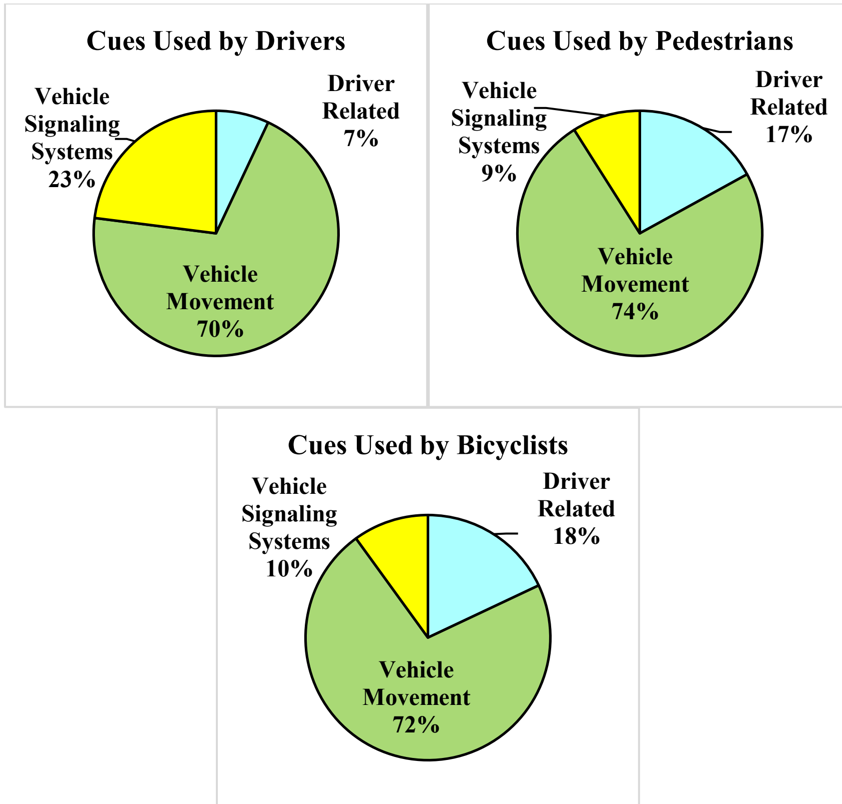


Figure 18. Cues used by participants

When comparing cues used in session 1 (prescribed route) to session 2 (naturalistic, unprescribed route), each of the participant subgroups had roughly the same proportions. The next sections of the report discuss each of the participant subgroups individually.

3.4.2 Drivers

As previously discussed, drivers tended to rely on cues from other drivers less than the other participant groups. The data from both sessions revealed that participants' mention of driver-related cues related to emotional projections 38 percent of the time, a value representing comments from 9 out of the 12 participants. In these cases, participants would assign a state of being to the other driver, usually based upon some behavioral component they felt they saw. Examples include "lazy," "in a hurry" or "late," "aggressive," "impatient," and "lost." Participants in the driver group mentioned using gestures from other drivers as the next most frequently cited driver-related cue (18% or 7 out of 12 participants), followed closely by head posture/gaze direction (17% or 7 out of 12 participants). Participants only mentioned eye contact 10 percent of the time, and only 4 of the 12 participants mentioned this as a cue they used. Participants also mentioned the presence of a driver in a vehicle 9 percent of the time, but this was usually when driving in parking lots. Drivers mentioned that other drivers appeared distracted in 8 percent of the total counts for driver-related cue. While this may not be directly related to interpreting driver intent, it certainly might impact how the other driver responds if he/she feels another driver is distracted away from the task of driving. Table 13 shows the number of participants out of 12 who mentioned the different driver-related cues, and Figure 19 shows the percent of total counts for each of the different cues that are driver-related.

Table 13. Number of driver group participants who mentioned driver-related behaviors

Driver-Related Behaviors	*N* (of 12)	Percentage of Drivers	Total Counts
Emotional projection	9	75%	30
Gesture	7	58%	14
Head posture/gaze direction	7	58%	13
Eye contact	4	33%	8
Presence of driver in vehicle	4	33%	7
Distracted	4	33%	6

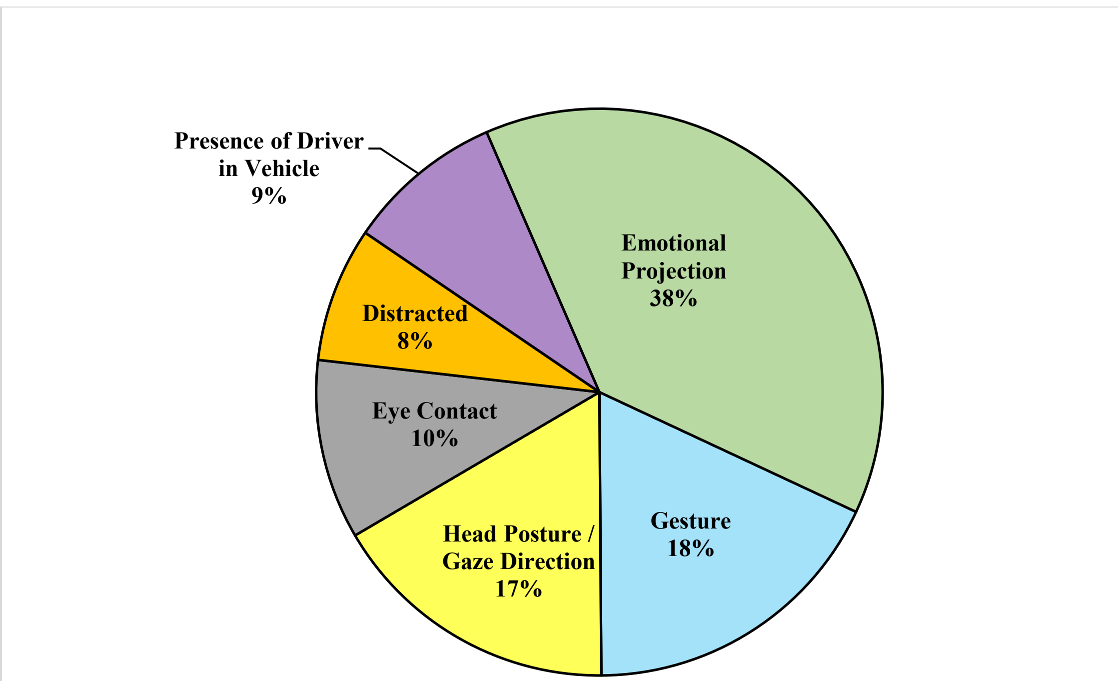


Figure 19. Percentage of total counts for driver-related cues – driver group

Vehicle-movement cues accounted for most of the cues mentioned by drivers. When looking at data for both sessions, a vehicle's position in lane and its approach rate were the two most commonly cited vehicle-movement cues (25% and 23%, respectively) and they were mentioned by all 12 participants. Seventeen percent of the vehicle-movement cues were distance away. In these cases, drivers said things like, "The car is far enough away that it is safe for me to pull out." Several other cues, including traffic volume, position in lane during turn, vehicle creeping, arrival order, and tailgating each represented 2 percent or less of the vehicle-movement cues mentioned. For example, position in lane during a turn only was commented on during a turning scenario. Similarly, arrival order was usually only discussed at intersections with stop signs.

Table 14 shows the number of participants out of 12 who mentioned the different vehicle-movement cues, and Figure 20 depicts the percent of total counts for each of the different cues that are vehicle movement-related.

Table 14. Number of driver group participants who mentioned vehicle-movement cues

Vehicle Movements	***N* (of 12)**	**Percentage of Drivers**	**Total Counts**
Position in lane	12	100%	207
Approach rate	12	100%	189
Lane change	12	100%	113
Slowing down	12	100%	88
Swerving/drifting in lane	9	75%	13
Position in lane during turn	8	67%	18
Vehicle creeping	8	67%	16
Speeding up	7	58%	10
Distance away	5	42%	142
Tailgating	5	42%	10
Arrival order	4	33%	7
Traffic volume	4	33%	4

Vehicle-signaling systems were the second most frequently used category of cues for drivers. When looking at data from both sessions, the use and non-use of a turn signal accounted for over half of these cues (54%) and was mentioned by all 12 participants. The illumination of brake lights represented 30 percent of the cues mentioned in this group and was mentioned by 11 of the 12 participants. Hazard lights and headlamp use did not represent a large percent of the cues mentioned (2% and 1%, respectively, and only mentioned by 4 and 2 participants). This is not surprising because the study was run during daylight hours and therefore headlamp use was likely not needed unless in inclement weather and use of hazard lights is not common.

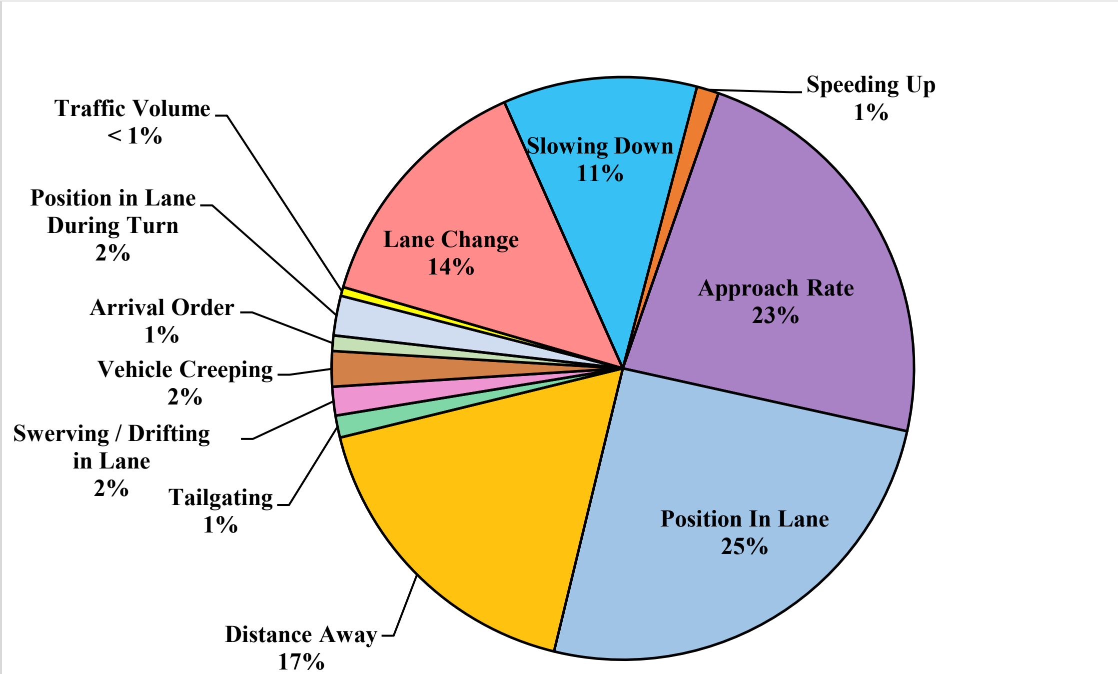


Figure 20. Percentage of total counts for vehicle related cues – driver group

Table 15 shows the number of participants out of 12 who mentioned the different vehicle signaling system cues, and Figure 21 depicts the percent of total counts for each of the different cues that are vehicle signaling system-related.

Table 15. Number of driver group participants who mentioned vehicle signaling system cues

Vehicle-signaling systems	*N* (of 12)	Percentage of Drivers	Total Counts
Turn signal	12	100%	144
Brake lights	11	92%	80
Backup lights	9	75%	21
Horn	8	67%	9
Hazard lights	4	33%	5
Headlamp flash	3	25%	5
Headlamp use	3	25%	3

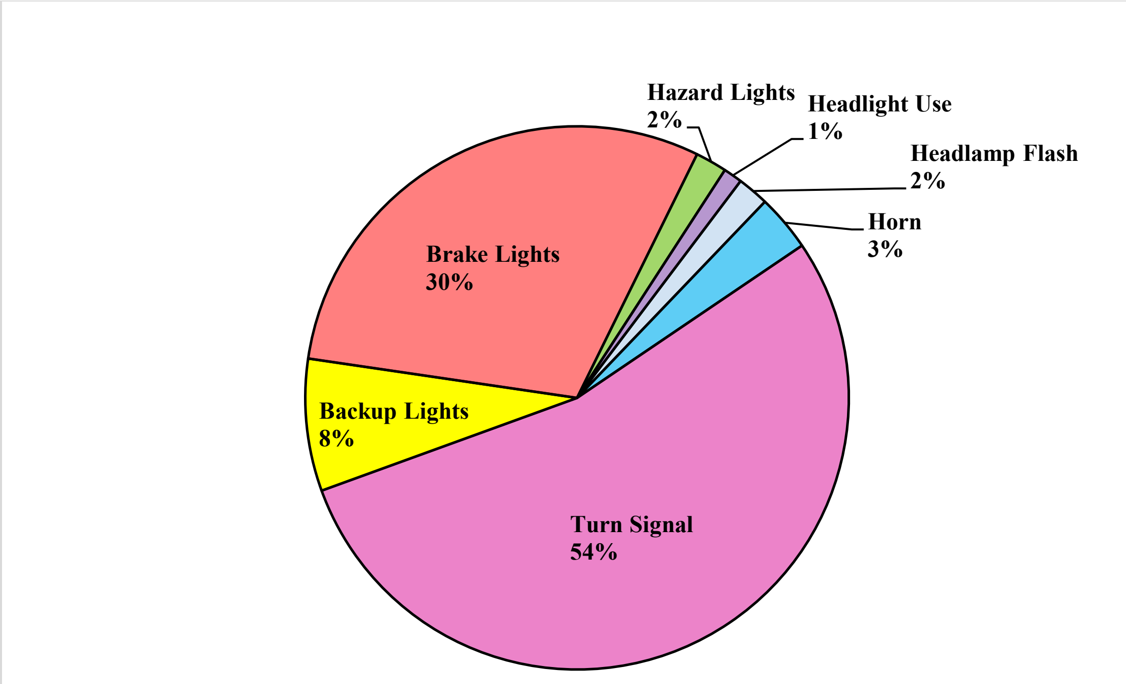


Figure 21. Percentage of total counts for vehicle signaling system-related cues – driver group

In all of the session 1 traffic scenarios, vehicle-movement cues were relied on most by participants in the driver group. In all scenarios, vehicle-movement cues represented more than 60 percent of the cues mentioned. Situations where driver-related cues were relied upon more included stop signs and turns, each accounting for 13 percent of the cues mentioned. However, in both of these situations, driver-related cues were equal to vehicle signaling system cues (also 13%) and the vehicle-movement cues represented approximately 75 percent of the cues mentioned. In the U-turn traffic context, 100 percent of the cues mentioned were vehicle movement-related. However, this finding should be interpreted with caution as there was only one U-turn on the drive, and this value only represents 7 of the 12 participants. The remaining 5 participants did not mention any cues used, possibly because no other vehicle was present during the maneuver. *Figure* ***22*** shows the proportion of cues mentioned for the eight different traffic contexts that occurred during session 1 for the driver group.

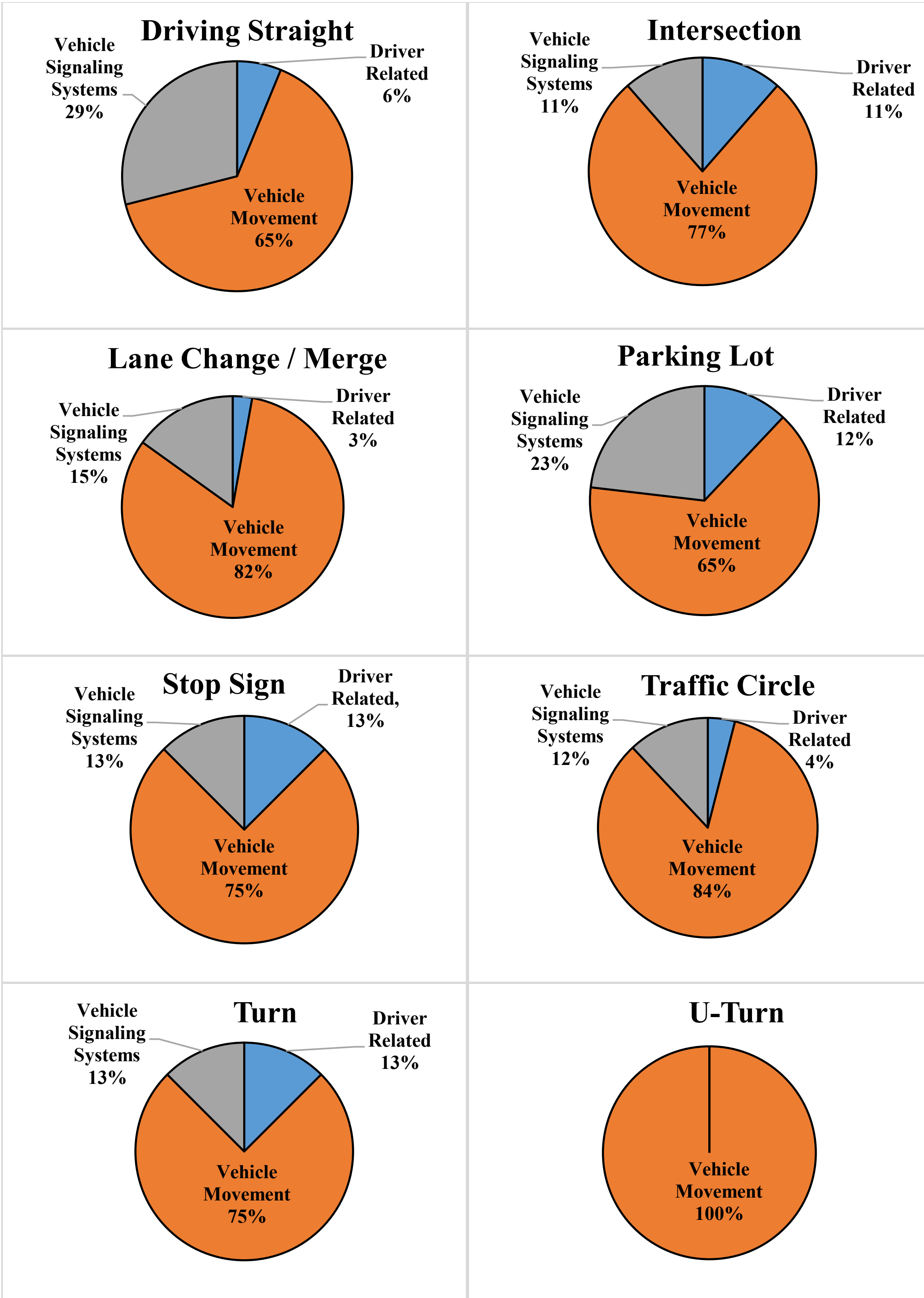


Figure 22. Percentage of cues used during different driving contexts – drivers

3.4.3 Pedestrians

As previously mentioned, pedestrian participants tended to mention driver-related cues more than participants in the driver group. Driver-related cues represented 17 percent of the cues used by pedestrians. When examining driver-related cues for both sessions, gestures initiated by the driver represented the most cues mentioned at 33 percent, and 15 out of 16 participants used driver gestures as a cue. Some examples of comments made by participants include, “The nod of her head confirmed she saw me and would not run me over,” “He lifted his hands off the wheel and motioned for me to keep walking,” and “If she had gestured or motioned to go forward, I would have because she was blocking the car behind her… I did not want to get in the situation where courtesy introduced ambiguity, so I just stopped and let her make the decision.” Also notable was eye contact, which represented 28 percent of the driver-related cues used. Examples of comments made by participants include, “I just look for eye contact; if I don’t have it, I don’t cross” and “The driver wasn't really making eye contact, just looking in my direction. To me that told me she was not going to give way.” With respect to less frequently mentioned cues, presence of a driver in the vehicle and verbal communication both accounted for less than 1 percent of the driver-related cues mentioned. Table 16 shows the number of participants out of 16 who mentioned the different driver-related cues, and Figure 23 depicts the percent of total counts for each of the different cues that are driver-related.

Table 16. Number of pedestrian group participants who mentioned driver-related cues

Driver-Related Behaviors	*N* (of 16)	Percentage of Pedestrians	Total Counts
Gesture	15	94%	94
Eye contact	14	88%	79
Emotional projection	12	75%	29
Distracted	12	75%	23
Head posture/ gaze direction	11	69%	58
Presence of driver in vehicle	1	6%	1
Verbal communication	1	6%	1

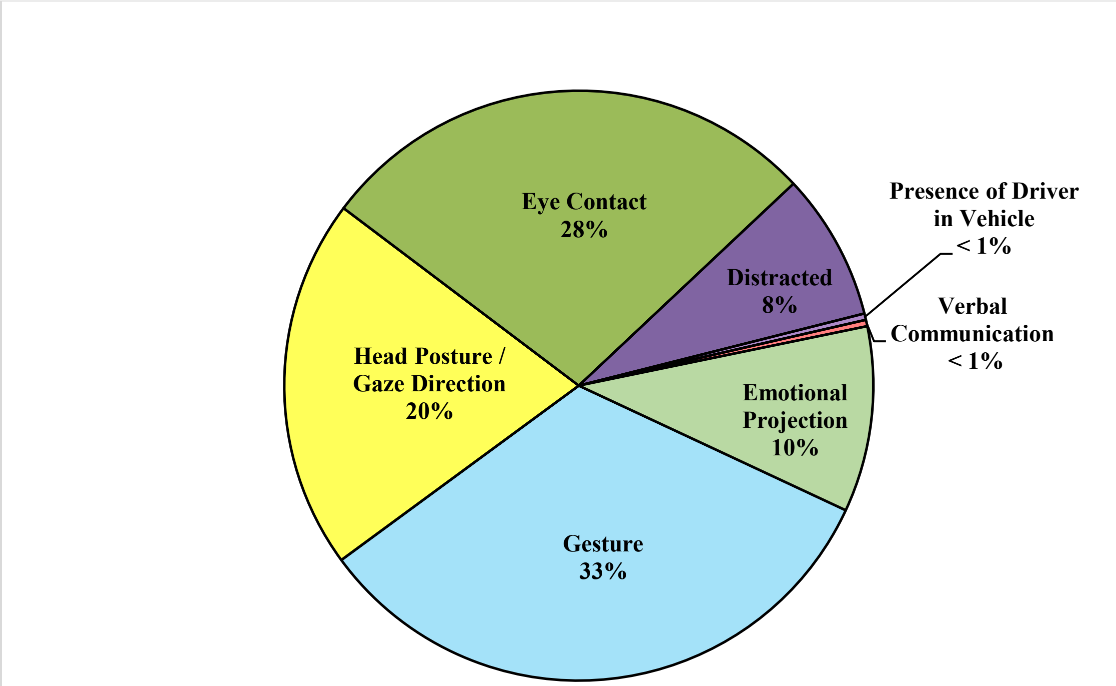


Figure 23. Percentage of total counts for driver-related cues – pedestrian group

Vehicle-movement cues accounted for most of the cues mentioned by pedestrians (74%). When looking at data for both sessions, a vehicle's direction of travel/orientation of tires was the most commonly cited cue (32%), and this cue was mentioned by all 16 participants. All 16 participants also mentioned the vehicle coming to a complete stop as a cue. This particular cue represented 24 percent of all vehicle-movement cues mentioned. Examples of comments made by participants include, "I was looking to verify the cars were stationary," "He came to a complete stop; he was not even creeping," and "I hesitate; I like to see cars stop." Nineteen percent of the vehicle-movement comments made were focused on vehicle approach rate.

While it only represents 4 percent of the total vehicle-movement cues mentioned, 13 of the 16 participants mentioned the distance between the crosswalk and where the vehicle stopped as something they pay attention to when crossing the street. In particular, pedestrians seemed to notice if stopped vehicles were positioned into the crosswalk or over the line. Table 17 shows the number of participants out of 16 who mentioned the different vehicle-movement cues, and Figure 24 depicts the percent of total counts for each of the different cues that are vehicle movement-related.

Table 17. Number of pedestrian group participants who mentioned vehicle-movement cues

Vehicle Movements	*N* (of 16)	Percentage of Pedestrians	Total Counts
Direction of travel/orientation of tires	16	100%	404
Vehicle came to complete stop	16	100%	296
Approach rate	16	100%	240
Slowing down	16	100%	105
Distance away	15	94%	65
Position in lane	14	88%	57
Distance from crosswalk	13	81%	45
Vehicle creeping	9	56%	24
Vehicle noise	6	38%	9
Traffic volume	3	19%	4
Speeding up	3	19%	3
Lane change	2	13%	2

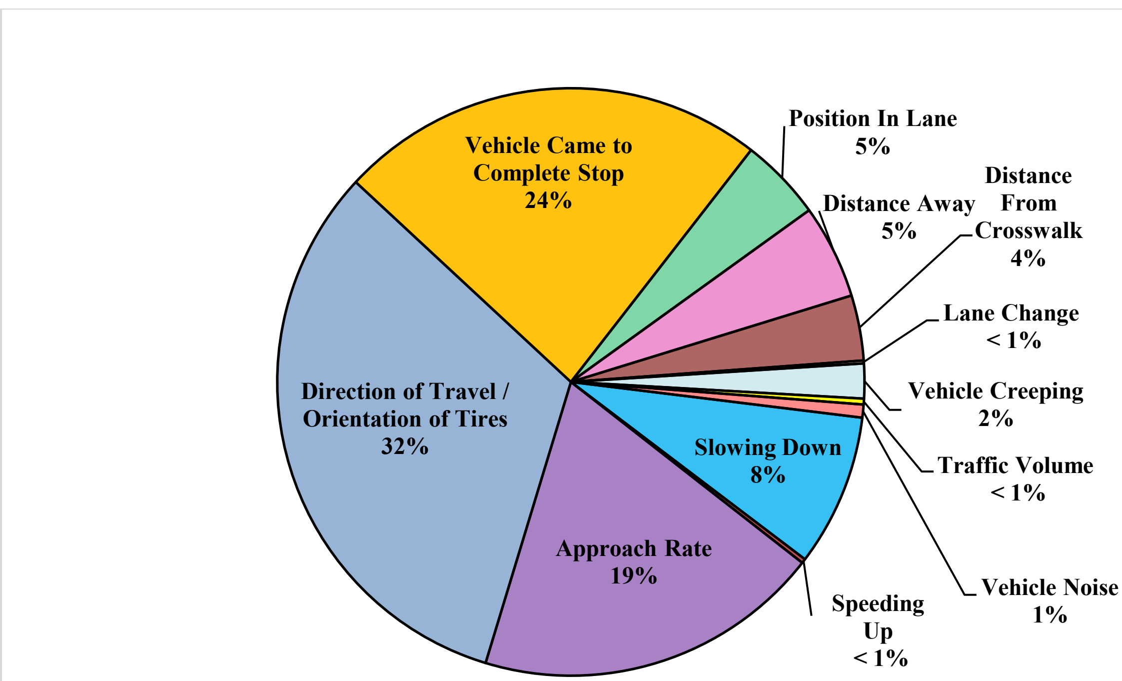


Figure 24. Percentage of total counts for vehicle-movement cues – pedestrian group

Vehicle signaling system cues represented 9 percent of the cues used by pedestrians. When looking at data from both sessions, the use and nonuse of a turn signal accounted for majority of these cues (92%) and was mentioned by 15 of the 16 participants. Table 18 shows the number of participants out of 16 who mentioned the different vehicle signaling system cues, and Figure 25 depicts the percent of total counts for each of the different cues that are related to vehicle-signaling systems.

Table 18. Number of pedestrian group participants who mentioned vehicle signaling system cues

Vehicle-signaling systems	***N* (of 16)**	**Percentage of Pedestrians**	**Total Counts**
Turn signal	15	94%	144
Horn	6	38%	6
Headlamp flash	4	25%	4
Backup lights	3	19%	3

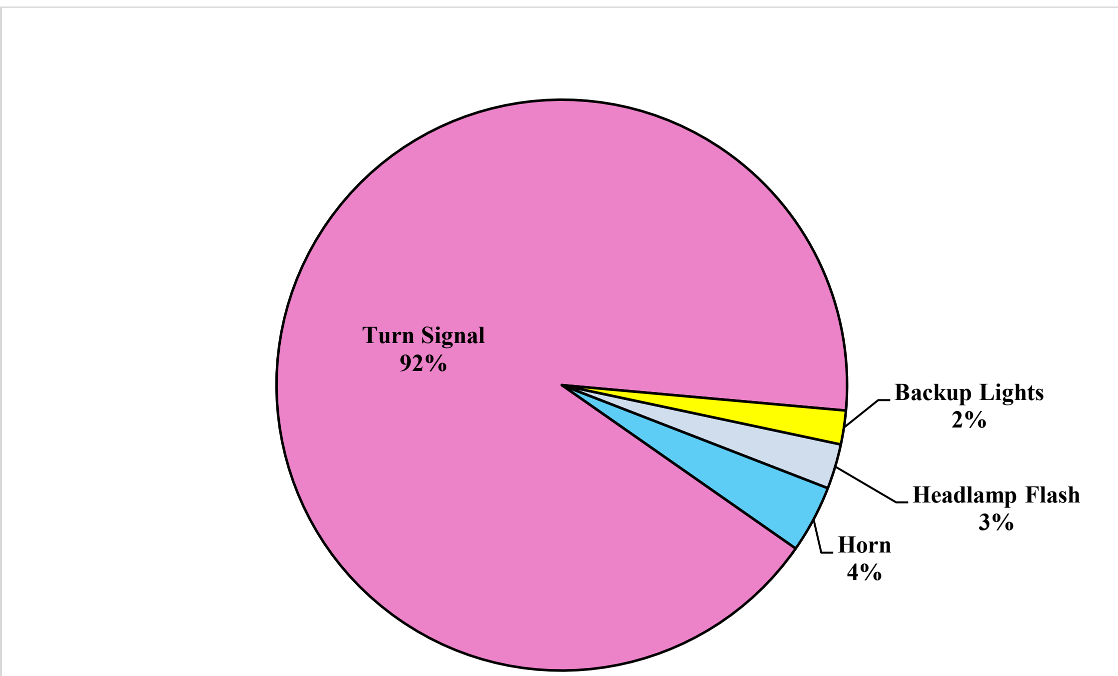


Figure 25. Percentage of total counts for vehicle signaling system cues – pedestrian group

In all of the session 1 traffic scenarios, participants in the pedestrian group relied most on vehicle-movement cues. In all scenarios, vehicle-movement cues represented 50 percent or more of the cues mentioned. Situations where driver-related cues were relied upon more included mid-block crossings, where driver-related cues accounted for 21 percent of the cues mentioned, as well as driveways and HAWK signal crossings, each accounting for 14 percent of the cues mentioned. Vehicle signaling system cues were seen most at stop signs, where they accounted for 22 percent of the cues mentioned, and 100 percent of these were turn signal use. Figure 26 shows the proportion of cues mentioned for the six different traffic scenarios that occurred during session 1.

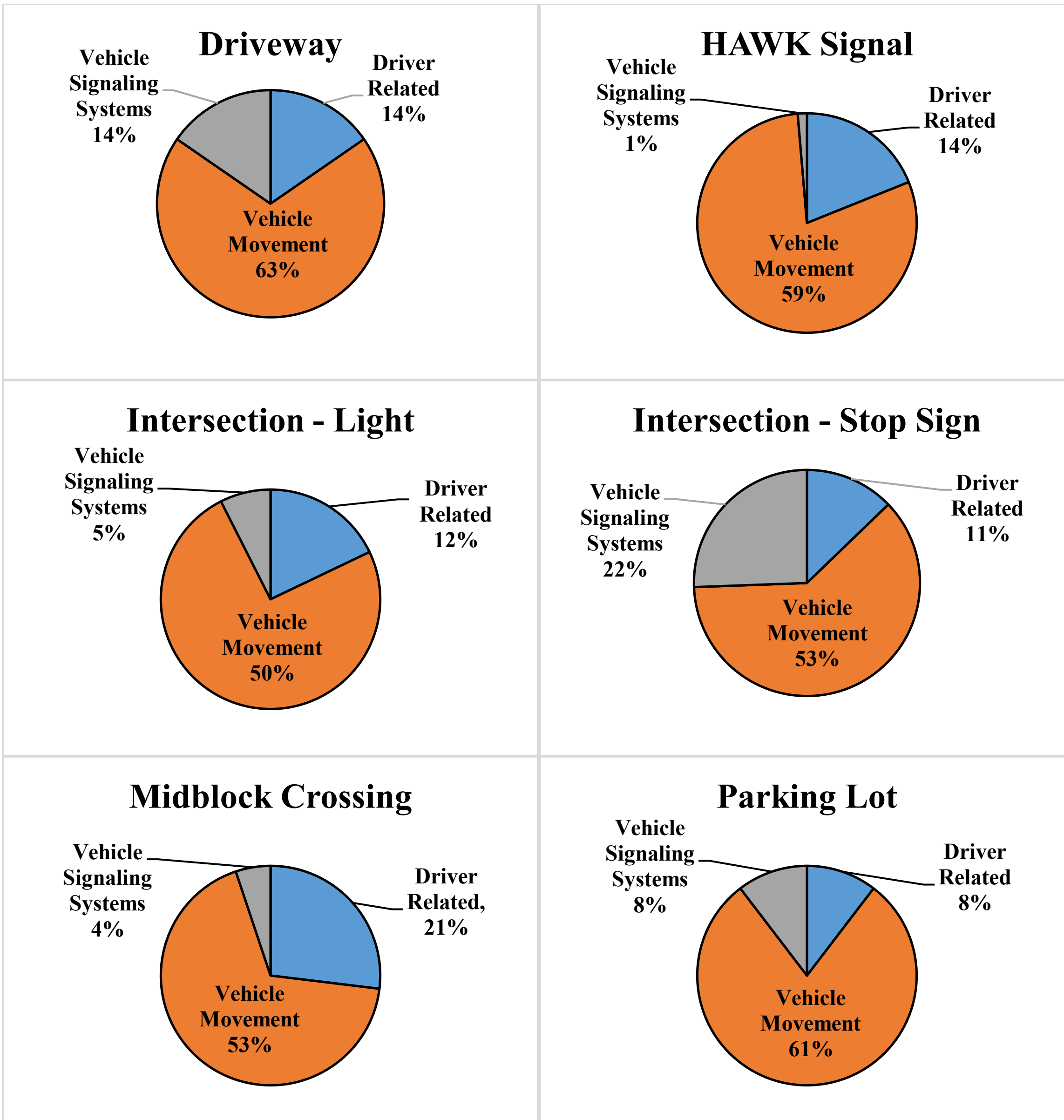


Figure 26. Percentage of cues used during different walking contexts - pedestrians

Six of the 16 pedestrian participants mentioned that they used the presence of other pedestrians crossing as a cue that it was safe to cross. Examples of comments include, "There were other people crossing the other direction at the same time…we were all a big group, so that made me feel really good" and "I knew the car was stopping for someone else in front of me." All 16 participants indicated that they rely heavily on the crosswalk signal to know when it is safe to cross (284 comments were made about using the crosswalk signal), yet throughout both sessions, 8 of the participants engaged in an improper cross 17 times, either by jaywalking or crossing against the traffic signal. Also, over the course of both sessions, 12 different participants commented a total of 50 times that they initiated communication with a driver by gesturing.

3.4.4 Bicyclists

Similar to pedestrians, bicyclists also mentioned driver-related cues more than the drivers did. Driver-related cues accounted for 18 percent of the total cues mentioned by bicyclists. When examining driver-related cues for both sessions, head posture/gaze direction cues represented the largest percentage at 30 percent, and all 12 participants mentioned it. This was followed by eye contact, which accounted for 20 percent of the total driver-related cues mentioned by bicyclists. Eye contact was mentioned by 10 of the 12 participants. One participant indicated that "she always seeks out eye contact." Unique to the bicycle group, presence of driver in vehicle was mentioned by all 12 participants and accounted for 13 percent of the total driver-related cues. This cue was most often mentioned in situations where participants were passing parked cars, and there was a concern about drivers pulling out or vehicle doors opening. Of the driver-related cues, verbal communication was only mentioned by 4 participants, and it accounted for only 2 percent of the total cues. Table 19 shows the number of participants out of 12 who mentioned the different driver-related cues, and Figure 27 depicts the percent of total counts for each of the different cues that are driver-related.

Table 19. Number of bicyclist group participants who mentioned driver-related cues

Driver-Related Behaviors	*N* (of 12)	Percentage of Bicyclists	Total Counts
Head posture/gaze direction	12	100%	94
Emotional projection	12	100%	55
Presence of driver in vehicle	12	100%	40
Eye contact	10	83%	61
Gesture	10	83%	33
Distracted	9	75%	23
Verbal communication	4	33%	5

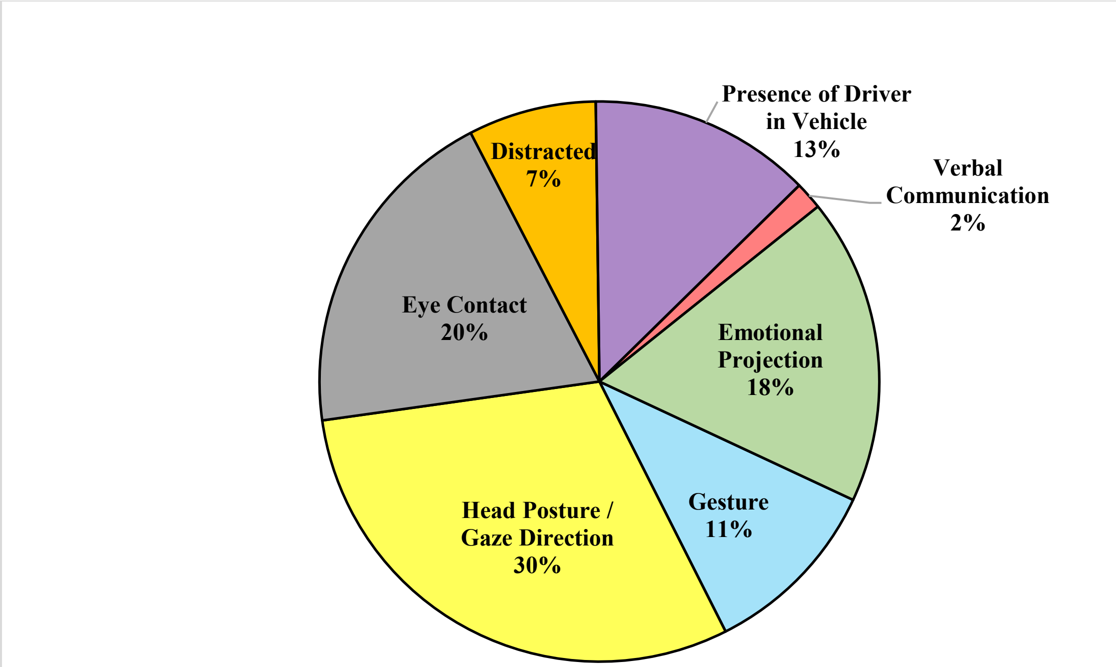


Figure 27. Percentage of total counts for driver-related cues – bicyclist group

Like the other two groups of participants, bicyclists mentioned vehicle-movement cues most frequently. When combining data for both sessions, a vehicle's direction of travel/orientation of tires was the most commonly cited cue (17%), and this cue was mentioned by all 12 bicyclists. Vehicle approach rate was the second most common vehicle-movement cue cited by bicyclists (16%) and was mentioned by all participants. One participant said, "This car behind me is moving slowly, so I am pretty sure he knows I am here." Unique to the bicyclist group are a set of three vehicle-movement cues that relate to the vehicle's position relative to the bicyclist, usually during a passing scenario. Eleven out of 12 participants mentioned the following distance of a vehicle behind them; all 12 made comments about a vehicle's distance when positioned next to them, and half of the participants made reference to a vehicle's distance in front of them. Examples of comments include, "I am fine when they are in the left-hand lane; when they are trying to share the right lane, it becomes nerve-racking," "The car behind me moved wide around me, so it clearly saw me," and "Keeping a reasonable distance; he is like 6 or 7 feet behind me." Vehicle noise was also a cue mentioned by all 12 participants and accounted for 10 percent of the vehicle-movement cues. Typically, bicyclists mentioned the sound of the vehicle accelerating or engine revving as something they paid attention to. For example, "I can hear his engine slow." Table 20 shows the number of participants who mentioned the different vehicle-movement cues, and Figure 28 depicts the percent of total counts for each of the different cues that are vehicle movement-related.

In total, vehicle signaling system cues represented 10 percent of all the cues mentioned by bicycle riders. Similar to pedestrians and drivers, data from both sessions indicate the use or non-use of the vehicle's turn signal accounted for the majority (71%) of the vehicle signaling system cues mentioned. Anecdotally, a majority of the participants who mentioned looking for turn signal use also admitted that they did not fully trust a lack of a turn signal to mean the driver was not intending to turn. Horn and brake lights each accounted for 10 percent of the vehicle signaling system cues mentioned. Table 21 shows the number of participants who mentioned the different vehicle signaling system cues, and Figure 29 depicts the percent of total counts for each of the different cues that are related to vehicle-signaling systems.

Table 20. Number of bicyclist group participants who mentioned vehicle-movement cues

Vehicle Movements	***N* (of 12)**	**Percentage of Bicyclists**	**Total Counts**
Direction of travel/orientation of tires	12	100%	211
Approach rate	12	100%	191
Vehicle noise	12	100%	126
Distance – next to	12	100%	113
Vehicle came to complete stop	12	100%	109
Position in lane	11	92%	146
Slowing down	11	92%	72
Lane change	11	92%	68
Distance – behind	11	92%	50
Distance away	11	92%	36
Vehicle creeping	10	83%	26
Vehicle crossed over double yellow line	8	67%	17
Vehicle door opening	7	58%	15
Traffic volume	6	50%	17
Distance – in front	6	50%	15
Speeding up	4	33%	8

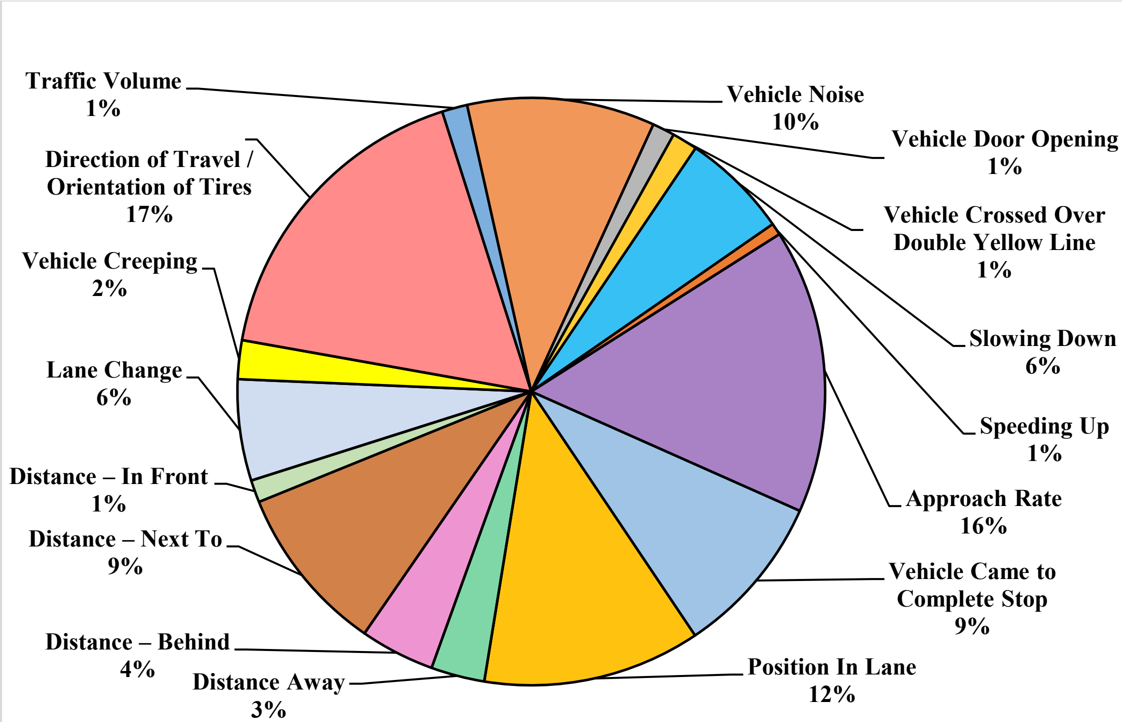


Figure 28. Percentage of total counts for vehicle-movement cues – bicyclist group

Table 21. Number of bicyclist group participants who mentioned vehicle signaling system cues

Vehicle-signaling systems	*N* (of 12)	Percentage of Bicyclists	Total Counts
Turn signal	12	100%	122
Brake lights	10	83%	18
Horn	8	67%	8
Backup lights	6	50%	7
Hazard lights	5	42%	7
Headlamp flash	1	8%	1

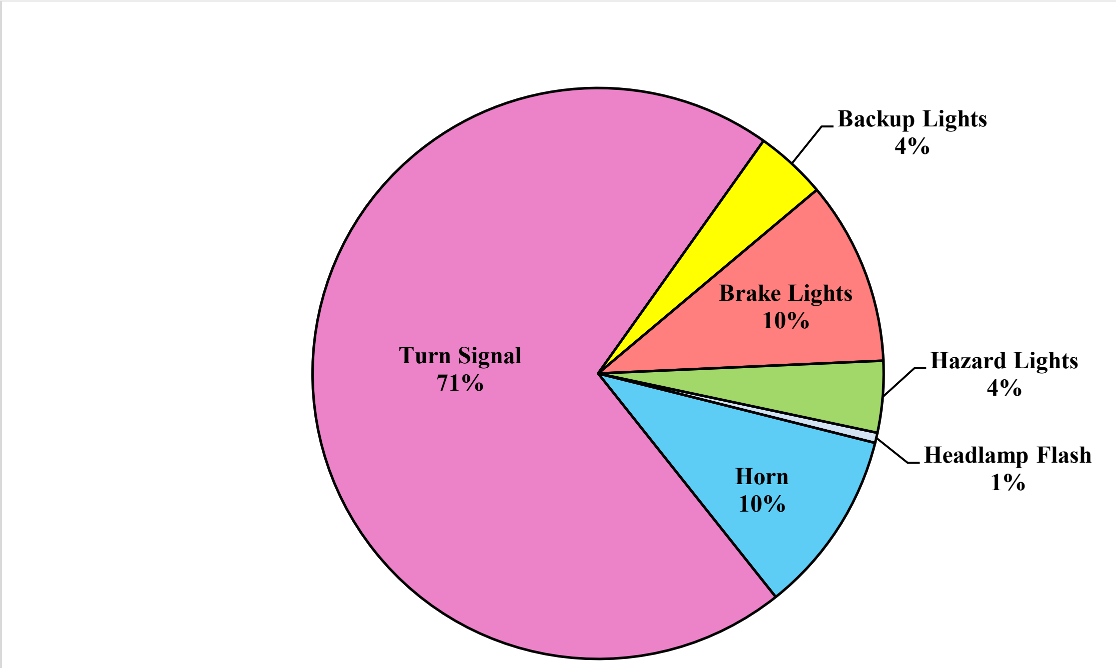
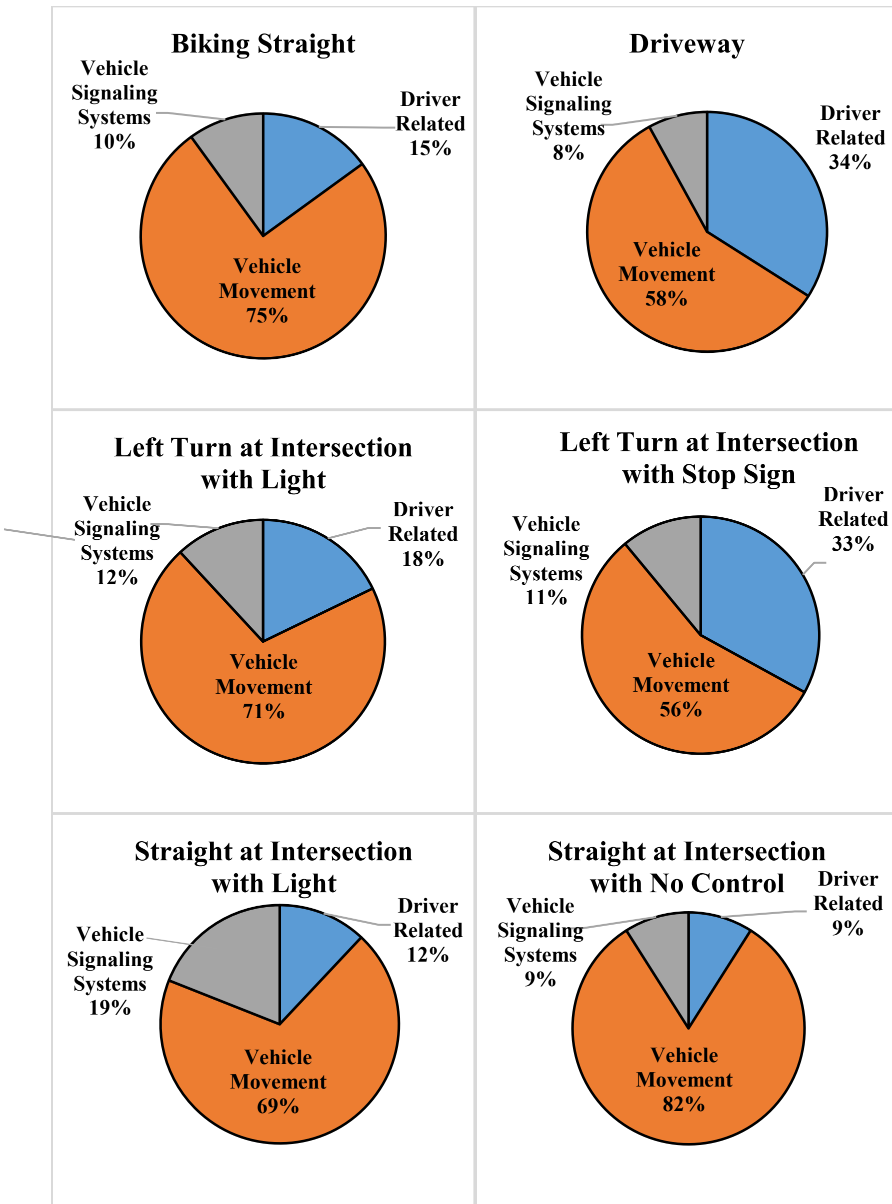


Figure 29. Percentage of total counts for vehicle signaling system cues – bicyclist group

Vehicle-movement cues were mentioned most frequently in all of the different roadway scenarios experienced by the bicyclist group except for when participants were making a right turn at an intersection with a stop sign. In this scenario, 50 percent of the cues mentioned were driver-related, 25 percent were vehicle movement related, and 25 percent were related to vehicle-signaling systems. However, these findings should be interpreted with caution because only 6 comments in total were made in this traffic scenario. Unlike drivers and pedestrians, several other traffic scenarios in session 1 resulted in notable percentages (greater than 20%) of driver-related cues being mentioned by bicyclists. These include driveways (34%), left turns at intersections with stop signs (33%), parking lots (25%), and when proceeding straight at an intersection with a stop sign (23%). While bicyclists were traveling straight, meaning they were not at an intersection of any type, participants would often comment on any vehicles that passed. Of the driver-related cues mentioned during the biking straight scenario type, 23 percent were related to emotional projection based upon their interpretation of the driver's behavior when passing them. For example, one person indicated, "This person is friendly because of how they passed me." Figure 30 shows the proportion of cues mentioned for the 11 different traffic scenarios that occurred during session 1.

Similar to pedestrians, bicyclists sought to initiate communication with drivers via gestures. All 12 participants initiated a gesture at some point during their session 1 or session 2 ride. In total, there were 69 instances where the bicycle rider mentioned gesturing to get a driver's attention. Additionally, 11 of the 12 participants chose to signal their intention (e.g., right or left turn) using hand signals. This happened in total 54 times during the session 1 and 2 rides. It is also important to note that participants sometimes chose to ride in a way that makes use of pedestrian facilities or ignores traffic controls. For example, 11 of the 12 participants chose to use a pedestrian crosswalk one or more times during their ride. In total, riders opting to use the pedestrian crosswalk occurred 63 times over both sessions. In addition, 9 of the bicyclists disobeyed traffic signals one or more times while participating in the study. In total, this occurred 31 times and was usual because the bicycle rider opted not to obey a stop sign.

Researchers also coded when participants expressed any general uncertainty with regard to their understanding of driver intent. Within each group, most of the participants expressed uncertainty at least once (pedestrians: 15 out of 16 participants; bicyclists: 11 out of 12 participants; drivers: 11 out of 12 participants). In total, pedestrian participants expressed uncertainty 41 times over the course of session 1 and 2. Bicyclists expressed uncertainty 72 times and drivers 61 times. Within each group, most of the participants expressed uncertainty at least once.



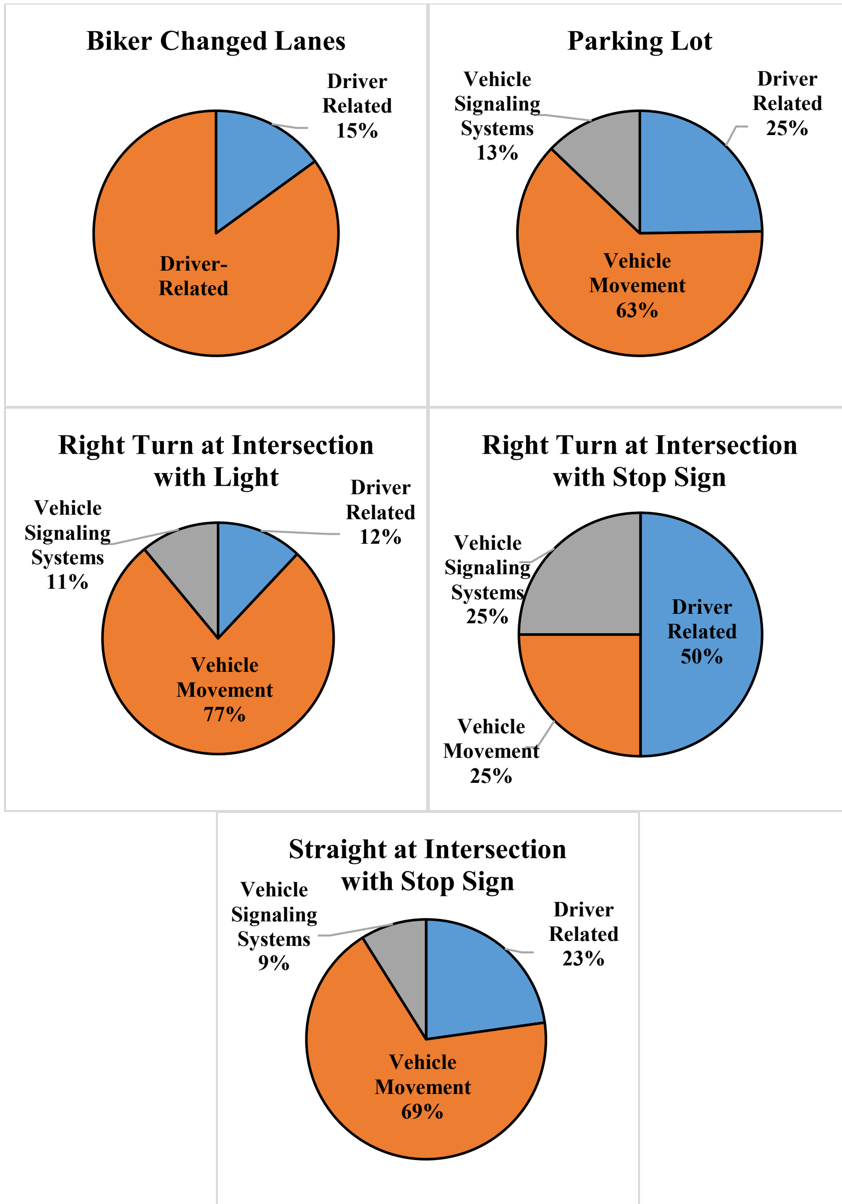


Figure 30. Percentage of cues used during different biking contexts – bicyclists

3.5 Discussion of Study 2

Overall, the results of this study suggest that vehicle-movement cues are used most frequently by each of the three groups of road users (drivers, pedestrians, and bicyclists) that were included in this study. Currently there is much variation between vehicles encountered in driving styles, which may lead to difficulty interpreting the intention of the driver behind the vehicle movements. The ADS vehicle has the potential to create more standardized vehicle-movement cues that can more easily be interpreted. It will be important for ADS vehicle movements to be "readable" and consistent with existing road user expectations. An interesting finding of the study that relates to vehicle movement is that bicyclists tended to pay a lot of attention to the vehicle distance with respect to proximity to their bike. Bicyclists were very cognizant of the distance of a vehicle behind, next to, and in front of them and often had their own thresholds for what constituted an appropriate distance away when passing. This is something the ADS vehicle could take into consideration when sharing the road with a bike rider, and perhaps not approach to pass until a certain distance between the vehicle and bike can be achieved while passing. An informal review by the study's authors found that laws concerning the minimum distance between the overtaking motor vehicle and a bicyclist vary by state, but 3 feet is the most frequently used value.

Pedestrians and bicyclists, considered to be vulnerable road users, relied more on driver-related cues over vehicle-signaling systems as the next most frequently used cues after those related to vehicle movement. Also, pedestrians and bicyclists (slightly more so) tended to initiate communication with drivers via gestures as a means of verifying they were visible to the driver. This finding has two interesting implications with respect to ADS vehicles. The first is that the ADS vehicle will not have a driver to provide driver-related cues. The ADS vehicle may have an occupant sitting in what is traditionally the driver seat, but this person may not be engaged or paying much attention to the vehicle's driving. Therefore, eye contact or gestures are not likely to be provided, and even if they are, it may provide a false sense of security to the pedestrian or the bicyclist because the person has no control over the vehicle. The second possible implication of this finding is that, as automated vehicles become more prevalent on public roadways, vulnerable road users may have a shift in what cues they use most, meaning they may tend to favor vehicle signaling over driver-related cues. To assist vulnerable road users in determining intent, and to avoid misinterpreting intent, driver-related cues may need to be replaced by an external human-machine interface (eHMI), or there should be a way for road users to clearly identify the ADS vehicle driving in ADS mode so that they can ignore any cues that passengers in the vehicle may provide.

With respect to vehicle-signaling systems, several pedestrian and bicyclist participants expressed that they do not always trust vehicle-signaling systems to properly convey the driver's intent. Specifically, participants indicated that a lack of a turn signal does not imply that the driver does not intend to turn or change lanes. However, with ADS vehicles, there is the potential that road users may start to put more trust in the use and nonuse of vehicle-signaling systems because the ADS vehicle will likely be programmed to always follow certain behaviors. While ADS vehicles may signal very reliably, this could lead vulnerable road users to rely too much on these signals, especially in cases where it is not clear whether the vehicle is under human control.

At the outset of the study, we hypothesized that certain traffic scenarios may be associated with certain cue types. For example, traffic scenarios with some ambiguity, such as 4-way stop sign intersections, may involve more driver-related cues when road users are trying to determine intent. The data does seem to support this hypothesis. For participants in the driver group, the traffic scenarios that resulted in a larger percentage of driver-related cues (scenarios where 12 – 13 percent of total cues used were driver-related) included stop signs, turns, and parking lots. For pedestrians, HAWK signals, mid-block crossings, and driveways were the scenarios with the largest percentage of driver-related cues (14 to 21 % of total cues used were driver-related). In general, bicyclists tended to rely more on driver-related cues than the other two groups did, but even more so when making a right or left turn, when at a stop sign, and when encountering driveways (33 to 50% of total cues used were driver-related). In each of these scenarios, eye contact, head position/gaze direction, and the use of a gesture were the driver-related cues that participants tended to focus on most. Manufacturers should consider the information conveyed by driver-related cues when designing the eHMI for ADS vehicles.

It is important to note that, in all of the traffic scenarios studied, except when bicyclists were making right turns, vehicle-movement cues were the most relied upon cues. However, it is important to recognize that some vehicle-movement cues, especially subtle shifts in lane position or speed, are human driver dependent. These cues might be lost in the driving style of an ADS vehicle.

A limitation of this study is that the data were collected only during daylight hours. It is likely that at night shared-road users have diminished ability to observe drivers' behavior within their vehicles. Assuming that road users recognize that driver-related cues are less available to them at night, they may adjust their expectations and may compensate for the loss of these cues by not seeking them out or relying on them. Perhaps conducting nighttime research with shared-road users would provide a useful surrogate for the loss of reliable driver-related cues for intent that will occur as the number of ADS vehicles on the roads grows.

4 Study 3 – Testing External Signaling System Concepts

4.1 Introduction

Previous project activities included a literature review, interviews with driving experts, and an on-road study. These tasks identified potential information needs, shared road users' perceptions and information desired, scenarios that present confusions and ambiguities, timing aspects of communication needs, and other factors. The next logical step was to develop methods to evaluate prototype designs that may address those needs. This study maps findings from the previous project activities to strategies and practices for communicating status and intent of the ADS vehicle, and then to a set of testable communication prototypes. This experiment used a method capable of examining a wide range of design approaches by overlaying digitally created interfaces on real vehicles recorded driving on real roads and evaluated effectiveness of these prototypes for conveying the intended message and developing measures that can be used early in the design process for ADS vehicle communication of intent. The primary purpose of this experiment, however, was to exercise and evaluate the research method.

4.2 Method

4.2.1 Overview

This study used a preliminary laboratory-based method in which research participants played the role of a pedestrian intending to cross a street at a crosswalk. Participants watched videos showing a vehicle approaching the crosswalk. For some of the videos, an eHMI provided information to the pedestrian. Vehicle behavior also varied across videos—the vehicle may yield early, yield late, not yield, or turn off the road at the intersection before reaching the crosswalk. At three points during each video, the video was paused, and participants answered questions about the vehicle and their assessment of whether or not the vehicle will yield to them. After each pause, the video restarted from the beginning.

4.2.2 Design

This study used a within-subjects design in which all participants experienced the same stimuli under the same conditions. Each trial was comprised of a combination of a vehicle-approach video and an external interface (or no interface). Each vehicle-approach video showed the vehicle engaging in a different action as it approached the crosswalk. Each interface communicated something about the vehicle's status or intent. Videos and interfaces are described in detail in the "Vehicle Approach Videos" and "ADS Communication Interfaces" subsections below. Given the novelty of the interfaces used in this study, it is important to assess participants' comprehension of them under both naïve and informed conditions. To do this, participants experienced all interfaces first without any explanation of what they mean (naïve trials). After experiencing all interfaces once, the experimenter explained what each interface meant before continuing the experiment, with all remaining trials being in an "informed" state. There were a total of 39 trials, excluding a practice trial.

4.2.3 Participants

Participants were recruited via Craigslist (Washington DC region, volunteers section) and Westat's intranet site. Westat employees were not eligible to participate, but they could refer friends and family. Potential participants were screened via telephone. Participants were required to be between the ages of 20 and 65, have normal or corrected-to-normal vision with no color blindness, and be fluent speaking and reading in English. They were also required to cross streets at least one a week as a pedestrian, without the use of mobility aids. There were 30 participants in this study, including 15 males (age M = 45, SD = 15) and 15 females (age M = 43, SD = 13).

4.2.4 Vehicle Approach Videos and Questions

All videos were recorded at a real intersection from the perspective of a pedestrian on the curb waiting to cross a crosswalk. Figure 31 shows the pedestrian's location marked with a red X. The camera view shows a view of traffic approaching the intersection from the east, as the pedestrian waits to cross from north to south. In each video, the same four-door sedan approaches the crosswalk in the left lane of a two-lane road in which the right lane is a parking lane. No other westbound traffic is visible in the videos. The driver of the vehicle cannot be seen through the windshield in any of the videos. The vehicle is initially traveling at 25 mph. The different vehicle actions taken in each video are described below. Figure 31 shows an aerial view of the approach to the crosswalk with distance markers. Markers are separated by approximately 37 feet, or one second of travel time at 25 mph. Each video begins with the vehicle approximately 70 feet upstream of marker 1 and continues until the vehicle reaches marker 4, stops, or turns off the road. The distance markers are referenced in the descriptions of the different videos below:

- Steady: vehicle continues through crosswalk with no change in speed
- Accelerating: Vehicle accelerates to 30 mph at marker 3 and continues through crosswalk
- Late stop: Vehicle begins braking at marker 3 and comes to full stop approximately 5 feet from crosswalk
- Early stop: Vehicle begins braking at marker 2 and comes to full stop at marker 3
- Left turn, signal: Vehicle signals left at marker 2, then turns left at intersection before crosswalk
- Left turn, no signal: Vehicle turns left at intersection before crosswalk without signaling
- Right turn, signal: Vehicle signals right at marker 2, then turns right at intersection before crosswalk
- Right turn, no signal: Vehicle turns right at intersection before crosswalk without signaling

Figure 31. Aerial view of crosswalk and vehicle approach, showing distance measurements from crosswalk and markers (imagery ©2019 Commonwealth of Virginia, U.S. Geological Survey)

Each video began with the vehicle approximately 75 feet (2 seconds) upstream of marker 1 (see Figure 31). When the vehicle reached marker 2, the video froze, and the experimenter asked the participant three questions with binary response options:

1. Is the vehicle in self-driving mode, or is there a driver in control?
2. Is the [VEHICLE/DRIVER] aware of your presence?
3. Is the [VEHICLE/DRIVER] going to yield to you or turn before the crosswalk, or is it going to continue through the crosswalk without yielding or turning?

For questions 2 and 3, the experimenter said "vehicle" if the participant believed that the vehicle was in self-driving mode, or "driver" if the participant believed that there was a driver in control. For question 3, yielding and turning before the crosswalk were combined as a single response option that encompassed all possibilities other than the vehicle continuing through the crosswalk without yielding. After each question, the experimenter asked the participant to rate their confidence in their answer on a 0 to 10 scale, where 0 represented no confidence at all, and 10 represented complete confidence.

After the participant completed these ratings for the vehicle at marker 2, the video restarted from the beginning and then froze with the vehicle at marker 3 (at entry point of intersection, approximately 75 feet from the crosswalk), and the participant answered the same three questions with confidence ratings for each. Finally, the video again restarted from the beginning and played until the vehicle either reached marker 4 (start of crosswalk), came to a stop before marker 4, or turned off the road before marker 4. Figure 32 shows the three freeze points for a trial in which the vehicle stopped before entering the crosswalk.

This design, in which participants were asked about the approaching vehicle at three distance points, had multiple purposes. First, this approach allowed the research team to determine how pedestrian comprehension and expectation evolves as a vehicle approaches. Second, it allowed the research team to investigate each interface at the time/distance point of greatest interest. For example, in most of the video scenarios, the vehicle does not communicate enough information at marker 2 for the participant to understand its status or its intent. At marker 3, however, the vehicle does clearly communicate its intent in most videos, though it does not always provide clear motion cues (e.g., slowing, beginning a turn maneuver). More information about the various combinations of video and communication interface is provided in Section 4.2.6.

Videos of the approaching vehicle were recorded in 4K resolution, at 60 frames per second, and were projected on a white wall using an LG 4K projector. A second projector showed the crosswalk that the participant was to imagine crossing on an adjacent wall. The two projected images abutted one another to provide the impression of a single continuous crosswalk from the participant's perspective, as seen in Figure 33.

Figure 32. Video stills showing three freeze points

Figure 33. Projected images of approaching vehicle and crosswalk from participant's perspective

4.2.5 ADS Communication Interfaces

Six distinct communication methods were investigated in this study. Five of the six were adapted from examples seen in the research literature, pilot deployments, or proposed concepts. The sixth was a headlamp flash, which is a communication method used by drivers that could potentially also be used by ADS vehicles. The interfaces were not all intended to be ideal exemplars, however, because an important objective of this study was to determine whether the research methods employed could differentiate the various interfaces in terms of comprehension, pedestrian behavior, and preference. All interfaces were computer-created mockups that were digitally inserted in the videos to appear that they were part of the vehicle. Participants, however, were informed that the interfaces were digital mockups; the researchers did not attempt to deceive participants into believing that the interfaces were actually on the vehicle seen in the videos.

ADS beacon

A green light on the front of the vehicle where the hood meets the windshield. The light is on when the vehicle is in automated mode. It is off when it is in manual mode. The image below shows the ADS beacon in use, from a frame of an actual video used in the study.

Figure 34. ADS beacon

<u>Light bar</u>

A light bar spanning the top of the windshield. Different patterns of light indicate whether the vehicle is in motion, yielding, or preparing to resume motion. "In motion" is represented by four light segments steady in the center of the display. "Yielding" is represented by two pairs of light segments symmetrically bouncing from the center to the outside of the display and back again. "Preparing to resume motion" is not used in this study but is represented by the same display as "moving" but with the lights flashing rather than steady.

Figure 35. Light bar "in motion" (left) and "yielding" (right)

<u>"I see you" eyes</u>

This display uses a pair of large eyes on the vehicle's grill to indicate the vehicle's awareness of a pedestrian. The eyes look straight ahead until a pedestrian is detected, then look in the direction of the pedestrian to simulate eye contact of a driver. The eyes also look in the direction of an upcoming signaled turn.

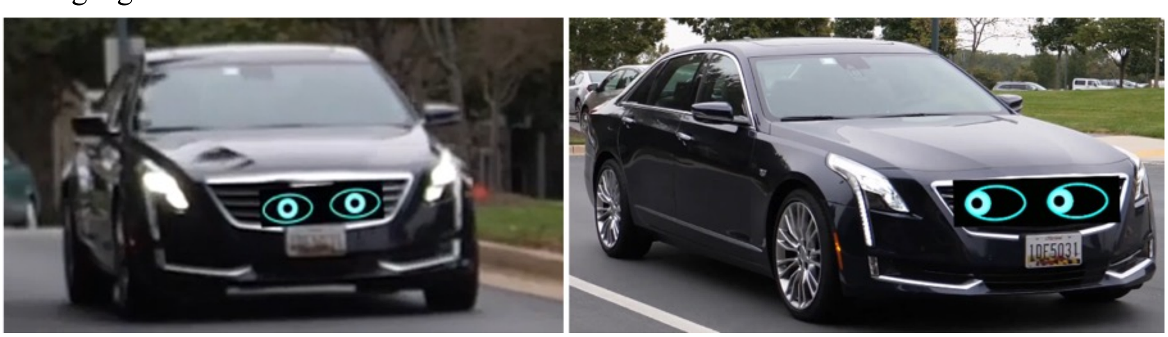


Figure 36. "I see you" eyes looking straight (left) and looking right (right)

Yielding text

The word “Yielding” is presented in the vehicle’s grill to indicate that it is yielding to a pedestrian. If the vehicle is not signaling that it will yield, the display is blank.

Figure 37. Yielding text

Pedestrian WALK/DON’T WALK symbols

WALK or DON’T WALK icon is presented on vehicle grill to indicate whether or not the vehicle is yielding to pedestrian. Icons are comparable to pedestrian crossing signals.

Figure 38. Pedestrian DON’T WALK (left) and WALK (right) symbols

Headlamp flash

Vehicle quickly flashes its headlamps twice, as drivers sometimes do to signal intent to yield to pedestrian.

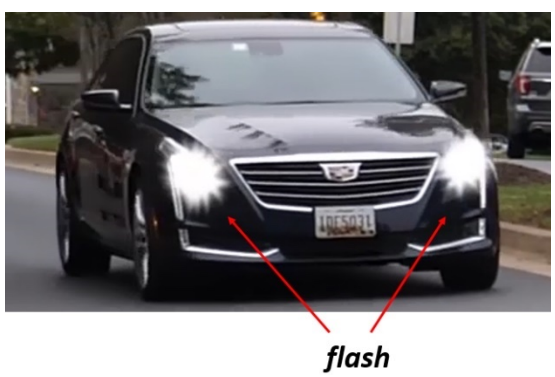


Figure 39. Headlamp flash

4.2.6 Set of Trials

Table 22 shows the various combinations of interface and video used in this study. The number in each cell indicates the number of trials in which that combination of interface and video occurred. The specific combinations were selected to allow all key comparisons to be made, and to ensure sufficient diversity of scenarios that participants could not guess the status or intent of the vehicle in the absence of eHMI or behavioral cues. Each used combination occurred once as an "informed" trial. For combinations that occurred more than once, a "+" superscript indicates that the combination was also used as a "naïve" trial (before systems are explained to the participant) and a "*" superscript indicates that the combination was used as "late interface" trial. For the majority of trials in which the vehicle will yield to the pedestrian, the interface indicating yielding behavior appears when the vehicle begins to decelerate. However, in two "late interface" trials, the yielding interface only appears when the vehicle has come to a full stop. There were a total of 39 trials, including baseline trials in which no external communication device was used.

Table 22. Combinations of interface and vehicle behavior used in study trials

Vehicle action	ADS beacon	Light bar yielding	Light bar not yielding	I see your eyes	Yielding text on grill	Pedestrian walk icon on grill	Pedestrian "Don't Walk" icon	headlamp flash	No communication yielding	No communication not yielding	**Total**
Steady speed	1		2^{+}				2^{+}	1		2^{+}	**8**
Accelerating										1	**1**
Late stop	2^{+}	3^{+*}		2^{+}	3^{+*}	2^{+}		2^{+}	2^{+}		**16**
Early stop		1		1	1	1		1	1		**6**
Left turn, signal	1		1							1	**3**
Left turn, no signal										1	**1**
Right turn, signal			1	1						1	**3**
Right turn, no signal										1	**1**
Total	**4**	**4**	**4**	**4**	**4**	**3**	**2**	**4**	**3**	**7**	**39**

$^{+}$Naïve trial
*Late interface trial
Practice 1 – Alternative oblivious video, no interface
Practice 2 – Medium Stop Video, no interface

4.2.7 Additional Data Collected

After participants experienced all interfaces in naïve trials, the experimenter asked them what they thought each interface was intended to communicate. The experimenter showed a still image of each interface (or two images, for interfaces that had more than one possible state) and allowed the participant to provide an open-ended answer about meaning. The experimenter wrote down the participant's response in a paraphrased form.

After completing all 39 video trials, participants completed a final questionnaire that asked three open ended questions:

1. Which of the communication interfaces that you saw today do you think would be best to use on real self-driving cars? Why?
2. How would you improve that interface, if you could?
3. Were any of the interfaces you saw today particularly confusing, or were there any designs that you thought were especially bad for any reason? Why?

4.2.8 Procedure

Upon arrival, participants read and signed an informed consent form. The experimenter then explained the purpose of the study and the research task. The experimenter then showed the participant a photo of the intersection used in the study from an approaching driver's point of view. The photo included a pedestrian waiting to cross at the curb and was shown to provide participants with additional context for the crossing scenario they were to experience. The participant was instructed to stand or sit in a space that provided an ideal viewing angle of the two projected images. The participant then completed one practice video trial, which included a video not used for the subsequent video trials in which the vehicle had no communication interface. Next, the participant completed the ten naïve trials. After that, the participant viewed photos of each of the interfaces they had experienced and stated what they believed the interface was intended to convey. Next, the experimenter explained the intended meaning of each of the interfaces. After that, participants completed the remaining 29 trials. Finally, the participant completed the final questionnaire described in Section 4.2.7.

4.3 Results of Study 3

4.3.1 Overview of Data

The primary data collected in this study were answers to three questions below and confidence ratings in those answers on a scale from 0 to 10:

1. Is the vehicle in self-driving mode or is there a driver in control?
2. Is the [VEHICLE/DRIVER] aware of your presence?
3. Is the [VEHICLE/DRIVER] going to yield to you or turn before the crosswalk, or is it going to continue through the crosswalk without yielding or turning?

When referred to in the subsequent text, these three questions are abbreviated as (1) Driver, (2) Aware, and (3) Yield, respectively. All three questions were asked three times during each video: once when the approaching vehicle was far away (time 1), once when the vehicle was just beginning to enter the intersection (time 2), and once when the vehicle either reached the crosswalk, came to a stop, or turned off the road (time 3). Supplementary data collected included perceived meanings of interfaces and interface preferences. The study design allowed the research team to investigate numerous research questions related to interface comprehension, interface timing, and pedestrian preferences. Importantly, this design also allowed the research team to evaluate this study methodology and determine which variables were most sensitive to differences between interfaces and which were best able to differentiate "good" from "bad" interfaces.

4.3.2 Treatment of Confidence Ratings

Every time participants answered the three key questions described in the previous subsection, they were also asked to rate their confidence in their answer on a scale from 0 (no confidence) to 10 (complete confidence). Contrary to expectations, confidence ratings were strongly bimodal, with participants expressing high levels of confidence in their responses, even when interfaces did not provide sufficient information for participants to be able to determine the correct response. When the binary response data and the 0 to 10 confidence ratings scales are viewed as a single -10 to +10 scale, participants rarely rated their confidence close to zero. This holds true for all three questions at all three time points. Figure 35 shows example data for whether or not the participant expects the vehicle will yield or not for each of the three time points. Positive ratings indicate a response of "will yield" and negative ratings indicate a response of "will not yield." The histograms are inclusive of all 39 trials for all 30 participants. While response bipolarity increased across time, even at time 1, participants had high confidence in their responses. As a result of this finding, the research team chose to collapse the outcome into three categories: Confident negative (-10 to -5), neutral/uncertain (-4 to +4), and confident positive (+5 to +10). These three categories may reflect participants' actual thinking better than the more detailed 0 to 10 scales.

Using a three-category outcome means that analyses cannot use a standard logistic or linear regression model, since there are more than two categories and the assumptions of these regression models no longer hold. As a result, the primary method used for subsequent analyses is ordered logistic regression (sometimes also referred to as "proportional odds" or "cumulative logistic" regression). Each model included main effects for time point and trial; a time-by-trial interaction was considered, but due to the small sample size of 30 participants, there was not enough power to support an interaction effect. Since trials are clustered within participants, we also include a random effect for participant.

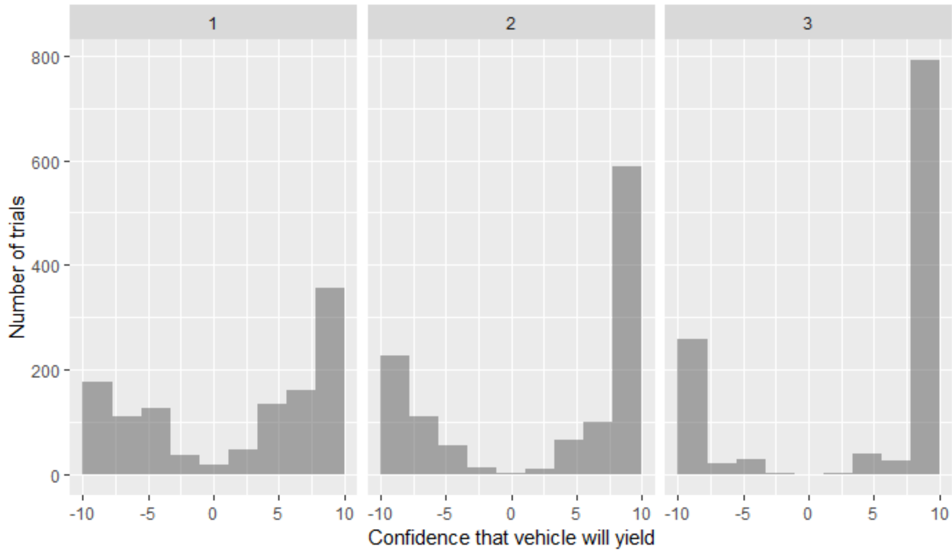


Figure 40. Participant confidence ratings at each time point for "Will the vehicle yield?"

4.3.3 Treatment of Time Point

All three questions and their associated confidence ratings were asked three times for each trial: first when the vehicle is far away, second when the vehicle is just entering the intersection, and third when the vehicle has arrived at the crosswalk or turned off the road. It is valuable to have these data for all three time points to understand how comprehension and confidence change over time and with changes to the interface and vehicle actions. However, for most trials, time point 2 is the most critical time point for understanding how each interface affects comprehension of whether the vehicle will yield or not. This is because for most trials—particularly those with "late stop" and "no yield" vehicle actions—the interface's final state begins shortly before time point 2, and the vehicle is still traveling at a steady speed and therefore not providing any kinematic cues that participants could use to determine whether or not the vehicle will yield. Therefore, in the following subsections, we generally address all three time points for each of the three questions, but also time point 2 separately for the Yield question.

4.3.4 Naïve Trials

Naïve trials were the first ten video trials completed by participants before the experimenter explained the meanings of the interfaces. These trials allowed the research team to explore the intuitiveness of the interfaces and participants' comprehension of them. Ordered logistic regression models including a random effect for participants were fit on the subset of naïve trials only for each of the three outcomes separately, with "no interface, late stop" as the reference level trial in each model[2] (Christensen, 2019; Lenth, 2019). After conducting the set of naïve trials, the experimenter asked participants to explain in their own words what they believed each

[2] All ordinal logistic regression models were fit via the clmm() function in the ordinal R package. "clmm" is an acronym for "cumulative link mixed model," which is the generalized version of an ordered logistic mixed model.

interface meant. Participants' explanations are described at the end of this Naïve trials subsection.

Driver

Figure 35 shows the probability of each of the three categorical responses for each time point for each interface. Actual participant responses are shown in solid lines, and regression model predictions are shown in dashed lines. *Table **23*** shows the model coefficients for interface and time point. Results show that for the reference "no interface, late stop" trial, a majority of participants believed that the vehicle was currently being operated by a driver at all three time points. For all other interfaces, other than headlamp flash and no interface, participants were significantly more likely to believe that the vehicle was currently in self-driving mode, indicating that participants generally interpreted the presence of an eHMI as evidence that the vehicle is self-driving. Figure 36 shows the estimated marginal means for each interface; that is, the average odds of moving to the next highest outcome category, with the associated 95% confidence intervals. Negative numbers indicate participants are more likely to respond that a driver is in control, and positive numbers indicate participants are more likely to respond that the vehicle is in self-driving mode. For example, the marginal mean for Beacon, late stop is 0.86. This means that under this condition, respondents are exp(0.86) = 2.4 times more likely to respond in the neutral or self-driving categories as compared to the driver category, and also 2.4 times more likely to respond that the vehicle is self-driving versus neutral or has a driver. Interfaces whose confidence intervals do not overlap with one another are significantly different than one another.

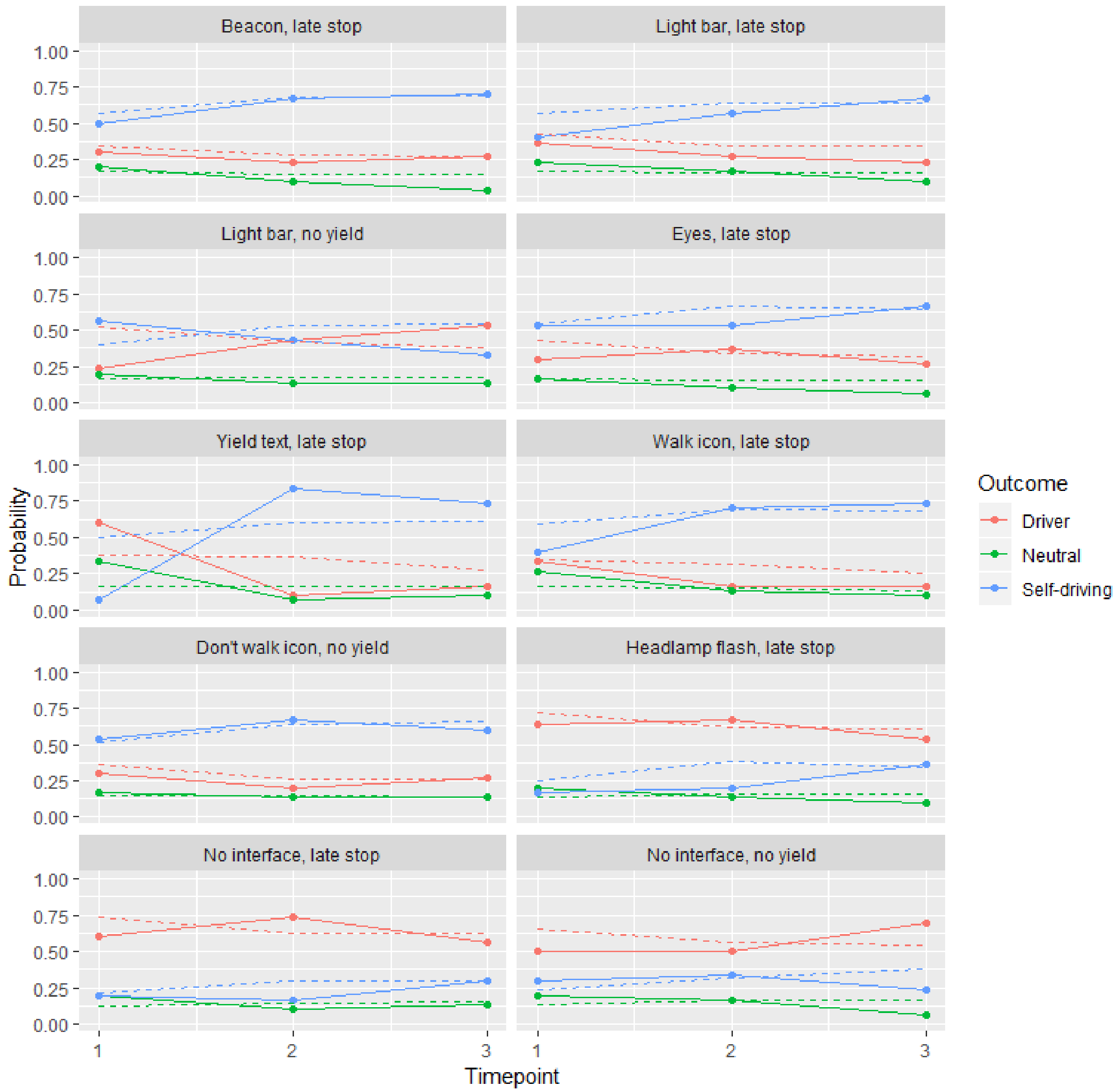
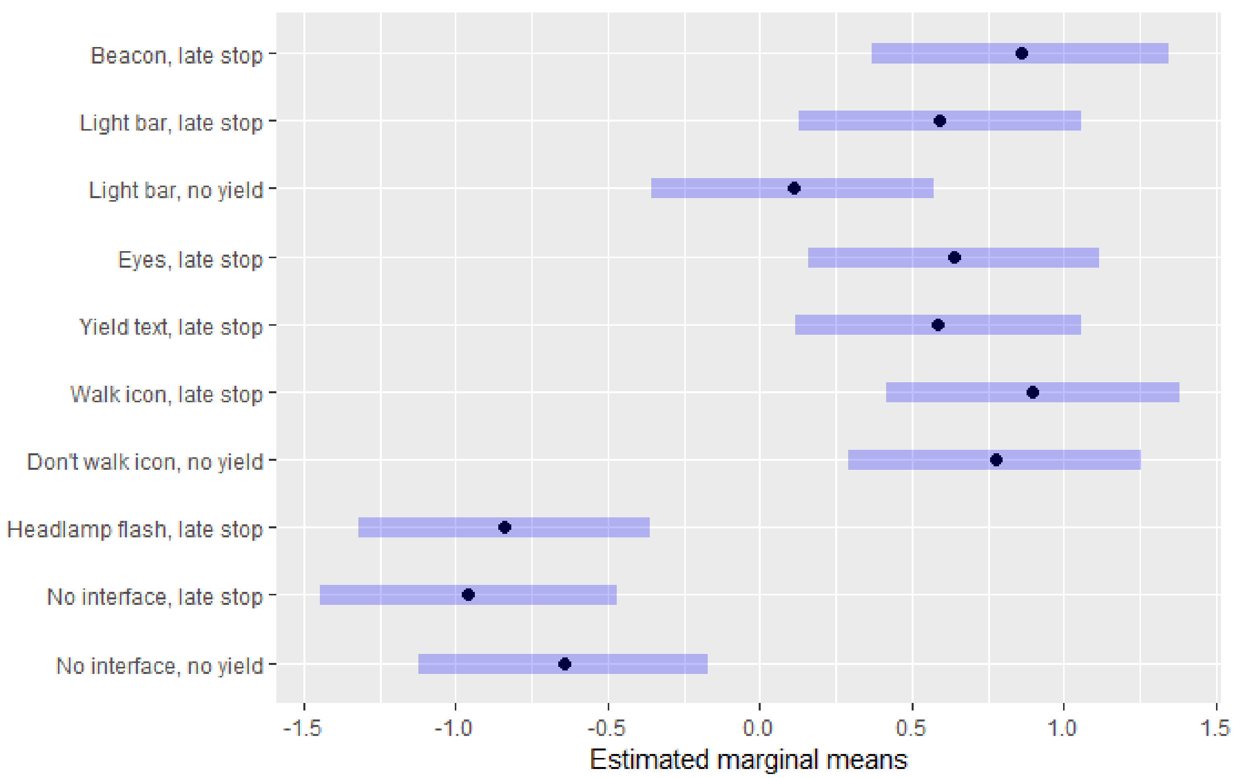


Figure 41. Plots indicating probabilities of categorical responses to Driver question (all time points)

Table 23. Model for Driver question (all time points)

	Estimate	Std. Error	z value	p value	Sig.
Beacon, late stop	1.8181	0.3149	5.774	<0.001	***
Don't walk icon, no yield	1.7335	0.3120	5.555	<0.001	***
Eyes, late stop	1.5968	0.3101	5.149	<0.001	***
Headlamp flash, late stop	0.1177	0.3096	0.380	0.704	
Light bar, late stop	1.5519	0.3059	5.073	<0.001	***
Light bar, no yield	1.0684	0.3038	3.517	<0.001	***
No interface, no yield	0.3138	0.3079	1.019	0.308	
Walk icon, late stop	1.8569	0.3118	5.955	<0.001	***
Yield text, late stop	1.5454	0.3066	5.041	<0.001	***
Timepoint 2	0.4757	0.1647	2.888	0.004	**
Timepoint 3	0.5383	0.1667	3.230	0.001	**



**p≤.05, **p≤.01, ***p<001*

Figure 42. Marginal means for each interface, including confidence intervals

Aware

Figure 37 shows the probability of each of the three categorical responses for each time point for each interface. Actual participant responses are shown in solid lines, and regression model predictions are shown in dashed lines. Table 24 shows the model coefficients for the interface and time point main effects. Results show that for the reference “no interface, late stop” trial, participants were about equally likely to believe that the vehicle/driver was aware of their presence or not aware of their presence at time points 1 and 2. At time point 3 when the vehicle came to a stop before the crosswalk, however, more than 80 percent of participants believed that the vehicle-driver was aware of their presence. Compared to the reference “no interface, late stop” trial, all trials in which the vehicle ultimately yielded to the pedestrian resulted in significantly more participants believing that the vehicle/driver was aware of their presence. None of the other trials in which the vehicle did not yield were significantly different than the reference trial. These findings suggest that, in this study method, whether or not the vehicle yields may be an important factor in whether or not participants believe that the vehicle/driver is aware of their presence. This finding may depend on participants’ naïve state during the presentation of this set of trials because participants were not yet informed of the explicit meanings of the various interfaces. Figure 38 shows the estimated marginal means of each interface and its associated 95% confidence interval. Negative numbers indicate that participants were more likely to respond that the vehicle/driver was not aware and positive numbers indicate that participants were more likely to respond that the vehicle/driver was aware. Interfaces whose confidence intervals do not overlap with one another are significantly different from one another.

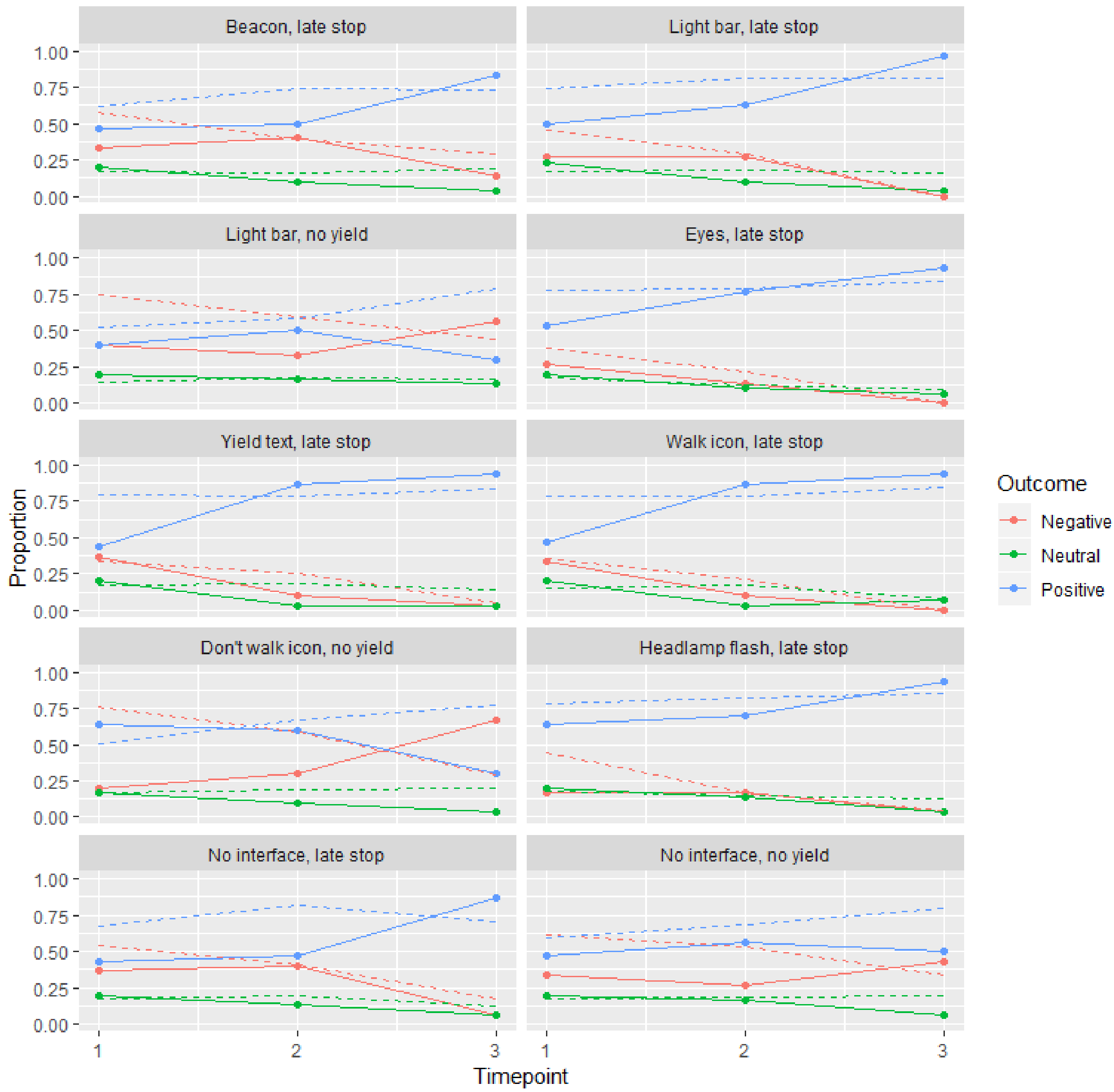


Figure 43. Plots indicating probabilities of categorical responses to Aware question (all time points)

Table 24. Model for Aware question (all time points)

	Estimate	Std. Error	z value	p value	Sig.
Beacon, late stop	-0.0244	0.3349	-0.073	0.942	
Don't walk icon, no yield	-0.4980	0.3334	-1.494	0.135	
Eyes, late stop	0.9450	0.3542	2.668	0.008	**
Headlamp flash, late stop	1.0809	0.3569	3.029	0.002	**
Light bar, late stop	0.6710	0.3444	1.948	0.051	
Light bar, no yield	-0.9894	0.3301	-2.998	0.003	**
No interface, no yield	-0.3764	0.3290	-1.144	0.253	
Walk icon, late stop	0.9755	0.3579	2.726	0.006	**
Yield text, late stop	0.9177	0.3554	2.582	0.010	**
Timepoint 2	0.6944	0.1854	3.744	<0.001	***
Timepoint 3	1.2741	0.1989	6.405	<0.001	***

$*p \leq .05$, $**p \leq .01$, $***p < .001$

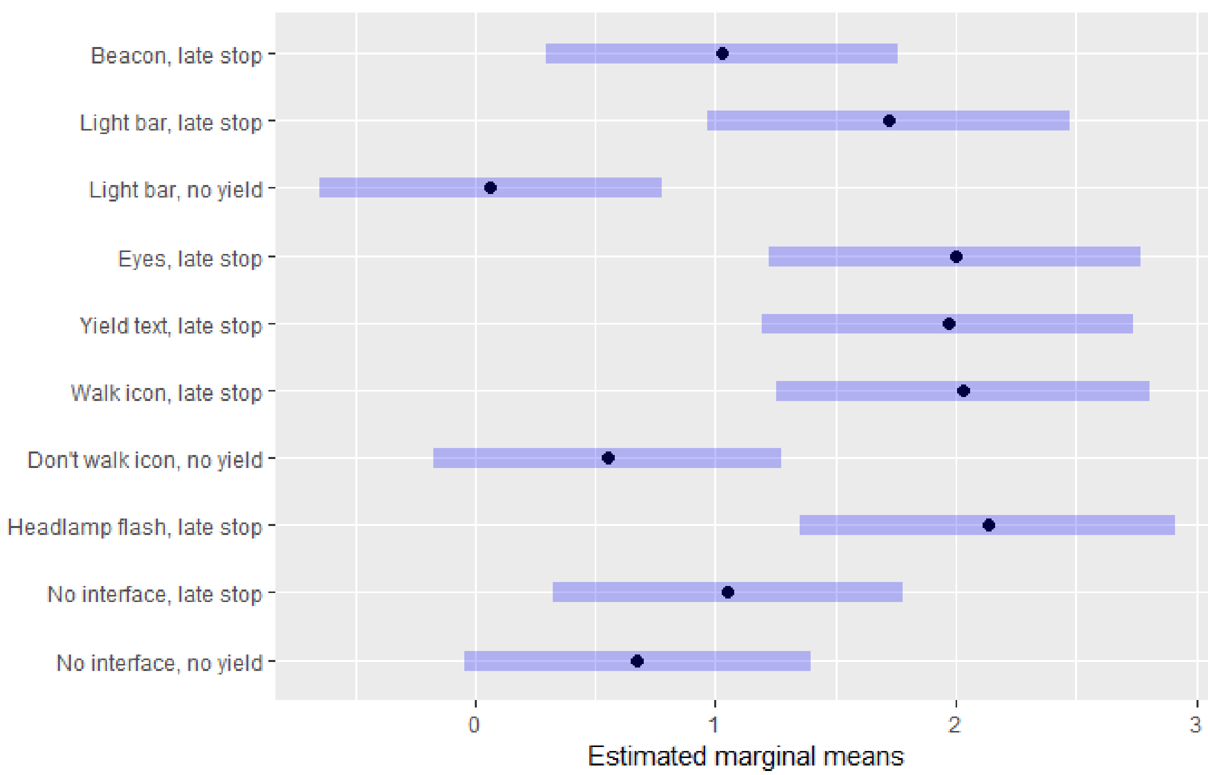


Figure 44. Marginal means for each interface, including confidence intervals

Yield

Figure 39 shows the probability of each of the three categorical responses for each time point for each interface. Actual participant responses are shown in solid lines, and regression model predictions are shown in dashed lines. Table 25 shows the model coefficients for the main effects of interface and time point. Results show that for the reference “no interface, late stop” trial, participants largely did not expect the vehicle to yield at time points 1 and 2. At time point 3 when the vehicle came to a stop before the crosswalk, however, approximately two-thirds of participants believed that the vehicle would yield. Compared to the reference “no interface, late stop” trial, most trials in which the vehicle had an interface were significantly more likely to result in participants reporting that the vehicle would yield. One exception was the don’t walk eHMI, which explicitly communicated that pedestrians should not cross. The other exception was the beacon. This result might indicate that participants did not understand the meaning of the beacon, or that a beacon indicating ADS status alone is not sufficient to communicate that the vehicle will yield to a pedestrian. Figure 40 shows the estimated marginal mean of each interface and its associated 95% confidence interval. Negative numbers indicate that participants were more likely to respond that the vehicle/driver would not yield, and positive numbers indicate that participants were more likely to respond that the vehicle/driver would yield. Interfaces whose confidence intervals do not overlap with one another are significantly different from one another.

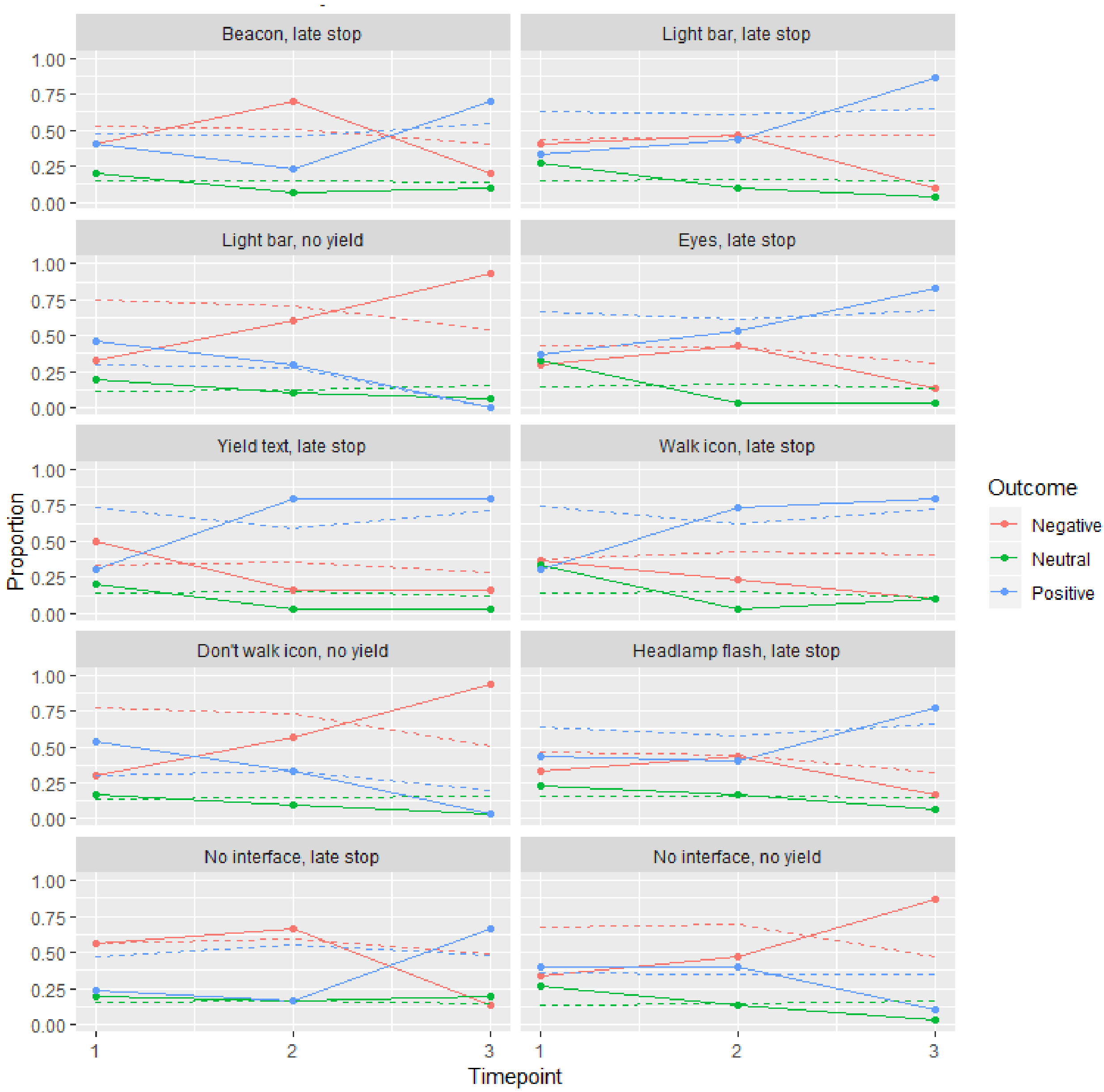


Figure 45. Plots indicating probabilities of categorical responses to Yield question (all time points)

Table 25. Model for Yield question (all time points)

	Estimate	Std. Error	z value	p value	Sig.
Beacon, late stop	0.2661	0.2975	0.895	0.371	
Don't walk icon, no yield	-0.5130	0.3057	-1.678	0.093	
Eyes, late stop	0.9313	0.3011	3.093	0.002	**
Headlamp flash, late stop	0.7709	0.2974	2.593	0.010	**
Light bar, late stop	0.7644	0.2984	2.562	0.010	*
Light bar, no yield	-0.6492	0.3071	-2.114	0.034	*
No interface, no yield	-0.3412	0.3002	-1.136	0.256	
Walk icon, late stop	1.1160	0.3033	3.680	<0.001	***
Yield text, late stop	1.1307	0.3093	3.655	<0.001	***
Timepoint 2	-0.0752	0.1666	-0.451	0.652	
Timepoint 3	0.5057	0.1697	2.980	0.003	**

$*p \leq .05$, $**p \leq .01$, $***p < .001$

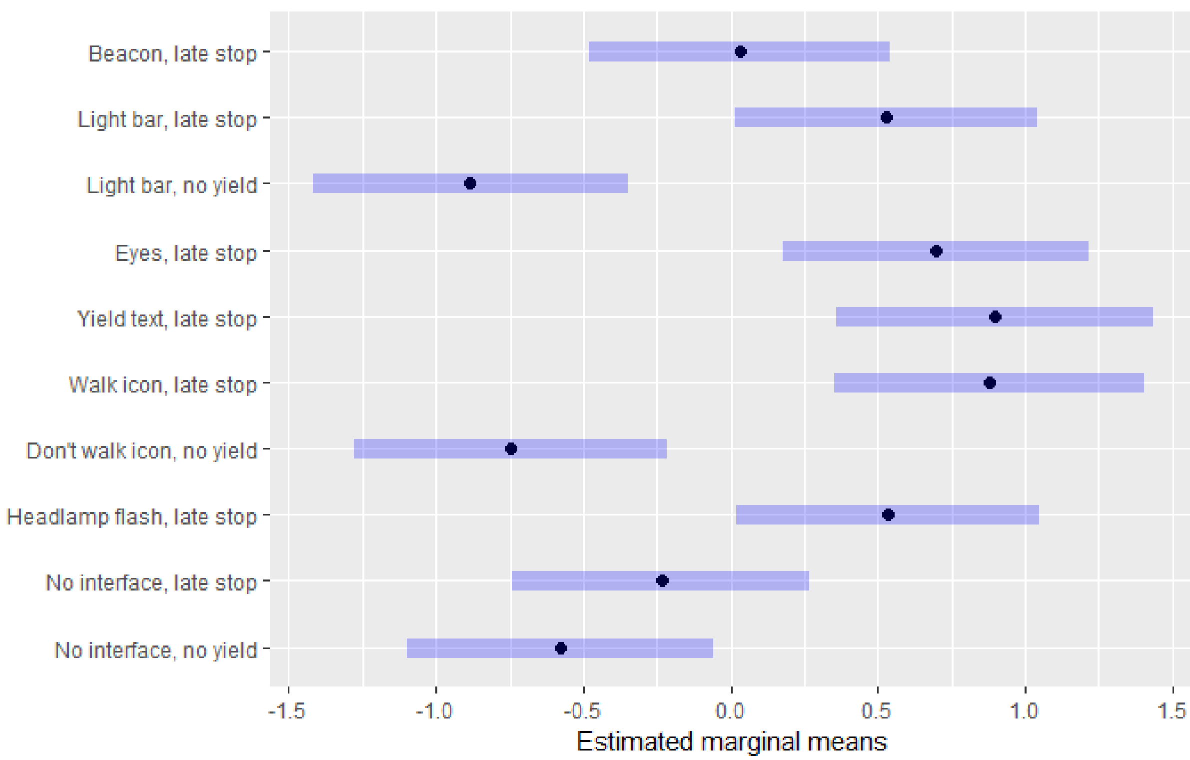


Figure 46. Marginal means for each interface, including confidence intervals

Table 26 shows results for the Yield question when focusing only on time point 2. Results show that all interfaces that communicated intent to yield or recognition of the pedestrian resulted in significantly greater likelihood that participants would believe that the vehicle will yield, relative to the reference trial. The strongest effects were seen for the Walk icon, yield text, and eyes, suggesting that these interfaces were among the most intuitively understood interfaces in this study. The beacon interface was not significantly different than the reference trial.

Table 26. Model for Yield question (time point 2)

	Estimate	Std. Error	z value	p value	Sig.
Beacon, late stop	-0.0337	0.6161	-0.055	0.956	
Don't walk icon, no yield	0.6927	0.5867	1.181	0.238	
Eyes, late stop	1.7267	0.6035	2.861	0.004	**
Headlamp flash, late stop	1.2721	0.5793	2.196	0.028	*
Light bar, late stop	1.3181	0.5850	2.253	0.024	*
Light bar, no yield	0.5690	0.5889	0.966	0.334	
No interface, no yield	1.2041	0.5786	2.081	0.037	*
Walk icon, late stop	3.0119	0.6659	4.523	<0.001	***
Yield text, late stop	3.5696	0.7143	4.997	<0.001	***

**p*≤.05, ***p*≤.01, ****p*<.001

Participant interpretations of naïve trial interfaces

After completing the set of naïve trials, participants were asked to explain what they thought each interface meant in their own words. *Figure **41*** shows the percentage of participants who correctly identified the meaning of each interface. Participants sometimes correctly explained one state of an interface but not the other, so interfaces that have two states have each state addressed separately. The headlamp flash interface was not included in this figure or the following summary because there was no "correct" interpretation; participants were told that the headlamp flash could potentially be used by a human driver or by an ADS vehicle.

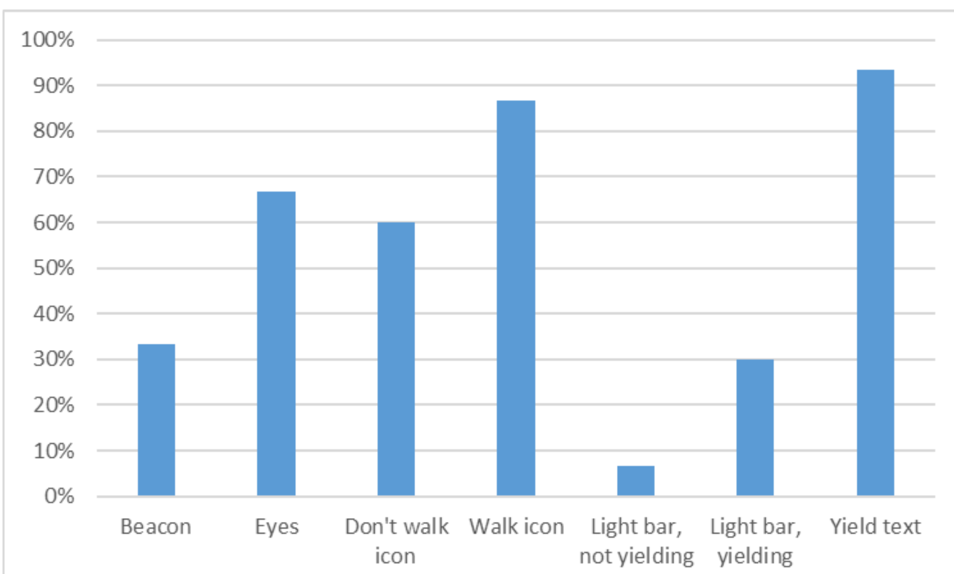


Figure 47. Percentage of participants who correctly identified intended meaning of each interface after naïve trials

When interpreting these results, it is important to consider not just the percentage of correct responses, but also the nature of the incorrect responses, as some interpretations might pose a greater safety hazard than others. Ten of the 30 participants were able to correctly identify the meaning of the beacon. Interestingly, 6 participants believed it meant that the car was going to keep going, possibly using a green "go" light to interpret the meaning. This finding could have important safety consequences. Nine participants were able to correct identify the meaning of the moving light bar, while only 2 participants were able to correctly identify the meaning of the static light bar. While many participants realized the indicator meant it was self-driving, they were not able to identify what each signal meant with regard to specific vehicle actions. Twenty participants were able to correctly identify the meaning of the eyes interface. They were able to recognize the eyes shifting as the system recognizing a pedestrian. Interestingly, 6 participants believed the eyes were a sensor and were looking around for cars or pedestrians. While they believed the car was self-driving, they were unable to correctly guess that the eyes would stay looking straight unless they saw a pedestrian, or the vehicle was turning. Twenty-eight participants were able to correctly identify the meaning of the yield text. One participant, however, thought the yield text meant that the pedestrian should yield to the car. Eighteen participants were able to correctly identify the meaning of the Don't Walk icon. Twenty-six participants were able to correctly identify the meaning of the Walk icon. However, one person said they were not sure if the car would actually stop.

4.3.5 Informed Trials

After participants experienced the first ten trials, the researcher explained the meaning of each of the interfaces. After this training, participants completed 29 additional "informed" trials. These trials included the same ten trials in the naïve set, as well as 19 others.

Driver

Figure 42 shows the probability of each of the three categorical responses for each time point for each of the ten interfaces that were also included as naïve trials. Actual participant responses are shown in solid lines and regression model predictions are show in dashed lines. Table 27 shows the model coefficients for the main effects of interface and time point. The table includes all 29 informed trials. Results show that for the reference "no interface, late stop" trial, a majority of participants believed that the vehicle was currently being operated by a driver at all three time points. For all other interfaces other than headlamp flash and no interface, participants were significantly more likely to believe that the vehicle was currently in self-driving mode, indicating that participants generally interpreted that the presence of an eHMI as evidence that the vehicle is self-driving. *Figure 43* shows the estimated marginal mean of each interface and the associated 95% confidence interval. Negative numbers indicate that participants were more likely to respond that a driver was in control, and positive numbers indicate that participants were more likely to respond that the vehicle was in self-driving mode. Interfaces whose confidence intervals do not overlap with one another are significantly different from one another.

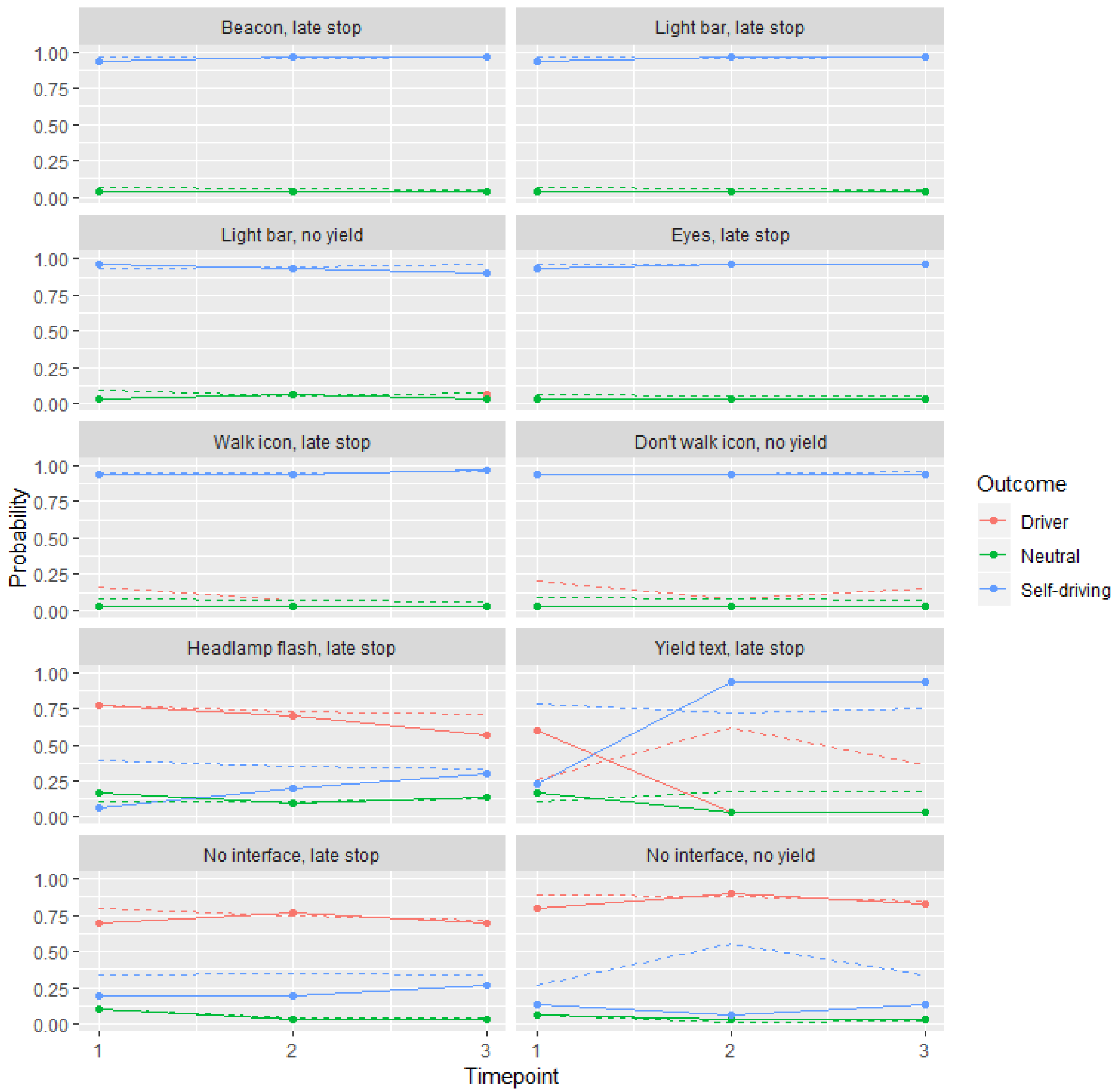


Figure 48. Plots indicating probabilities of categorical responses to Driver question (informed trials)

Table 27. Model for Driver question (all time points, informed trials)

	Estimate	Std. Error	z value	p value	Sig.
Beacon, late stop	5.2159	0.5864	8.895	<0.001	***
Beacon, left turn with signal	3.6378	0.3990	9.118	<0.001	***
Beacon, no yield	4.9597	0.5415	9.159	<0.001	***
Don't walk icon, no yield	4.7329	0.5081	9.315	<0.001	***
Eyes, early stop	4.9649	0.5424	9.153	<0.001	***
Eyes, late stop	5.2159	0.5864	8.895	<0.001	***
Eyes, right turn with signal	4.7748	0.5119	9.328	<0.001	***
Headlamp flash, early stop	1.0370	0.3400	3.050	0.002	**
Headlamp flash, late stop	0.0836	0.3492	0.239	0.811	
Headlamp flash, no yield	-0.0663	0.3534	-0.188	0.851	
Light bar, early stop	4.952	0.5410	9.153	<0.001	***
Light bar, late stop	5.2159	0.5864	8.895	<0.001	***
Light bar, late stop, late interface	4.7627	0.5111	9.318	<0.001	***
Light bar, left turn with signal	3.2928	0.3789	8.690	<0.001	***
Light bar, no yield	4.7639	0.5101	9.340	<0.001	***
Light bar, right turn with signal	3.8717	0.4175	9.273	<0.001	***
No interface, accelerating	-0.6346	0.3791	-1.674	0.094	
No interface, early stop	0.1614	0.3466	0.466	0.641	
No interface, left turn no signal	-1.2899	0.4278	-3.015	0.003	**
No interface, left turn with signal	-1.3807	0.4376	-3.155	0.002	**
No interface, no yield	-0.9236	0.4029	-2.292	0.022	*
No interface, right turn no signal	-1.1457	0.4168	-2.749	0.006	**
No interface, right turn with signal	-1.3297	0.4355	-3.053	0.002	**
Walk icon, early stop	5.2294	0.5882	8.891	<0.001	***
Walk icon, late stop	4.9578	0.5414	9.157	<0.001	***
Yield text, early stop	5.2219	0.5873	8.891	<0.001	***
Yield text, late stop	2.6781	0.3545	7.555	<0.001	***
Yield text, late stop, late interface	1.6356	0.3345	4.890	<0.001	***
Timepoint 2	0.1694	0.1470	1.152	0.249	
Timepoint 3	0.3603	0.1491	2.417	0.016	*

*$p \leq .05$, **$p \leq .01$, ***$p < .001$

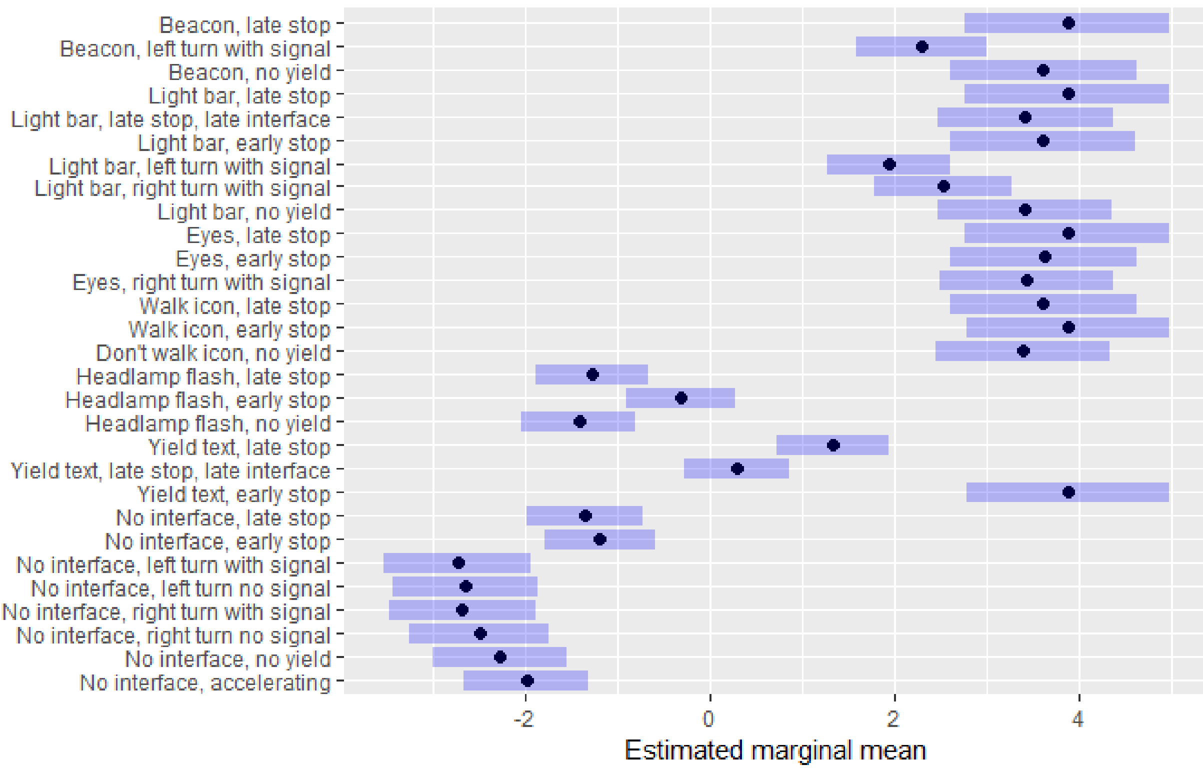


Figure 49. Marginal means for each interface, including confidence intervals

<u>Aware</u>

Figure 44 shows the probability of each of the three categorical responses for each time point for each of the ten interfaces that were also included as naïve trials. Actual participant responses are shown in solid lines, and regression model predictions are show in dashed lines. Table 28 shows the model coefficients for the main effects of interface and time point. The table includes all 29 informed trials. Results show that for the reference "no interface, late stop" trial, participants were evenly divided over whether the vehicle/driver was aware of their presence at the crosswalk. For all other interfaces other than headlamp flash and no interface, participants were significantly more likely to believe that the vehicle was currently in self-driving mode, indicating that within the context of this study participants generally interpreted the presence of an eHMI as evidence that the vehicle is self-driving. Figure 45 shows the estimated marginal mean of each interface and the associated 95% confidence interval. Negative numbers indicate participants are more likely to respond that the vehicle/driver is not aware of the pedestrian, and positive numbers indicate participants are more likely to respond that the vehicle/driver is aware of the pedestrian. Interfaces whose confidence intervals do not overlap with one another are significantly different from one another.

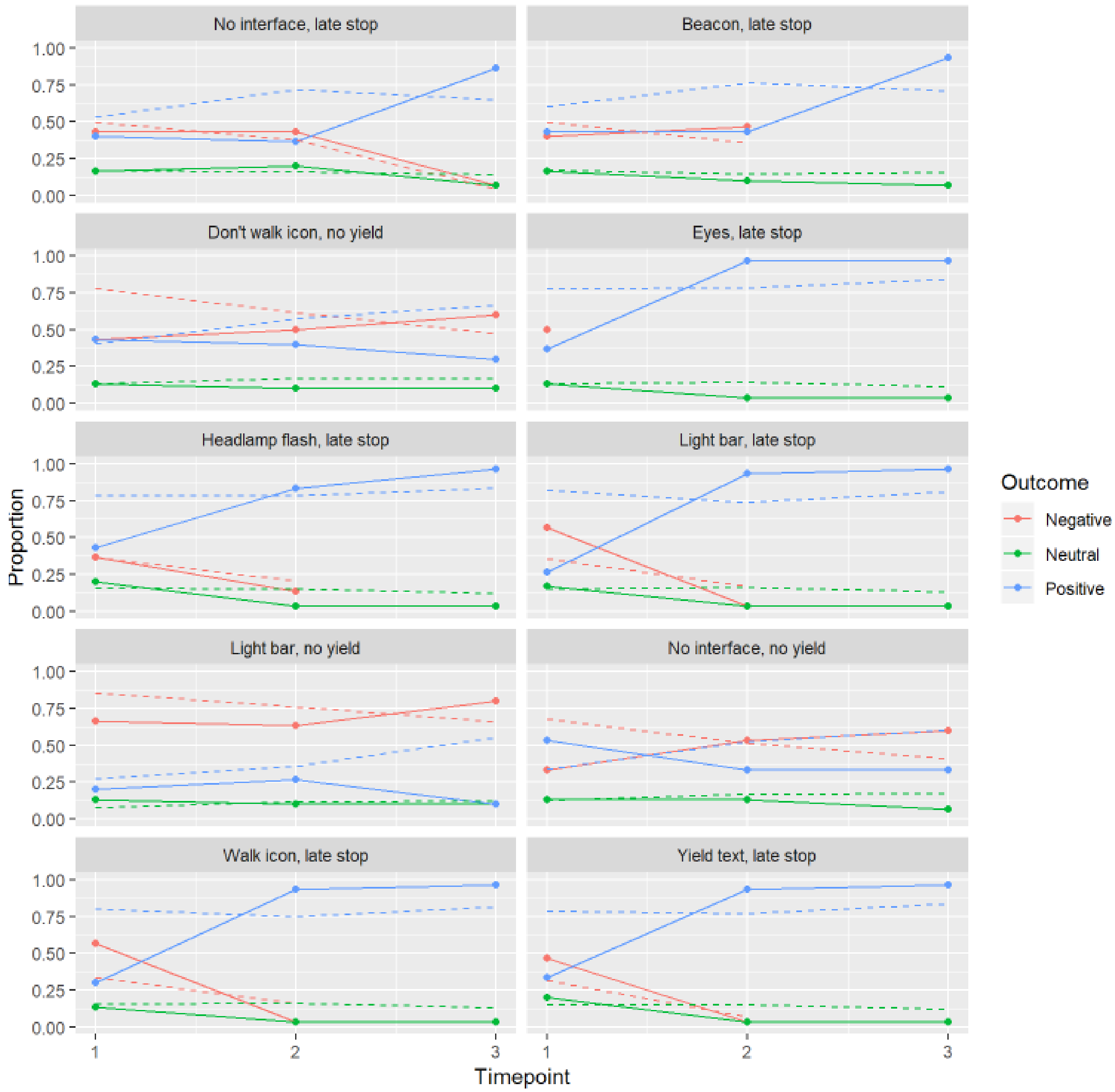


Figure 50. Plots indicating probabilities of categorical responses to Aware question (informed trials)

Table 28. Model for Aware question (all time points, informed trials)

	Estimate	Std. Error	z value	p value	Sig.
Beacon, late stop	0.2054	0.3206	0.641	0.522	
Beacon, left turn with signal	-0.3502	0.3142	-1.115	0.265	
Beacon, no yield	-0.5173	0.3147	-1.644	0.100	
Don't walk icon, no yield	-0.9790	0.3181	-3.077	0.002	**
Eyes, early stop	2.5261	0.4482	5.637	<0.001	***
Eyes, late stop	1.1320	0.3477	3.256	0.001	**
Eyes, right turn with signal	-0.5809	0.3115	-1.865	0.062	
Headlamp flash, early stop	2.9215	0.4936	5.919	<0.001	***
Headlamp flash, late stop	1.0471	0.3407	3.073	0.002	**
Headlamp flash, no yield	0.2980	0.3232	0.922	0.357	
Light bar, early stop	2.8652	0.4932	5.81	<0.001	***
Light bar, late stop	0.8548	0.3365	2.54	0.011	*
Light bar, late stop, late interface	-0.6314	0.3179	-1.986	0.047	*
Light bar, left turn with signal	-1.5369	0.3202	-4.799	0.000	***
Light bar, no yield	-2.0994	0.3414	-6.15	0.000	***
Light bar, right turn with signal	-0.9292	0.3147	-2.952	0.003	**
No interface, accelerating	-1.3058	0.3235	-4.036	<0.001	***
No interface, early stop	1.3123	0.3499	3.751	<0.001	***
No interface, left turn no signal	-0.1773	0.3127	-0.567	0.571	
No interface, left turn with signal	-0.7449	0.3125	-2.384	0.017	*
No interface, no yield	-0.8538	0.3202	-2.666	0.008	**
No interface, right turn no signal	-0.7596	0.3132	-2.425	0.015	*
No interface, right turn with signal	0.1710	0.3176	0.538	0.590	
Walk icon, early stop	2.6722	0.4682	5.708	<0.001	***
Walk icon, late stop	0.9107	0.3395	2.683	0.007	**
Yield text, early stop	3.0981	0.5256	5.895	<0.001	***
Yield text, late stop	1.0524	0.3413	3.084	0.002	**
Yield text, late stop, late interface	-0.3641	0.315	-1.156	0.248	
Timepoint 2	0.7530	0.1117	6.744	<0.001	***
Timepoint 3	1.2053	0.116	10.388	< 0.001	***

**p≤.05, **p≤.01, ***p<.001*

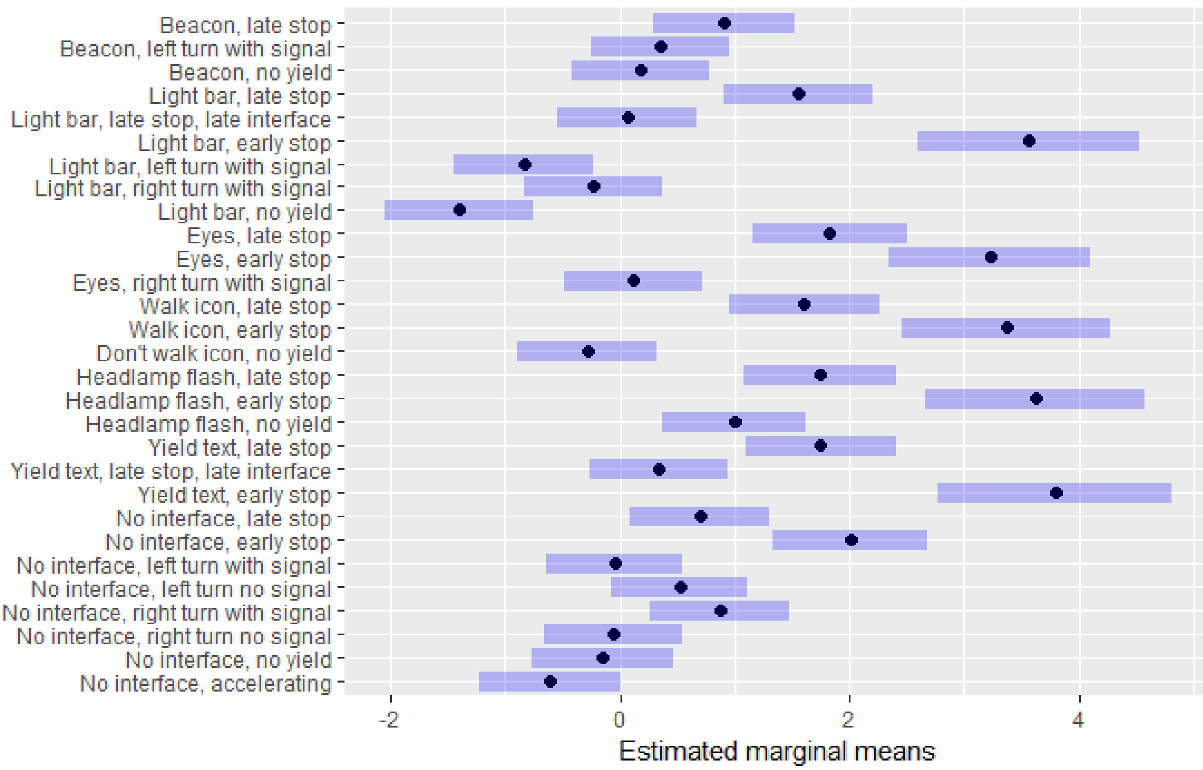


Figure 51. Marginal means for each interface, including confidence intervals

<u>Yield</u>

Figure 46 shows the probability of each of the three categorical responses for each time point for each of the ten interfaces that were also included as naïve trials. Actual participant responses are shown in solid lines, and regression model predictions are show in dashed lines. *Table* ***29*** shows the model coefficients for the categorical data obtained for this question. The table includes all 29 informed trials. Results show that for the reference "no interface, late stop" trial, participants were evenly divided over whether the vehicle would yield at time point 1, largely confident that it would not yield at time point 2 (with the vehicle still approaching at full speed), then largely confident that it would yield at time point 3 (when the vehicle had come to a stop just before the crosswalk). For all other interfaces other than headlamp flash, beacon, and interfaces explicitly communicating that the vehicle would not yield, participants were significantly more likely to believe that the vehicle would yield. For the "don't walk icon, no yield" and "no interface, no yield" trials, participants were significantly less likely to believe that the vehicle would yield, relative to the reference trial. Figure 47 shows the estimated marginal mean of each interface and associated 95% confidence interval. Negative numbers indicate participants are more likely to respond that the vehicle will not yield, and positive numbers indicate participants are more likely to respond that the vehicle will yield. Interfaces whose confidence intervals do not overlap with one another are significantly different from one another.

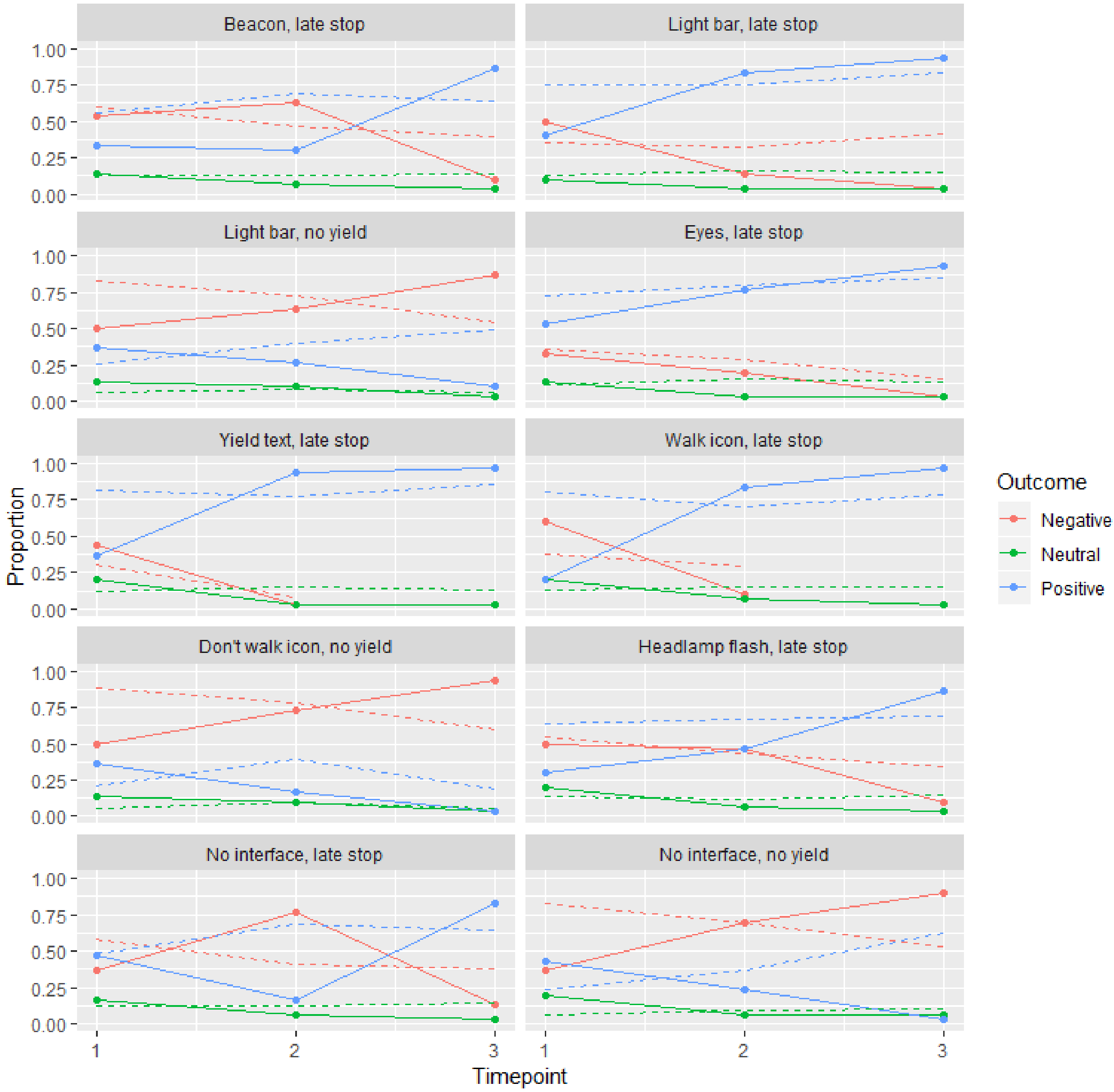


Figure 52. Plots indicating probabilities of categorical responses to Yield question (informed trials)

Table 29. Model for Yield question (all time points, informed trials)

	Estimate	Std. Error	z value	p value	Sig.
Beacon, late stop	0.0126	0.3166	0.040	0.968	
Beacon, left turn with signal	3.4365	0.5263	6.529	<0.001	***
Beacon, no yield	-0.5822	0.3177	-1.833	0.067	
Don't walk icon, no yield	-1.6994	0.3442	-4.937	<0.001	***
Eyes, early stop	2.7423	0.4317	6.352	<0.001	***
Eyes, late stop	1.3406	0.3415	3.925	<0.001	***
Eyes, right turn with signal	3.1992	0.4939	6.478	<0.001	***
Headlamp flash, early stop	2.1590	0.3795	5.690	<0.001	***
Headlamp flash, late stop	0.2871	0.3163	0.908	0.364	
Headlamp flash, no yield	-0.4089	0.3195	-1.280	0.201	
Light bar, early stop	2.5412	0.4172	6.091	<0.001	***
Light bar, late stop	1.1803	0.3364	3.508	<0.001	***
Light bar, late stop, late interface	0.1981	0.3175	0.624	0.533	
Light bar, left turn with signal	2.0179	0.3745	5.389	<0.001	***
Light bar, no yield	-1.3312	0.3336	-3.990	<0.001	***
Light bar, right turn with signal	2.8454	0.4473	6.361	<0.001	***
No interface, accelerating	-1.7226	0.3477	-4.954	<0.001	***
No interface, early stop	1.5558	0.3424	4.544	<0.001	***
No interface, left turn no signal	1.7905	0.3586	4.994	<0.001	***
No interface, left turn with signal	2.9187	0.4460	6.545	<0.001	***
No interface, no yield	-1.3069	0.3319	-3.938	<0.001	***
No interface, right turn no signal	1.7967	0.3584	5.013	<0.001	***
No interface, right turn with signal	3.3841	0.5250	6.446	<0.001	***
Walk icon, early stop	3.4386	0.5268	6.527	<0.001	***
Walk icon, late stop	0.9353	0.3266	2.864	0.004	**
Yield text, early stop	3.9800	0.6418	6.201	<0.001	***
Yield text, late stop	1.4734	0.3441	4.282	<0.001	***
Yield text, late stop, late interface	0.0183	0.3160	0.058	0.954	
Timepoint 2	0.5592	0.1225	4.565	<0.001	***
Timepoint 3	1.1819	0.1304	9.067	<0.001	***

$*p \leq .05$, $**p \leq .01$, $***p < .001$

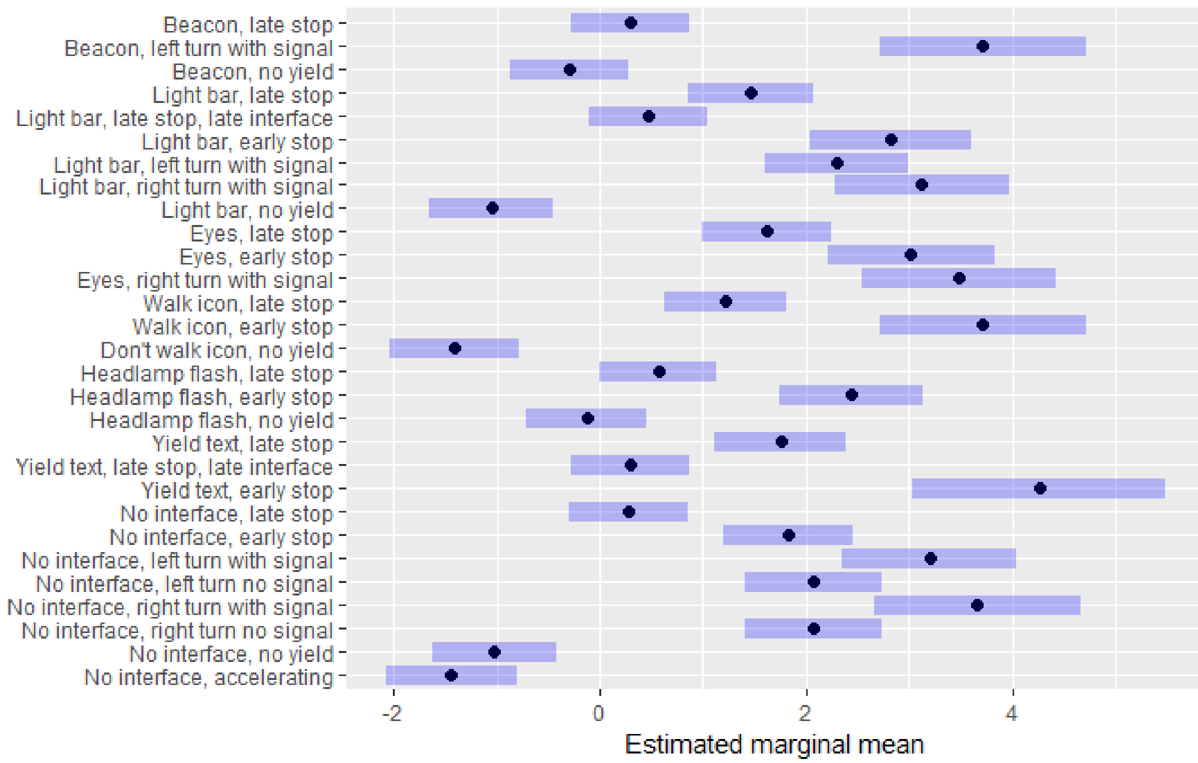


Figure 53. Marginal means for each interface, including confidence intervals

Table 30 shows results for the Yield question when focusing only on time point 2. Results show that all interfaces that communicated intent to yield or recognition of the pedestrian resulted in significantly greater likelihood that participants would believe that the vehicle will yield, relative to the reference trial. The strongest effects were seen for the Walk icon, yield text, eyes, and light bar. The beacon was not significantly different than the reference trial.

Table 30. Model for Yield question (time point 2, informed trials)

	Estimate	**Std. Error**	**z value**	**p value**	**Sig.**
Beacon, late stop	0.9831	0.6622	1.485	0.138	
Don't walk icon, no yield	0.1362	0.6838	0.199	0.842	
Eyes, late stop	3.8132	0.7104	5.368	<0.001	***
Headlamp flash, late stop	1.9596	0.6500	3.015	0.003	**
Headlamp flash, no yield	2.7832	0.6623	4.202	<0.001	***
Light bar, late stop	4.3749	0.7525	5.814	<0.001	***
Light bar, no yield	0.9273	0.6593	1.406	0.160	
No interface, no yield	0.5241	0.6757	0.776	0.438	
Walk icon, late stop	4.4800	0.7552	5.932	<0.001	***
Yield text, late stop	5.7004	0.9449	6.033	<0.001	***

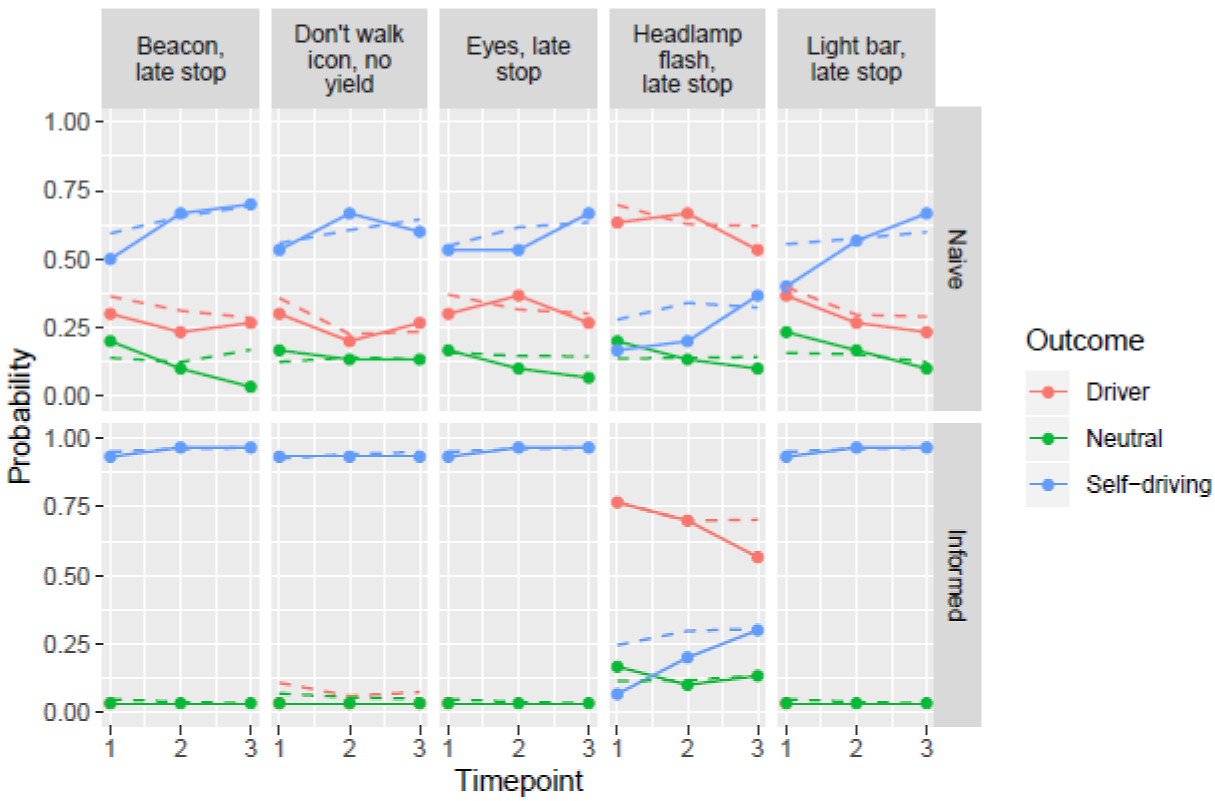
$*p \leq .05$, $**p \leq .01$, $***p < .001$

4.3.6 Training Benefits

The same ten trials that were presented as naïve trials were later presented again as informed trials. We can compare each naïve-informed pair of trials to determine which interfaces benefit most from training, or put another way, which interfaces perform worse when no training is provided. The main analyses (paired comparisons contrasts) used data collapsed across time points. Additional analyses are described for time point 2 separately, where appropriate. All paired-comparison tests were conducted using a Tukey adjustment for multiple comparisons.

Driver

Figure 48 shows paired comparisons for each of the trials that was presented in both the naïve and informed trial groups. Actual participant responses are shown in solid lines and model predictions are show in dashed lines. Table 31 shows significance tests for each of the paired comparisons with time points collapsed. Results show that for all eHMIs, participants were significantly more likely to answer correctly in the informed set of trials than in the naïve set. Headlamp flash and "no interface, late stop" were not significantly different between naïve and informed trials. Note that headlamp flash was explained to participants as a method of communication that could be used by drivers of by a vehicle in self-driving mode, so it is not surprising that training did not result in a significant change in participant responses.



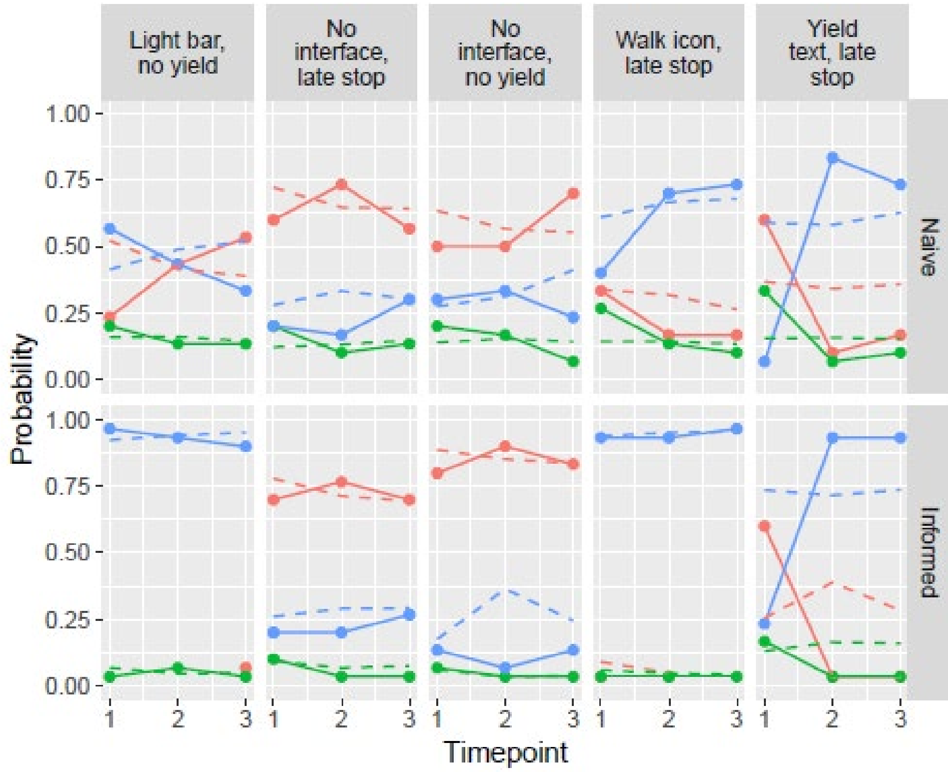


Figure 54. Probabilities of categorical responses to Driver question comparing naïve and informed trials

Table 31. Paired comparisons contrasts for responses to Driver question (naïve versus informed trials)

Contrast	**Estimate**	**Std. Error**	**z ratio**	**p value**	**Sig.**
Beacon, late stop	-2.777	0.561	-4.951	<.0001	***
Don't walk icon, no yield	-2.374	0.480	-4.948	<.0001	***
Eyes, late stop	-2.974	0.559	-5.32	<.0001	***
Headlamp flash, late stop	0.337	0.319	1.058	0.2902	
Light bar, late stop	-3.036	0.557	-5.45	<.0001	***
Light bar, no yield	-3.093	0.476	-6.493	<.0001	***
Walk icon, late stop	-2.487	0.513	-4.852	<.0001	***
Yield text, late stop	-0.631	0.315	-2.007	0.0448	*
No interface, late stop	0.309	0.331	0.932	0.3513	
No interface, no yield	1.497	0.370	4.047	0.0001	***

**p≤.05, **p≤.01, ***p<.001*

<u>Aware</u>

Figure 49 shows paired comparisons for each of the trials that was presented in both the naïve and informed trial groups. Actual participant responses are shown in solid lines and model predictions are show in dashed lines. Table 32 shows significance test results for this question with time point collapsed. Results show few significant changes from naïve to informed trials.

The only significant changes were in three “no yield” trials; for the “no yield” light bar, don’t walk icon, and no interface trials, participants were significantly more likely to believe that the vehicle/driver was not aware of their presence in the informed trial.

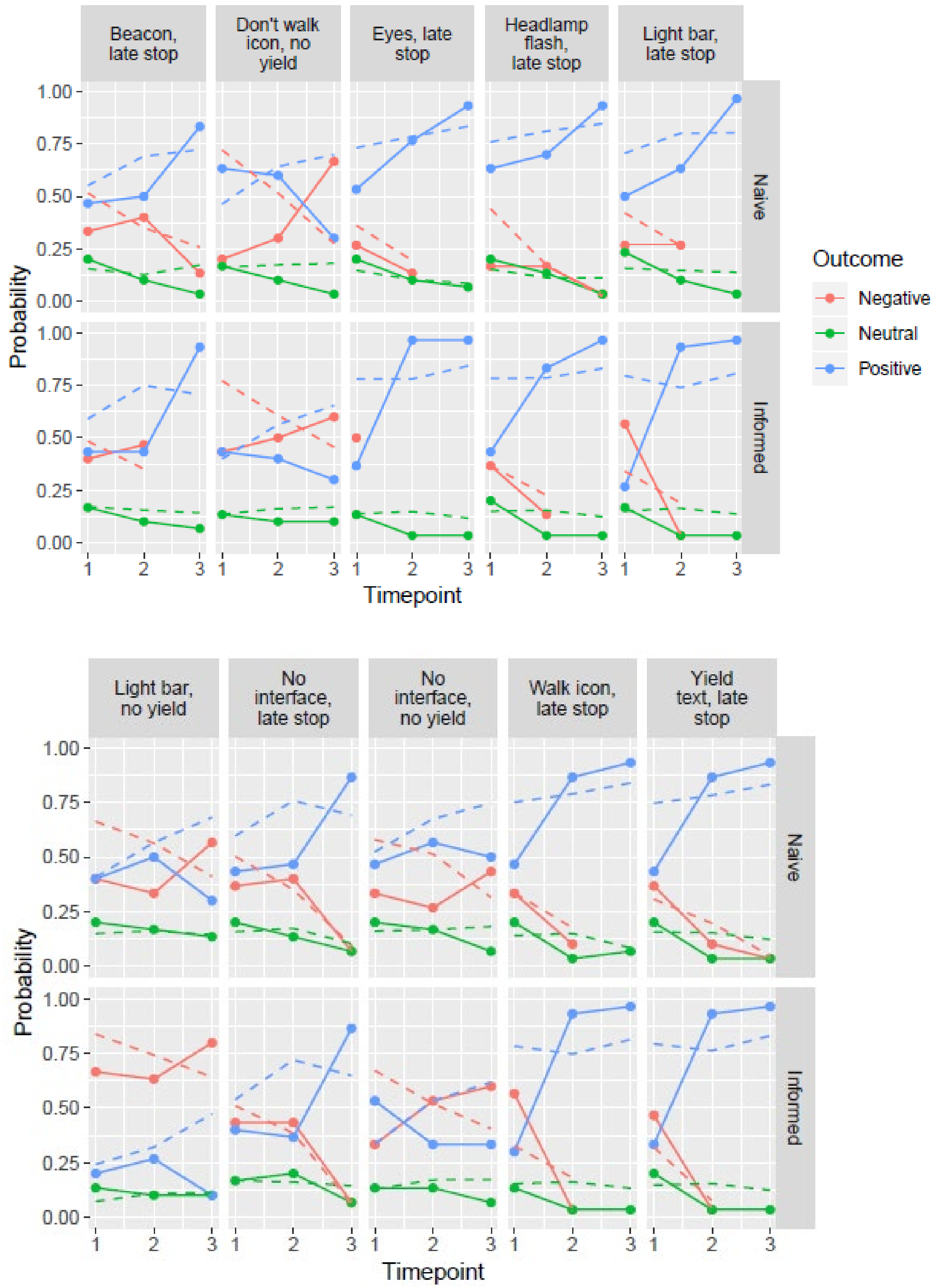


Figure 55. Probabilities of categorical responses to Aware question comparing naïve and informed trials

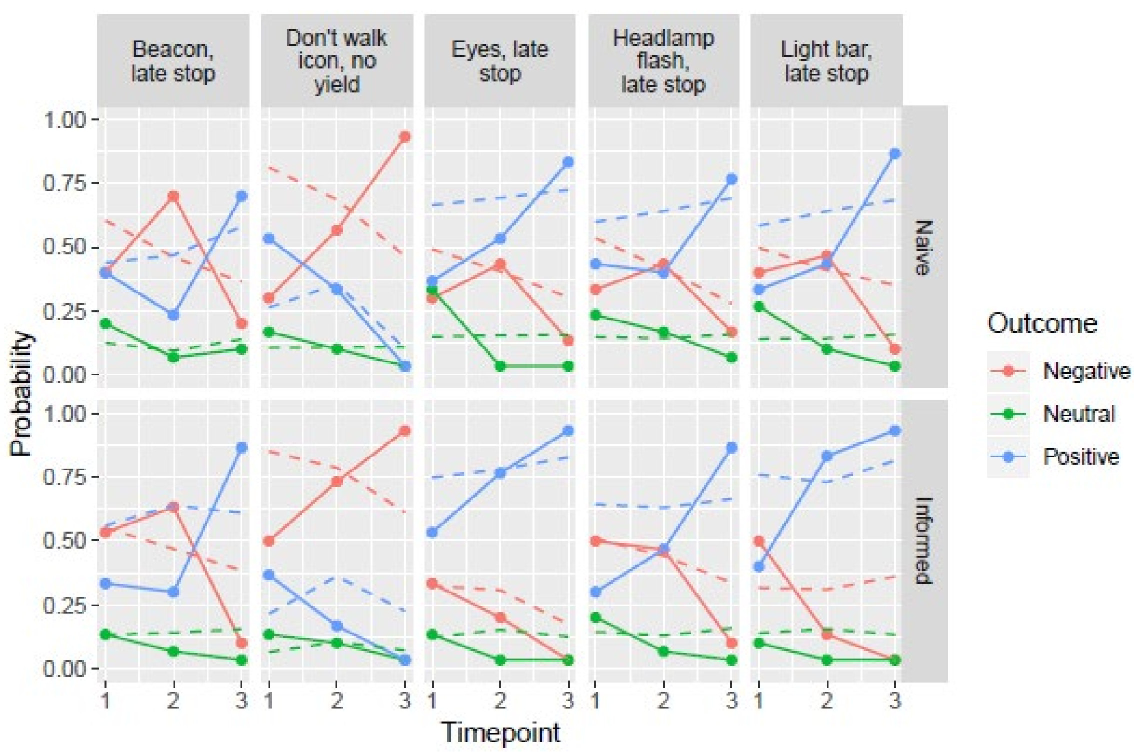
Table 32. Paired comparisons contrasts for responses to Aware question (naïve versus informed trials)

Contrast	Estimate	Std. Error	z ratio	p value	Sig.
Beacon, late stop	-0.0006	0.324	-0.002	0.9984	
Don't walk icon, no yield	0.7160	0.318	2.255	0.0242	*
Eyes, late stop	-0.0523	0.369	-0.142	0.8873	
Headlamp flash, late stop	0.1631	0.364	0.448	0.6544	
Light bar, late stop	-0.0260	0.350	-0.074	0.9408	
Light bar, no yield	1.3725	0.335	4.101	<.0001	***
Walk icon, late stop	0.2190	0.365	0.601	0.5481	
Yield text, late stop	0.0288	0.364	0.079	0.9369	
No interface, late stop	0.2237	0.318	0.704	0.4811	
No interface, no yield	0.7043	0.316	2.232	0.0256	*

$*p\leq.05$, $**p\leq.01$, $***p<.001$

Yield

Figure 50 shows paired comparisons for each of the trials that was presented in both the naïve and informed trial groups. Actual participant responses are shown in solid lines and model predictions are shown in dashed lines. Table 33 shows significance test results for this question with time point collapsed. Results show few significant changes from naïve to informed trials. Participants were more likely to believe that the vehicle would yield in the informed trials for three late stop trials: eyes, light bar, and yield text.



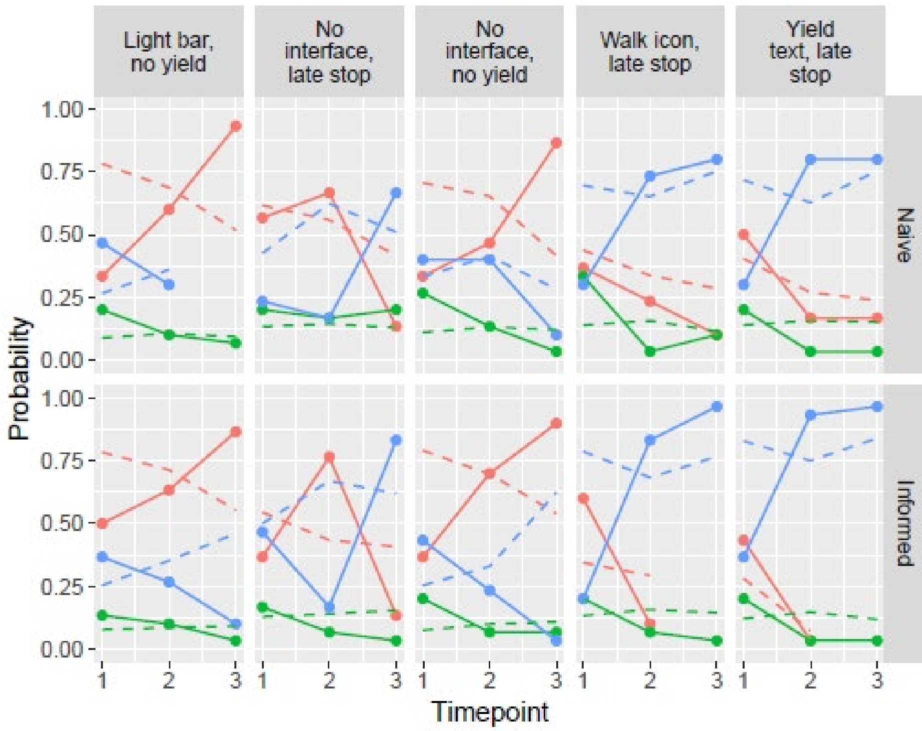


Figure 56. Probabilities of categorical responses to Yield question comparing naïve and informed trials

Table 33. Paired comparisons contrasts for responses to Yield question (naïve versus informed trials)

Contrast	Estimate	Std. Error	z ratio	p value	Sig.
Beacon, late stop	-0.1919	0.308	-0.623	0.5332	
Don't walk icon, no yield	0.6404	0.341	1.877	0.0605	
Eyes, late stop	-0.7657	0.333	-2.297	0.0216	*
Headlamp flash, late stop	0.0722	0.306	0.236	0.8134	
Light bar, late stop	-0.8099	0.328	-2.469	0.0136	*
Light bar, no yield	0.1643	0.333	0.493	0.6222	
Walk icon, late stop	-0.2050	0.322	-0.637	0.5242	
Yield text, late stop	-0.7066	0.343	-2.059	0.0395	*
No interface, late stop	-0.4429	0.304	-1.456	0.1453	
No interface, no yield	0.4698	0.324	1.448	0.1475	

*$p \leq .05$, **$p \leq .01$, ***$p < .001$

Table 34 shows results for the Yield question when focusing only on time point 2. Similar to the results collapsed across time points, there were few significant differences between naïve and informed trials. In the informed trials, participants were significantly more likely to believe that the vehicle would yield for the "light bar, late stop" and "walk icon, late stop" trials, and less likely to believe that the vehicle would yield for the "no interface, no yield" trial.

Table 34. Paired comparisons contrasts for responses to Yield question (time point 2)

Contrast	Estimate	Std. Error	z ratio	p value	Sig.
Beacon, late stop	-0.546	0.629	-0.868	0.3856	
Don't walk icon, no yield	1.006	0.616	1.635	0.1021	
Eyes, late stop	0.622	0.562	1.107	0.2684	
Headlamp flash, late stop	-0.106	0.554	-0.191	0.8486	
Light bar, late stop	-2.360	0.657	-3.590	0.0003	***
Light bar, no yield	0.165	0.589	0.281	0.7787	
Walk icon, late stop	-2.788	1.131	-2.466	0.0137	*
Yield text, late stop	-1.024	0.807	-1.268	0.2047	
No interface, late stop	0.460	0.638	0.721	0.4709	
No interface, no yield	1.305	0.509	2.564	0.0103	*

*$p \leq .05$, **$p \leq .01$, ***$p < .001$

4.3.7 Beacon Versus No Interface

The ADS beacon interface is distinct from the other interfaces used in this study in that it does not communicate intent; it only communicates that the vehicle is in automated mode. As such, it is important to evaluate the performance of the beacon relative to the no-interface conditions. This section compares the beacon against "no interface" for both "late stop" and "no yield" vehicle actions. All data in this section come from the informed set of trials.

Driver

Figure 51 shows the results for the Driver question. Comparisons between the beacon interface and no interface are shown for trials presented in both the late-stop and no-yield conditions. Actual participant responses are shown in solid lines, and model predictions are shown in dashed lines. Table 35 shows significance test results for this question with time point collapsed. Results show that for the ADS beacon trials, nearly all participants believed that the vehicle was self-driving at all three time points; whereas in the no-interface trials, a majority of participants believed that a driver was in control at all three time points.

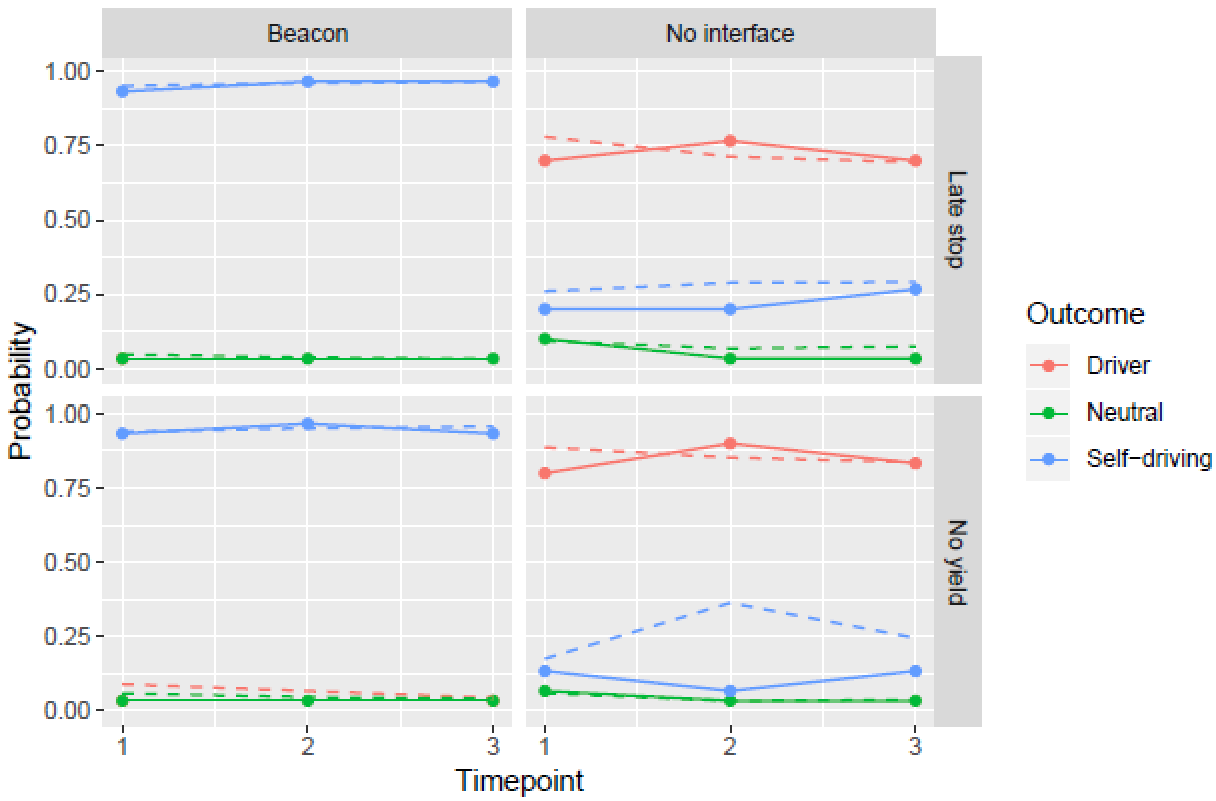


Figure 57. Probabilities of categorical responses to Driver question comparing Beacon and No Interface trials

Table 35. Paired comparisons contrasts for responses to Driver question

Contrast	Estimate	Std. Error	z ratio	p value	Sig.
Late stop, Beacon - No interface	4.91	0.573	8.575	<.0001	***
No yield, Beacon - No interface	5.52	0.556	9.926	<.0001	***

$*p \leq .05$, $**p \leq .01$, $***p < .001$

<u>Aware</u>

Figure 52 shows the results for the Aware question. Comparisons between the beacon interface and no interface are shown for trials presented in both the late stop and no yield conditions. Actual participant responses are shown in solid lines, and model predictions are shown in dashed lines. Table 36 shows significance test results for this question with time point collapsed. Results show no significant differences between the beacon and no interface trials for whether or not the vehicle/driver was aware of the pedestrian. This result suggests that the presence of a beacon did not help participants feel recognized by the vehicle.

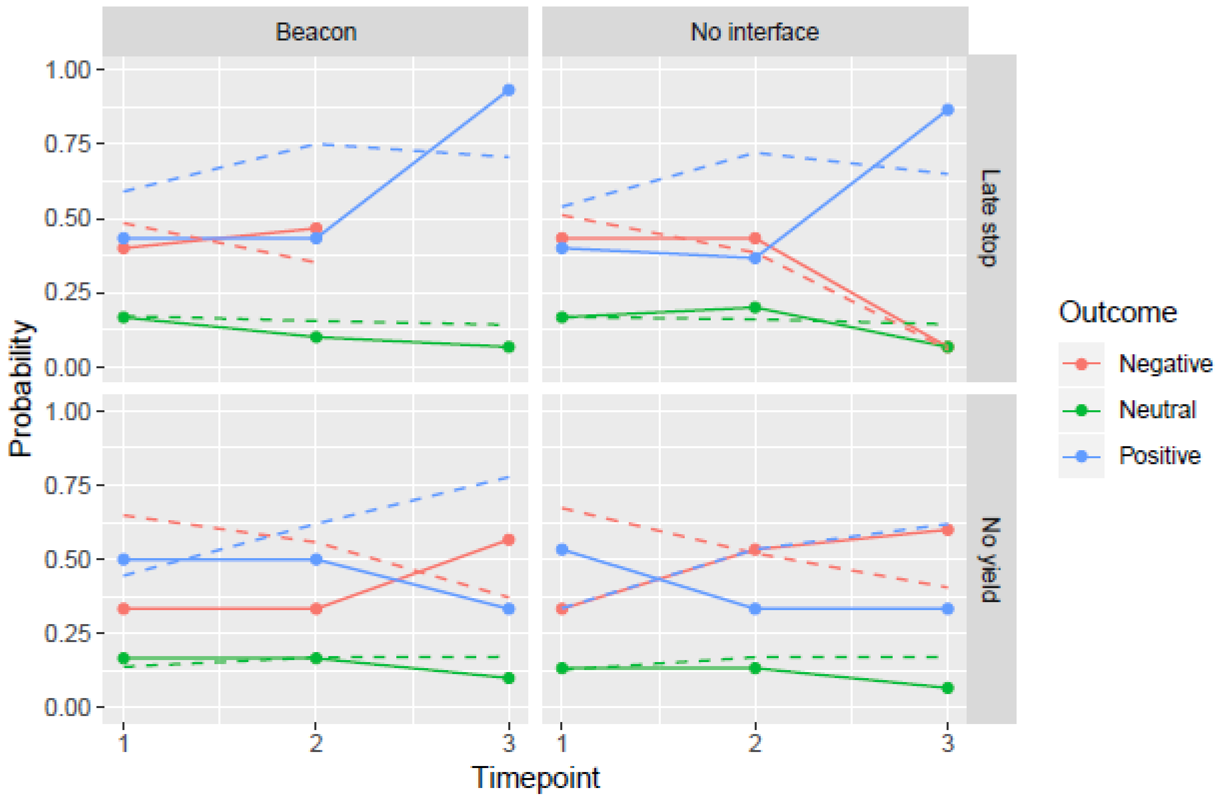


Figure 58. Probabilities of categorical responses to Aware question comparing Beacon and No Interface trials

Table 36. Paired comparisons contrasts for responses to Aware question

Contrast	Estimate	Std. Error	z ratio	p value	Sig.
Late stop, Beacon - No interface	0.213	0.319	0.667	0.5049	
No yield, Beacon - No interface	0.352	0.315	1.118	0.2636	

**p≤.05, **p≤.01, ***p<.001*

Yield

Figure 53 shows the results for the Yield question. Comparisons between the beacon interface and no interface are shown for trials presented in both the late-stop and no-yield conditions. Actual participant responses are shown in solid lines, and model predictions are shown in dashed lines. Table 37 shows significance test results for this question with time point collapsed. Results show no difference between beacon and no interface for late stop, but a significant difference for no yield. In the no-yield trials, participants were more likely to (incorrectly) believe that the vehicle would yield in the beacon condition, suggesting that the presence of the beacon made participants more confident that the vehicle would yield to them. When looking only at time point 2, there were no significant differences between beacon and no interface.

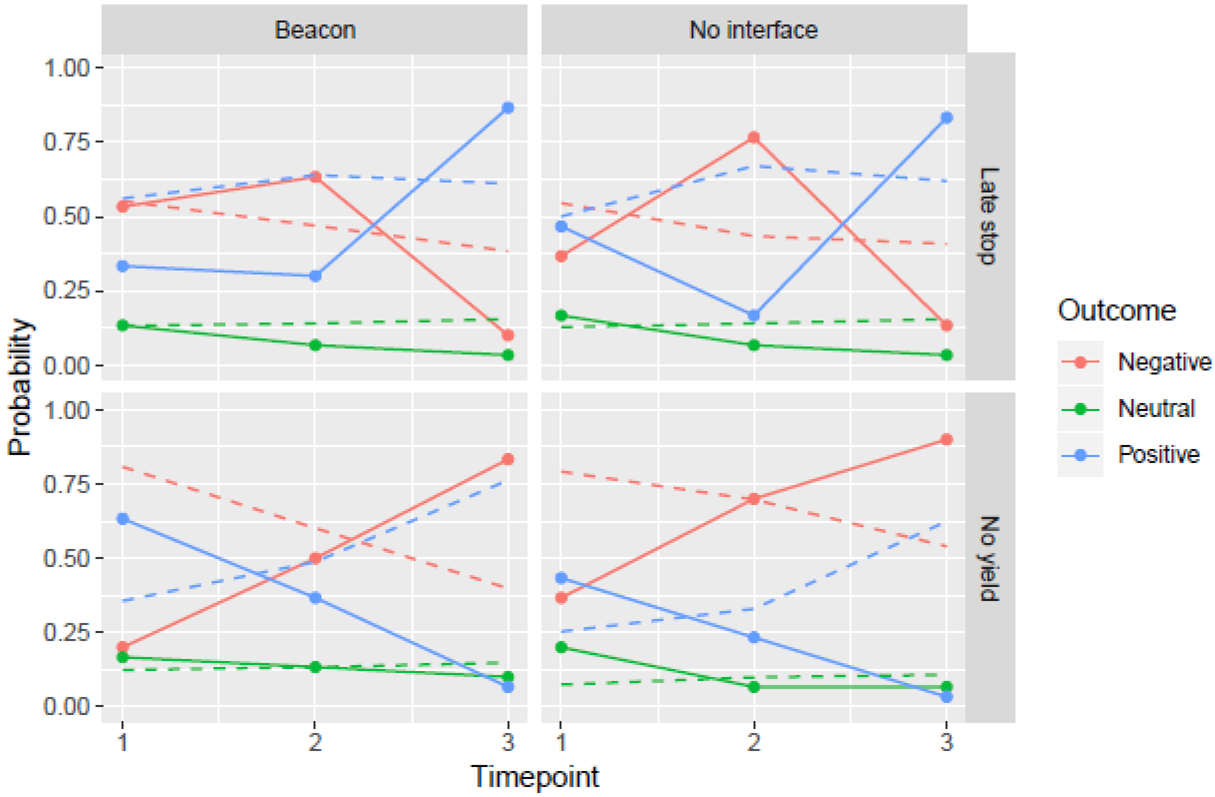


Figure 59. Probabilities of categorical responses to Yield question comparing Beacon and No Interface trials

Table 37. Paired comparisons contrasts for responses to Yield question

Contrast	Estimate	Std. Error	z ratio	p value	Sig.
Late stop, Beacon - No interface	0.0124	0.310	0.04	0.9682	
No yield, Beacon - No interface	0.6983	0.322	2.167	0.0302	*

**p≤.05, **p≤.01, ***p<.001*

4.3.8 Timing of "Yielding" Message

If an ADS vehicle is going to yield to a pedestrian, it can communicate that fact as soon as the decision has been made or at a later time. In this study, we compared two yield message times—just before the vehicle begins to decelerate and when the vehicle comes to a stop. These comparisons were made for two interfaces—light bar and yielding text. The "late stop" vehicle action was used for both pairs of trials. Only the Yield question data were analyzed to address this topic.

<u>Yield</u>

Figure 54 shows the results for the Yield question. We compared trials with an early signal by the interface (top two graphs) to trials with a late signal by the interface (bottom two graphs). Actual participant responses are shown in solid lines and model predictions are shown in dashed lines. While the figure shows all three time points, analyses only used time point 2. Table 38 shows significance test results for this question. Unsurprisingly, results show that participants were significantly more likely to recognize that the vehicle would yield at time point 2 if an eHMI indicates this intention before time point 2. At time point 3, however, participants almost universally believe that the vehicle will yield, regardless of condition.

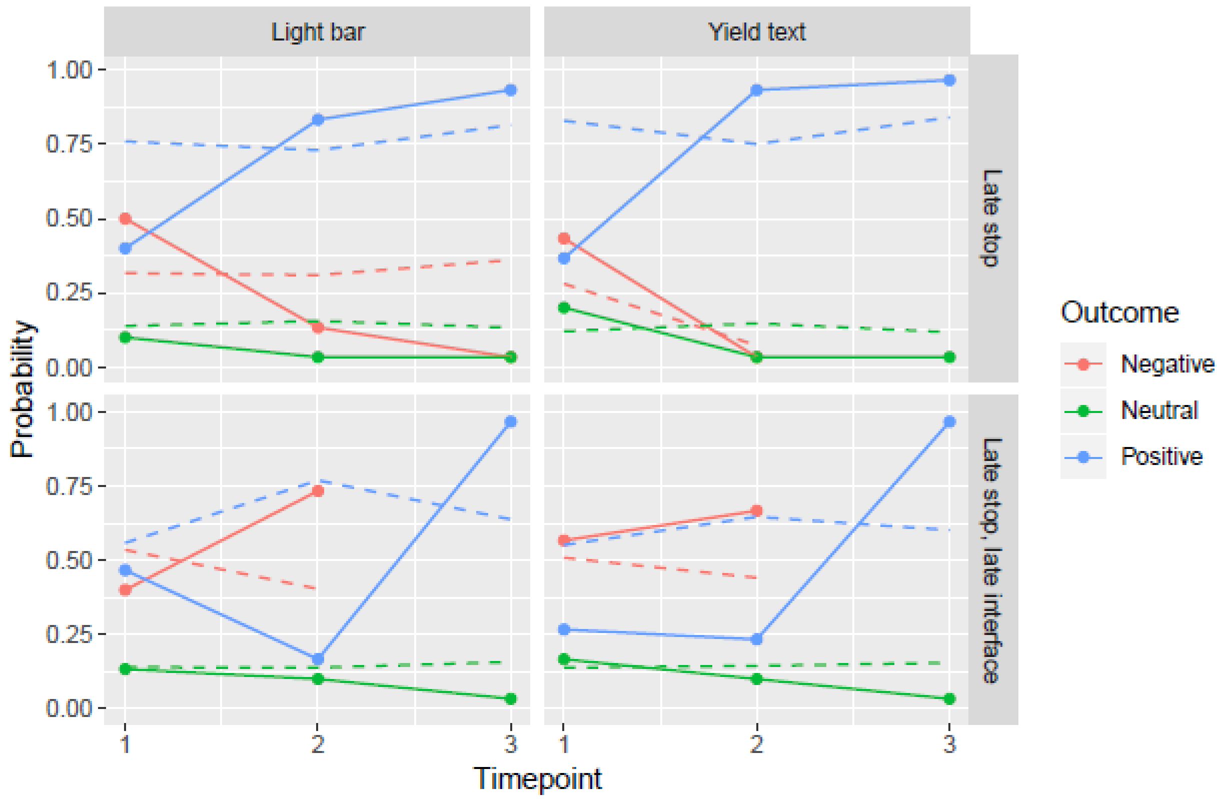


Figure 60. Probabilities of categorical responses to Yield question comparing early to late signalling by the interface

Table 38. Paired comparisons contrasts for responses to Yield question (early versus late signal)

Contrast	Estimate	Std. Error	z ratio	p value	Sig.
Light bar late stop time 2, early - late interface	0.947	0.33	2.87	0.0041	**
Yield text late stop time 2, early - late interface	1.401	0.336	4.17	<.0001	***

$*p \leq .05$, $**p \leq .01$, $***p < .001$

4.3.9 Communicating That Vehicle Will Not Yield

There are various ways that an ADS vehicle can communicate that it does not intend to yield, or it can opt to communicate nothing at all. This analysis compares beacon, don't walk icon, light bar, headlamp flash, and no interface. The headlamp flash condition was included because even though flashing headlamps is often used to communicate intent to yield, it is an ambiguous message that might be used for other reasons. These analyses consider only the Yield question for informed trials in which the vehicle does not yield.

Yield

Figure 55 shows the probability of each of the three categorical responses for each time point for each interface. Actual participant responses are shown in solid lines, and regression model predictions are shown in dashed lines. Paired comparisons show that most interfaces (including no interface) are not significantly different than one another (see Table 39). However, the don't walk icon was significantly more effective in communicating that the vehicle would yield than the beacon and the headlamp flash. When analyzing time point 2 alone, the only significant paired comparisons revealed that the headlamp flash was significantly *worse* at communicating intent to yield than the don't walk icon, light bar, and even no interface at all (see Table 40).

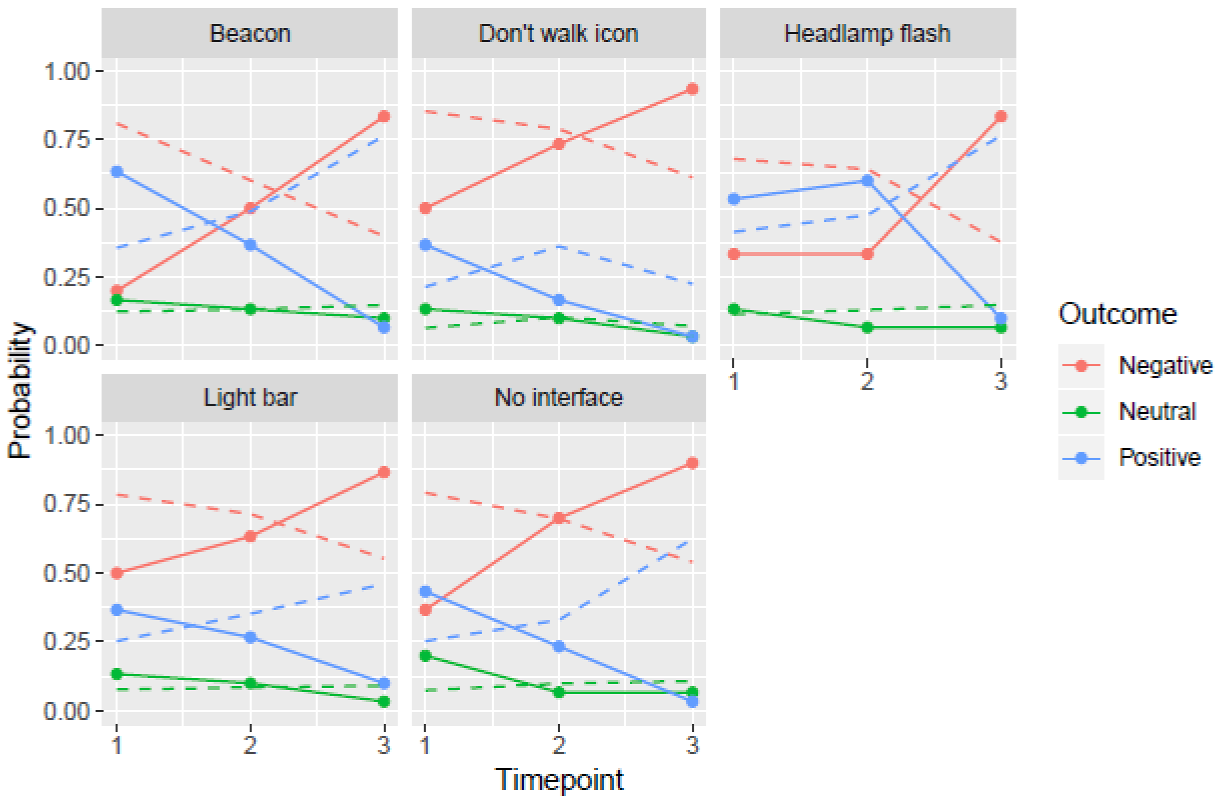


Figure 61. Probabilities of categorical responses to Yield question comparing five interfaces

Table 39. Paired comparisons contrasts for responses to Yield question for trials in which the vehicle did not yield (all time points)

Contrast	Estimate	Std. Error	z ratio	p value	Sig.
Beacon, no yield - Don't walk icon, no yield	1.0720	0.333	3.218	0.0113	*
Beacon, no yield - Headlamp flash, no yield	-0.1587	0.311	-0.510	0.9864	
Beacon, no yield - Light bar, no yield	0.7221	0.324	2.228	0.1691	
Beacon, no yield - No interface, no yield	0.6983	0.322	2.167	0.1923	
Don't walk icon, no yield - Headlamp flash, no yield	-1.2307	0.335	-3.672	0.0022	**
Don't walk icon, no yield - Light bar, no yield	-0.3499	0.347	-1.010	0.8510	
Don't walk icon, no yield - No interface, no yield	-0.3738	0.345	-1.084	0.8150	
Headlamp flash, no yield - Light bar, no yield	0.8808	0.326	2.702	0.0537	
Headlamp flash, no yield - No interface, no yield	0.8570	0.324	2.643	0.0628	
Light bar, no yield - No interface, no yield	-0.0238	0.336	-0.071	1.0000	

$*p\leq.05$, $**p\leq.01$, $***p<.001$

Table 40. Paired comparisons contrasts for responses to Yield question for trials in which the vehicle did not yield (time point 2)

Contrast	Estimate	Std. Error	z ratio	p value	Sig.
Beacon, no yield - Don't walk icon, no yield	1.389	0.602	2.306	0.1430	
Beacon, no yield - Headlamp flash, no yield	-1.064	0.562	-1.892	0.3218	
Beacon, no yield - Light bar, no yield	0.644	0.574	1.122	0.7950	
Beacon, no yield - No interface, no yield	1.050	0.594	1.767	0.3927	
Don't walk icon, no yield - Headlamp flash, no yield	-2.453	0.615	-3.987	0.0006	***
Don't walk icon, no yield - Light bar, no yield	-0.745	0.622	-1.198	0.7524	
Don't walk icon, no yield - No interface, no yield	-0.339	0.638	-0.531	0.9842	
Headlamp flash, no yield - Light bar, no yield	1.708	0.586	2.915	0.0293	*
Headlamp flash, no yield - No interface, no yield	2.114	0.607	3.486	0.0045	**
Light bar, no yield - No interface, no yield	0.406	0.614	0.661	0.9646	

$*p\leq.05$, $**p\leq.01$, $***p<.001$

4.3.10 Final Questions

After participants completed the 39 study trials, they answered three final questions. The questions were:

1. Which of the communications you saw today do you think would be best to use on real self-driving cars?
2. How would you improve that interface if you could?
3. Were any of the interfaces you saw today particularly confusing, or were any of the designs especially bad for any reason?

Figure 56 shows the percentage of participants who named each interface their favorite. Some participants named more than one favorite, and in these cases, all responses from a participant were counted. There was a total of 39 responses from the 30 participants. The figure shows that the walk and don't walk icons was the clear favorite of participants, with half of participants naming it a favorite interface. The next best interfaces—yield text, light bar, and eyes—were each named a favorite by 12 to 16 percent of participants. Explanations for why the walk and don't walk icons were best emphasized that these symbols were very familiar to pedestrians and very clear in their meaning. A few participants also noted that the walk and don't walk icons are understood regardless of a pedestrian's native language.

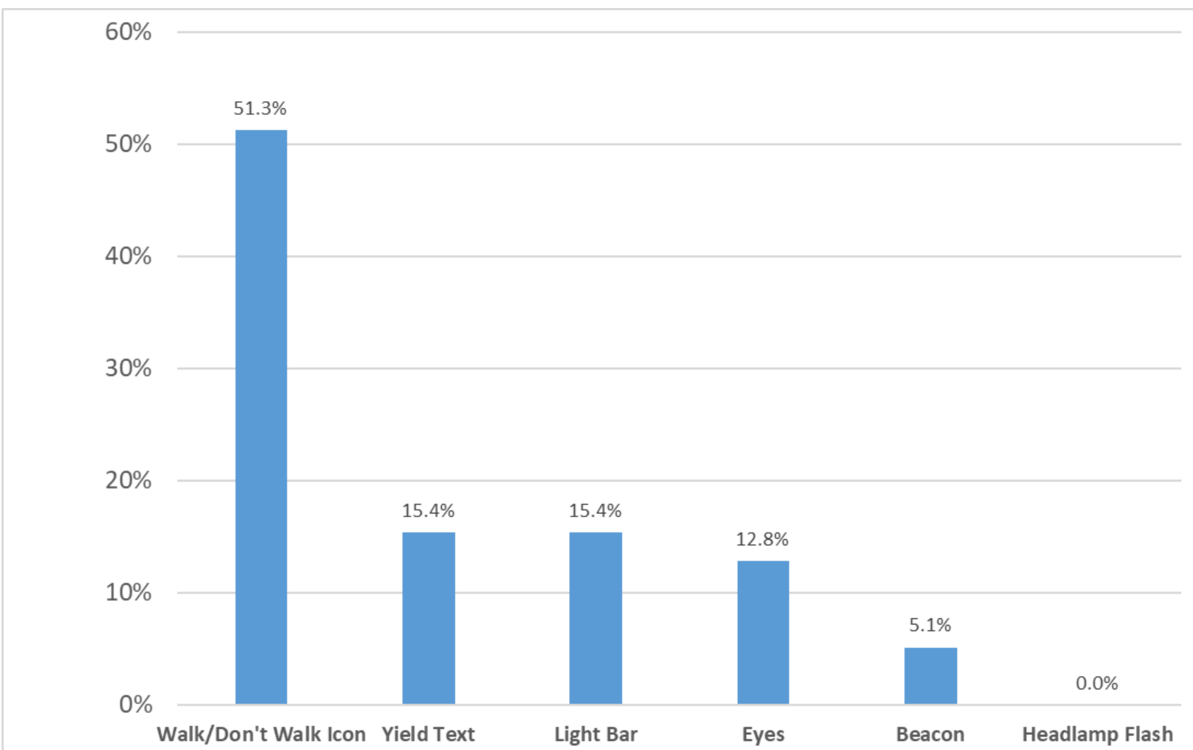


Figure 62. Percentage of participants who named each interface as a favorite

Participants' ideas for improving interfaces included making eHMIs more noticeable, including making them bigger, brighter, or adding flashing. One participant suggested adding an auditory component. A few participants also suggested that the interfaces should indicate earlier that they intend to yield.

The interfaces most frequently named as the least favorite were the light bar and the beacon. The light bar was unpopular because participants felt that it was unintuitive and hard to understand. The beacon was unpopular because participants felt that it didn't provide enough useful information to a pedestrian (e.g., will the vehicle yield?). As noted previously, before the meaning of the beacon was explained many participants interpreted its green color as a "go" signal to cross the street. The color might have contributed to the unpopularity of the beacon, which emphasizes the importance of considering the unintended messages that might be conveyed by eHMIs.

4.4 Discussion of Study 3

Methodological considerations

Results suggest that the study method was successful in discriminating between interfaces in terms of responses to the three questions. There were differences between interfaces for the three questions across a range of trials and key comparisons. These differences were largely consistent with the open-ended feedback that participants provided during the sessions regarding interfaces that were most comprehensible and clear in their meaning.

One surprising result revealed in this study was participants' limited use of the lower portion of the 0 to 10 confidence rating scale. Participants overwhelmingly rated their confidence 5 or higher, even when the trial video gave them no indication of what the correct answer should be. Such overconfidence often has been noted in the decision-making research literature (Moore & Healy, 2008).

As a result of this outcome, the research team deviated from the initial plan to analyze confidence on a continuous scale from -10 to +10, and instead opted for three confidence categories (confident negative (-10 to -5), neutral/uncertain (-4 to +4), and confident positive (+5 to +10). These three categories may reflect participants' actual thinking better than the more detailed 0 to 10 scales. This revised approach necessitated a change to the analysis plan as well, with a revised approach using ordered logistic regression. Even with this categorical approach, neutral/uncertain responses were rare relative to the confident categories. It is not clear why participants rarely indicated low confidence.

For any future use of this methodology, there are a number of options available to address this limited use of the lower portion of the 0 to 10 confidence rating scale. First, while the present study's instructions clearly stated the meanings of the scale end points, instructions to participants could make more explicit that the lower portion of the scale should be used when they are not confident in the correct response. Second, instead of using confidence scales, participants can be directly asked to make categorical responses. These categories could be the same three created *post hoc* for this study (i.e., confident negative, uncertain, confident positive), or an alternative approach. Pilot testing and/or cognitive testing could help to identify effective approaches to capturing and analyzing confidence ratings.

In this study, participants answered questions and gave confidence ratings at three time points for each video (vehicle far away, vehicle entering intersection, vehicle at crosswalk or turned off road). The purpose of this approach was to determine how participants' understanding of the situation and the eHMI change due to vehicle position and kinematics, and due to status/changes in the eHMI. At time point 1, participants rarely had sufficient information to determine if the vehicle would yield because an eHMI was either not present or had not yet reached its final state. At time point 3, vehicle position and kinematics alone were usually enough to determine if the vehicle would yield (e.g., vehicle turned off road, came to stop before crosswalk, or reached crosswalk without slowing). Time point 2, therefore, was the most important time point for analysis because, for most of the key trials, the eHMI, if present, had entered its final state, but the vehicle had not begun to change its kinematics in ways that give cues to its intention. This was true of the core set of trials (the set used for naïve trials), where the vehicle either came to a stop just before the crosswalk (7 trials) or continued through the crosswalk without yielding (3 trials).

This was not true, however, for some trials outside of the core set described above. For some trials (e.g., early stop), the eHMI entered its final state by time point 1; and for trials in which the vehicle turned off the road before reaching the crosswalk, the vehicle had visibly begun its turning motion and/or signaling to turn. For late interface trials, the eHMI did not signal its intent until just before time point 3. This design allowed for a wide range of interface characteristics, but not all trials were comparable at equivalent time points.

The main set of analyses conducted in this study combined responses for all three time points, for any given trial. This approach potentially gives the best overall picture of participant understanding of an approaching vehicle using a particular implementation of an eHMI, but it might also dilute the findings for any one time point. This is why, where appropriate, the research team also analyzed time point 2 separately for the Yield question. Yield results for time point 2, however, did not appear to differentiate between interfaces any better than the all-time-points data did, possibly because of reduced statistical power.

Finally, the design of the trials in this study could potentially have influenced participants' expectations. As noted above, for the core set of ten trials used for the naïve trials, the vehicle yielded in seven of them. Across all trials, the vehicle was more likely than not to yield to the pedestrian, especially if the vehicle had an eHMI, which could have resulted in a general expectation that the vehicle would yield. It was also often possible for participants to tell if the vehicle was capable of self-driving—even if no eHMI was active—if the vehicle had a blank eHMI screen on the grill versus no eHMI screen at all. While it is not clear to what extent, if any, the study design created expectations that affected results, the possibility that this could happen should be considered when designing similar studies.

Study findings

Results of this study reveal that, for the one traffic scenario tested, participants were generally able to recognize that the presence of an eHMI indicated that the vehicle was in self-driving mode, and if the vehicle yielded, they indicated that the vehicle recognized their presence, even before the meanings of the interfaces had been explained. All eHMIs (with the exception of the beacon) also helped participants recognize that the vehicle would yield under naïve conditions. Training on the meaning of the interfaces further enhanced comprehension of all eHMIs. Overall, under both naïve and informed conditions, the results suggest that eHMIs led to improved comprehension of the vehicle's status and intentions relative to a no-interface baseline condition.

Unsurprisingly, results show that participants could comprehend the intentions of a yielding vehicle earlier if the vehicle's eHMI changed to its final state when it began decelerating rather than when it reaches a stop, and participant feedback suggests that earlier notification is preferred. Despite this finding, there may be good reasons for vehicles to display "yielding" messages later. For example, a "yielding" message does not necessarily indicate *where* the vehicle intends to come to a stop and might mislead pedestrians into stepping out into its path. Unexpected conditions such as black ice could also cause to vehicle to travel beyond its intended stopping location.

The questions asked at the end of the study showed that the don't-walk and walk icons were the preferred interface of most participants because the icons are universally recognized and clear in their meaning. This interface also performed particularly well in the video trials. It is important to note, however, that despite these potential benefits, this interface might not necessarily be appropriate for use as an eHMI. First, the walk and don't walk icons (also known as the walking person and upraised hand, respectively), have clear meanings and requirements as defined in Section 4E.01 of the Manual on Uniform Traffic Control Devices (Federal Highway Administration, 2012), and use on a vehicle might not be permitted. Second, these icons indicate an action for the pedestrian to take, which might not necessarily be safe (e.g., other vehicles might not yield to pedestrian) or legal (if vehicle yields to jaywalking pedestrian. Interfaces that suggest a pedestrian action have the potential to mislead pedestrians into taking an unsafe or illegal action, though there is not sufficient real-world data to indicate whether or not this is a problem.

<u>Limitations</u>

There are a number of limitations to note about this experiment. This experiment used a single daylight crossing scenario (four-way residential intersection with 25 mph speed limit, crosswalk, and no traffic control devices). In all trials, participants focused on a single direction of oncoming traffic and there was only one vehicle approaching. There were no other pedestrians present. This single, relatively non-complex scenario is not representative of the diversity of crossing situations, and therefore it is not clear how well this research method might work in other scenarios.

Similarly, in the videos recorded for this study, it was not possible for participants to see inside the vehicle. While this design was intentional and realistic in some crossing scenarios, it also eliminated the ability of participants to look at the driver as a cue regarding whether the driver is in control of the vehicle, to assess the driver's intention to yield, or to negotiate right-of-way. Previous research, including the prior studies conducted in this project, identified such cues as important to pedestrians.

All participants were English-fluent and lacked any notable physical or cognitive disabilities. A more diverse group of participants would be needed to evaluate the appropriateness of this method for various vulnerable road user groups.

Finally, we note that while this method did ask participants whether or not they expect the oncoming vehicle to yield, it did not investigate actual pedestrian behavior or intention to step out into the travel lane. Pedestrian behavior in the real world is complex, and pedestrians' expectations of vehicle behavior do not necessarily dictate their crossing behavior or the likelihood of potential conflicts.

5 Conclusions

The first two research studies conducted for this project provided insights about the information that the ADS vehicle should communicate to shared road users, while the third study developed and exercised a preliminary lab-based protocol for evaluating early eHMI prototype designs for ADS vehicles. Based on the findings from Study 1 and Study 2, we found that shared road users (pedestrians, bicyclists, and drivers) most often use implicit cues provided by vehicle movements and vehicle position on the roadway to predict intent. However, they also frequently look for, expect to see, and rely upon cues provided directly by the driver such as head pose, eye contact, posture, and gestures. The use of these driver-related cues depends on both the traffic scenario and shared road-user type. For example, bicyclists, in particular, were very concerned about being seen by nearby drivers and frequently relied on eye contact and gestures, even soliciting these by initiating communication themselves. Driver-related cues were used mostly when vehicles were in close proximity to the shared road user. ADS vehicles may need an eHMI to interact effectively with shared road users in these situations. The eHMI may help support shared road users' expectations and help them to predict the vehicle's movements just as driver-related cues are currently used. This could potentially lead to better public acceptance of ADS vehicles.

In Study 3, we developed preliminary methods to assess the effectiveness of communication from an approaching ADS vehicle to pedestrians. Presentation of eHMI designs as video overlays was an effective way to visualize interface designs within projected, high-fidelity dynamic visual scenes. Some advantages of this method are that the vehicle depicted can be viewed life-sized without the need for participants to wear virtual reality goggles. Another advantage is the precise repeatability of the stimuli for all participants. The stop-motion video segments allowed researchers to assess participants' understanding of the eHMI when the vehicle was at different distances.

For each trial in this study, participants indicated whether they thought the vehicle was operated by a driver or in self-driving mode, whether the driver or vehicle was aware of their presence, and whether the vehicle would yield to them or not. After answering each question, participants rated their confidence in their answer on a scale from 0 to 10. Results of this study showed that the preliminary method successfully differentiated between various eHMIs and vehicle approach actions across the three key questions for the traffic scenario depicted in this study. Results show that eHMIs that clearly and intuitively indicate intended vehicle action or suggested pedestrian action resulted in the highest comprehension levels and highest levels of satisfaction. Interfaces that were unfamiliar and unintuitive were unpopular, even after the meanings of the interfaces were explained. A beacon interface that indicated that the vehicle was in self-driving mode was effective in communicating that fact but was not effective at communicating vehicle intention.

Surprisingly, confidence ratings in this study were bimodal, with participants rarely rating their confidence below 5. The reasons for this outcome are unclear, but future applications of this method should consider approaches to ensure appropriate ratings. One potential way to address this overconfidence in future research is to provide participants with three distinct response options (i.e., yes, no, don't know) rather than binary options with confidence scales, and to provide instructions that clearly and objectively delineate the different response options.

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Appendix A: Full Listing of Codes Applied to Participants' Responses in Study 2

Codes for Bicyclists

Cue Used Variables

Driver-Related

Vehicle Movement

Vehicle Signaling Systems

Driver-Related Cues

Vehicle Movement

Vehicle Signaling Systems

Driver-Related Cues

Gesture – Driver Initiated

Head Posture/Gaze Direction

Eye Contact

Distracted

Presence of Driver in Vehicle

Verbal Communication

Emotional Projection

Vehicle Movement Cues

Slowing Down

Speeding Up

Approach Rate

Vehicle Came to Complete Stop

Position in Lane

Distance Away

Distance – Behind

Distance – Next To

Distance – In Front

Lane Change

Vehicle Creeping

Direction of Travel/Orientation of Tires

Traffic Volume

Vehicle Noise

Vehicle Door Opening

Vehicle Crossed Over Double Yellow Line

Vehicle Signaling System Cues

Headlamp Flash

Horn

Turn Signal

Backup Lights

Brake Lights

Hazard Lights

Bicyclist Initiated Action Variables

Bicyclist Signaled

Gesture – Bicyclist Initiated

Biking on Sidewalk

Used Crosswalk

Bicyclist Disobeyed Traffic Signal

Misc. Variables

General Uncertainty

License Plate (out of state)

Violation of Expectations/Traffic Laws

Codes for Drivers

Cue Used Variables

Driver-Related

Vehicle Movement

Vehicle Signaling Systems

Driver-Related Cues

Gesture – Driver Initiated

Head Posture/Gaze Direction

Eye Contact

Distracted

Presence of Driver in Vehicle

Emotional Projection

Vehicle Movement Cues

Slowing Down

Speeding Up

Approach Rate

Position in Lane

Distance Away

Tailgating

Swerving/ Drifting in Lane

Vehicle Creeping

Arrival Order (at stop sign)

Position in Lane During Turn

Traffic Volume

Lane Change

Vehicle Signaling System Cues

Headlamp Flash

Horn

Turn Signal

Backup Lights

Brake Lights

Hazard Lights

Headlight Use

Misc. Variables

General Uncertainty

Violation of Expectations/Traffic Laws

Codes for Pedestrians

Cue Used Variables

Driver-Related

Vehicle Movement

Vehicle Signaling Systems

Driver-Related Cues

Gesture – Driver Initiated

Head Posture/Gaze Direction

Eye Contact

Distracted

Presence of Driver in Vehicle

Verbal Communication

Emotional Projection

Vehicle Movement Cues

Slowing Down

Speeding Up

Approach Rate

Direction of Travel/ Orientation of Tires

Vehicle Came to Complete Stop

Position in Lane

Distance Away

Distance from Crosswalk

Lane Change

Vehicle Creeping

Traffic Volume

Vehicle Noise

Vehicle Signaling System Cues

Headlamp Flash

Horn

Turn Signal

Backup Lights

Other Cues Used

Other Pedestrians

Used Crosswalk Signal

Pedestrian Initiated Action Variables

Gesture – Pedestrian Initiated

Improper Cross (jaywalking, cross against signal)

Misc. Variables

General Uncertainty

License Plate (out of state)

Violation of Expectations/Traffic Laws

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National Highway Traffic Safety Administration

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