Modeling Social Situation Awareness in Driving Interactions

Navit Alalouf Klein
navit@campus.technion.ac.il
Technion Israel Institute of Technology
Technion City, Haifa, Israel

Hauke Sandhaus
hgs52@cornell.edu
Cornell University, Cornell Tech
New York, New York, USA

David Goedicke
dg536@cornell.edu
Cornell Tech
New York, New York, USA

Avi Parush
avip@campus.technion.ac.il
Technion Israel Institute of Technology
Technion City, Haifa, Israel

Wendy Ju
wendyju@cornell.edu
Cornell Tech
New York, New York, USA

ABSTRACT

The design of self-driving vehicles requires an understanding of the social interactions between drivers in resolving vague encounters, such as at un-signalized intersections. In this paper, we make the case for *social situation awareness* as a model for understanding everyday driving interaction. Using a dual-participant VR driving simulator, we collected data from driving encounter scenarios to understand how (*N=170*) participant drivers behave with respect to one another. Using a social situation awareness questionnaire we developed, we assessed the participants' social awareness of other driver's direction of approach to the intersection, and also logged signaling, speed and speed change, and heading of the vehicle. Drawing upon the statistically significant relationships in the variables in the study data, we propose a Social Situation Awareness model based on the approach, speed, change of speed, heading and explicit signaling from drivers.

CCS CONCEPTS

• **Human-centered computing → User studies**; **Mixed / augmented reality**;

KEYWORDS

Driving encounters, unsignaled intersections, social situational awareness (SA), virtual reality (VR), autonomous vehicles

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1 INTRODUCTION

Encounters with other drivers in other vehicles are social encounters, and drivers need to be aware of the social aspects to interact and negotiate the situation effectively. Endsley [7] famously defined situational awareness as a combination of three elements: (1) perception of elements in an environment within a specific time and space frame, (2) comprehension of their meaning, and (3) projection of their status in the near future. This is particularly relevant in the traffic context as drivers critically need to adapt to the changing needs and goals within the driving task while seamlessly responding to the other drivers who are executing an identical process. In this paper, we make a case for Social Situation Awareness in driving interactions. Social Situation Awareness is the perception, comprehension, and modeling of the explicit and implicit social behaviors of other actors in driving interactions; this awareness enables drivers to anticipate and coordinate their vehicle's interactions with that of other vehicles.

To understand how people attend to social situations in driving, we ran a (*N=170*) study in a multi-driver virtual reality driving simulator to gather data on interactions between drivers in driving encounter scenarios. After each interaction, participants were administered a VR-embedded questionnaire developed to assess their social situation awareness, particularly the shared perception and comprehension of the drivers. This study was conducted with pairs of participants from two locations, Israel and New York; this multi-site sampling [1] improves replicability and validity of the study by broadening the participant base, rather than assuming that the findings found in one locale can generalize to drivers in all other locations. Running the study in two locations also allows us to test whether there are differences in the study results in both locations. The data of the intersection encounters from this study were then used to understand statistically significant relations between measures to model social situation awareness.

This work is the first of its kind. Its primary contribution is the concept of *social situation awareness*, which specifically addresses the social aspects of situation awareness present in multi-party driving interaction. In our research, social situation awareness is elicited using our multi-driver interaction study protocol, measured using our Social Situation Awareness Questionnaire, and predicted by our Social Situation Awareness model. These novel instruments were developed to better understand social situation awareness, and constitute secondary contributions of this research.

2 RELATED WORK

This project is premised on the importance of understanding the way drivers interact with one another in everyday driving. Effective social communication is crucial for safe and efficient driving, as it helps to prevent collisions, reduces congestion, and promotes smooth traffic flow. Factor et al. [9] argue that some crashes are not the result of individually risky behaviors, but rather the results of "social accidents," caused by interactions between people from different social groups interpreting and responding to situations differently. The social factor of driving is particularly important given the advent of autonomous driving; Oskar Juhlin presciently noted that if autonomous vehicles "are socially incompetent, this could lead to ambiguity and misunderstandings which put serious strains on other road users." [15] In this section, we draw upon prior work to develop the concept of *social situation awareness*, which addresses drivers' needs to attend to and be cognizant of other drivers and road users to interact safely.

2.1 Driving Encounters

Over the years, numerous studies have proposed a wide range of theoretical perspectives on road traffic interactions, including safety perspectives [5], game-theoretic perspectives [20], sociological perspectives [14], and communication and linguistics perspectives [25]. Markkula et al. [17] integrated these perspectives to develop a definition of *driving encounters* for addressing collision avoidance, order of access, coordination, reciprocity, and communication. The author defined *driving interaction* as "a situation in which the behavior of at least two road users can be interpreted as being influenced by the likelihood that they will occupy the same region of space at the same time in the near future."

Until roughly five years ago, human participant studies on research on driving interaction largely focused on "driving style." For example, Sagberg et al. [27]'s detailed review of driving style includes metrics that can be grouped into the following common categories: longitudinal control (measured by speed, acceleration, jerk, headway distance and time), lateral control (lane choice, steering angle, lateral position and acceleration), gap acceptance (time between vehicles at a crossing, passing gap when overtaking), visual behavior (the area of fixation, direction of looking, fixation length and frequency, and mirror checking), errors and violations (use of indicator, number of infractions, and other unusual maneuvers, near accidents, inappropriate honking, gestures made to other users, and driving posture).

2.2 Driving Interactions as Social Situations

Framing driving encounters as social encounters between two drivers helps to account for the necessity of explicit and implicit communication between drivers, as well as social norms such as the right-of-way.

Markkula et al. [17] definition of driving encounters focuses on driving communication and negotiation. The authors note all driving behavior has one of the following basic three effects: 1) achieving own movement or perception, 2) signaling to others about own movement or perception, and 3) requesting movement or perception from other road users. They highlight that implicit road communication occurs when pragmatic road actions are perceived by other road users to be signaling intent or requesting response.

What is still missing from Markkula et al. [17]'s model is the perception, awareness and planning, which undergird the encounters Markkula et al. [17] highlights. To address this gap, we look to situation awareness as a framework with which to understand the degree which drivers are aware of the social aspects of driving encounters.

2.3 Social Situation Awareness

We define *social situation awareness* in driving interaction to be an inherent part of a driver's general situation awareness [7]. This definition draws in understandings of social awareness from social psychology; social awareness takes various forms but primarily involves self-awareness and the awareness of the other [29]. In driving encounters, social awareness is required for effective social encounters because it helps drivers coordinate their actions safely.

We posit that social situation awareness involves the perception of other drivers, comprehension of the social situation, and projection and response to the social dynamics of the on-road interaction. In the elemental case of two-driver interaction, each driver has a degree of awareness of key aspects of the other driver and the driving encounter scenario they find themselves in, and also an awareness of how their *own* actions are perceived and influence the other driver. This framing differs significantly from cognitive models of situation awareness, for example, from Baumann and Krems [2], Gugerty [11], or Matthews et al. [18]; those models do not capture the perception, planning and operation that Markkula et al. [17] note are required to interact with other drivers on the road.

We believe that a social situation awareness model also improves upon communication models, such as Markkula et al. [17]'s, which focus on what people notice about the social context, but do not explicitly address the recognition and projection highlighted in situation awareness modeling. Parush et al. [24] have made similar models of communication and team situation awareness in medical teams and have examined how differences in these models affect team performance [23]: social situation awareness can model what participants are perceiving, comprehending, and projecting about the actions of other actors, and thereby helps explain how actors decide to communicate or elicit a response from the other parties.

2.4 Driving Interaction Studies

Driving interaction studies, wherein multiple drivers can respond dynamically to one another's presence and behavior, are rare. This is due in part to the relative scarcity of multi-driver simulation platforms for research.

Multi-participant interaction studies have primarily taken place at large centers for driving research; they involve large, dedicated physical driving simulation rigs for the participants. Multi-driving interaction was first performed in simulation by Hancock and De Ridder in 2003 [12]; they placed two participants into adjacent full-vehicle simulators that share a single virtual world to understand collision avoidance behaviors. In 2011, Muhlbacher et al. developed a platform to study interactions between four drivers in a platooning scenario [19]. Researchers at the Institute for Transportation Studies at the German Aerospace Center (DLR) created a Modular and Scalable Application Platform for ITS Components (MoSAIC) to understand interactions between V2V connected vehicles and non-equipped vehicles [22], cooperative lane change maneuvers [13], and traffic-light assistance [26]. In the US, a recent collaboration between University of Wisconsin-Madison and University of Iowa researchers tested the feasibility of conducting driver-pedestrian simulator experiments with multiple people. [16]

Virtual reality may offer a way to make multi-participant simulation studies more common, as VR headsets are relatively inexpensive, and 3D gaming environments such as Unity and Unreal Engine are widely available to develop. Recent research by Bazilinskyy et al. [3] has used coupled VR headset simulation built on game engines to demonstrate the capability to run pedestrian-driver interaction studies. Similarly, researchers at the University of Leeds and the Lincoln Center for Autonomous Systems in the UK used VR and participant tracking to have two people with VR headsets walk freely across a space play to a game of "Sequential Chicken" with their vehicle avatars in a driving simulation environment [4]. Goedicke et al. [10]'s Strangeland driving simulator uses Unity to look at how pairs of drivers interact with one another in on-road driving situations.

What is missing to date from this ongoing multi-person interaction research is a thorough investigation of the mechanisms of influence between road users. In research discussed in the section above, the measures of interaction have included visual attention (*Where does the participant look?*), participant behavior (*Does the driver wait or go?*), participant performance *(Do the vehicles collide? Does the driver react quickly? Does the driver handle the vehicle well?*), and participant subjective assessments (*Does the participant feel the vehicle drove well? Communicated well?*). We believe that the proposed social situation awareness model can help to pull these disparate measures together into a more coherent whole.

3 STUDY

The primary purpose of our study is to better understand drivers' behavior during encounters, specifically the social dynamics expressed through explicit and implicit communication used by participants and its relations with their behavior. The study is intended to elicit how pairs of drivers behave in situations where the right-of-way is unclear. For example, in an unsignalized four-way intersection, if two cars approach the intersection from opposite directions, the right-of-way is not completely defined and is dependent on the driver's ability to follow the legal driving rules, which is that the first vehicle to arrive at the intersection can cross or the driver on the right side has the legal right-of-way.

3.1 Method

The driving encounter scenarios are the independent variable of this study; the dependent variables are participants' implicit and explicit communications, driving behaviors, and their situation awareness. The study uses a repeated measures design, with both participants driving in each scenario.

3.1.1 Participants. The study included a total of 170 participants, 85 dyads: 42 in Israel and 43 in New York. Due to motion sickness during a study, 9 dyads were stopped in the middle and were excluded from the data analysis (5 from Israel and 4 from New York). The majority of participants were between the ages of 18 and 34 (85%), and the proportion of females to males was nearly equal (46% and 54%, respectively). 97% of the participants had driver's licenses, 28% for less than 5 years, and 45% for between 5-10 years. 33% of the driving participants reported driving 1-2 days a week on average, and 23% reported 3-4 days a week. 80% had not driven in other countries around the world. In addition, most of the participants reported a lack of experience in VR games (18% never played and 38% are novices). Most participants did not report any known issues of motion sickness during VR games (42%). Since the study was conducted in pairs, the participants were asked about their acquaintance with the other study participant; 47% of them reported not knowing each other.

3.2 Apparatus

We used Goedicke et al. [10]'s open-source Strangeland driving simulator, which enables multi-participant driving interaction in seven different driving encounters. This simulator records vehicle motion, such as wheel and steering wheel motion, indicator lights, driver position, and hand gestures for both participants' virtual cars. Additional tools were added to support the recording and post-facto replay of the entire study.

The simulator was physically situated in a laboratory, and participants sat next to one another (see Figure 1); they were not explicitly told that they were in the same virtual world. Each driver observed partial representations (captured by the VR headset's hand and head tracking) of themselves in the VR world, including a reflection of their avatar face in the mirror and their hands on the steering wheel. Each could also see the other driver's avatar in the other vehicle when they encountered one another in the virtual scenarios.

3.3 Study design

Seven intersection traffic scenarios involving unclear right-of-way were developed for the study. We used crash scenario ranking statistics (crash frequency, economic cost, and functional years lost)[6, 21] around multi-vehicle incidents to generate our encounter scenarios. These encounter scenarios were designed to require participants to communicate and negotiate with one another with their virtual cars to complete their driving tasks, that is cross the intersection safely and successfully.

The seven intersection scenarios were divided into two groups based on the direction of approach to the intersection: side approach (can lead to sequential conflict) and opposite direction approach (can lead to partial head-on conflict) (see Appendix A) The participants were able to drive freely within the simulator; to coordinate the interaction of the participants, the intersection scenarios were controlled by traffic control, such as traffic lights located a block before the intersection for each participant, which turned green at the same time [28]. While we considered other viable methods to increase the likelihood of encounters, such as dynamic modified speed adjustment [12][28], and dynamic route length change, these were not ultimately used in our study.

Figure 1: (a) Physical layout of the laboratory in Israel. (b) Driver perspective of SSA questions in the VR world at the end of a scenario. Also see supplementary video.

3.3.1 Dependent Variables.

Social Situation Awareness questionnaire. Endsley [8]'s Situation Awareness (SA) model was adapted to assess and compose objective Social Situation Awareness measures. We formulated a set of SA questions that focused on the environment, the other driver, and themselves, to assess self-perception and the perception of the other relative to the self. Specifically, we focused on the shared perception and understanding through explicit communication, such as signaling, and through implicit communication in various driving cues, such as speed and direction of driving. The resulting SSA models specifically show the inter-connected flow of perceptions and understanding of self and the other, related to the right-of-way social norm, all culminating in the outcome of crossing the intersection. These questions were embedded as part of the VR simulation.

Baumann and Krems [2] noted that the "construction of SA is a comprehension process that yields a mental representation of the meaning of different elements of a traffic situation." This helped us to devise social situation awareness questions around identifying those basic elements that can influence a driver's situation awareness—objective driving scenario facts that a participant can perceive about themselves and the other driver. These elements were referred to as situational elements. For each vehicle, the situational elements are {*location, right-of-way, speed, signaling, and car's heading*}. The Right-of-Way is the fundamental element that sets the social norm for the driving interaction. Signaling represents explicit communication, and location, speed, and heading represent implicit social cues as to the behaviors and intentions of the driver. Each element requires shared social situation awareness to be perceived by each of the drivers in the interaction, who will then determine their next action based on their comprehension and projection of that element. Based on this logic, we have developed three questions for each situational element and its associated action. For a detailed explanation of how we developed the questions, see Appendix B.

Driving Behavior. Using time-stamped data and vehicle position, we analyzed where each participant's vehicle was at each time point in the scenario. During each scenario, key measures were recorded from the virtual driving simulator. The simulator system recorded hand, head, steering wheel, and driving paddle movements. Steering direction, position, speed, movement duration, and response time were derived from the event logs of the simulation environment. These, in turn, were used to define the possibility of encounter, right-of-way, approaching speed, approaching speed change, signaling, heading, and first to enter the intersection. These parameters were used to establish the "ground truth" for scoring the responses to the situation awareness questions.

3.4 Procedure

After a basic VR orientation, the participants entered the VR world and drove for approximately 40 minutes in 12 different driving scenarios. The driving instructions were displayed on the vehicle's dashboard (see Figure 1 Second row on the left), and each participant drove the vehicle as instructed using the steering wheel and pedal. Drivers drove across a curvy road section to familiarize themselves with how the vehicle maneuvers in the VR world. They stopped at a red traffic light and drove into the intersection simultaneously.

After they negotiated right-of-way and passed the intersection, they came to a complete stop at a "do not enter" sign. Here, they answered the situation awareness questionnaire. The questions were presented in the virtual world as shown in Figure 1 in the second row on the right. A screenshot of the scenario's scenery was displayed above the question to contextualize the question for each participant. To avoid influencing the perception and memory of the participants, this image was created exclusively from their perspective, using only scenery and no vehicles. The questionnaire has some conditional elements; participants who did not see the other vehicle, for example, were not asked more detailed questions about that vehicle. At most nineteen questions were presented to the participants in each scenario, covering the three levels of SA for the list of situation awareness questions). The order of scenarios were randomized for each pair of participants using a Latin Square design. After answering all questions, both participants were advanced to the next scenario.

At the conclusion of the study, after the removal of the VR headsets, participants were asked to complete a demographic questionnaire that included questions about their driving experience.

3.5 Data analysis

For the analysis reported in this paper, we focused on analyzing the intersection driving encounter scenarios for the study; this analysis does not include the five non-intersection driving encounter scenarios.

3.5.1 Inclusion criteria. Since the objective of this study is to gain a better understanding of driver behavior during encounters, we included the *potential for an encounter* as a criterion for inclusion. The criteria consist of two rules: first, all seven intersections must have been completed to the end, and second, based on the objective ground truth, there must have been a possibility for encounter, so both participants must have been in any combination of areas #3 and #4 at the same time (both in area #3, one in area #3 and the other in area #4, and vice versa). Based on these criteria, 21 dyads were excluded from the analysis of the data. There were 55 dyads included in the data analysis, 26 from Israel and 29 from New York.

3.5.2 Social Situation Awareness Scoring and Analysis. To determine the correctness of the responses, the objective calculated ground truth was matched with each social situation awareness question. This allowed us to examine and score each response to determine the correctness of each participant's social situation awareness in each scenario.

Since the key measure for social situation awareness is the percentage of correct responses to the Social Situation Awareness questions, the statistical analysis we implemented is based on non-parametric statistics. Specifically, we utilized the Chi-Square test of independence, a statistical hypothesis test used to determine if a significant association exists between two categorical variables within a given sample.

4 RESULTS

The analysis of the driving simulation data focused on the driving behaviors of the participants and their social situation awareness. We calculated several alternative models of social situation awareness, which we detail here.

4.1 Social Situation Awareness Agreement

Social Situation Awareness Agreement metrics determine the degree to which a driver's perceptions and understandings match or differ from those of the other driver. Specifically, in social situation awareness agreement we addressed two questions: 1) Is there a difference between awareness to one's own actions and awareness to the other's actions? and 2) To what extent do the two drivers have similarly correct awareness? Addressing these questions is based on answers to these six situational elements in the social situation awareness questionnaire: right-of-way, speed, speed change, vehicle heading, signaling, and who entered the intersection first.

- *Overall Agreement.* 90% of the participants agree and are correct about the other driver's speed change. On the other end, only 22% of participants correctly agreed about who had the right of way.
- *Right of way (ROW).* A chi-squared test of independence was conducted to examine the relationship between the two participants' estimates of their and the other driver's right of way.
- *Speed.* There was a high social situation awareness agreement to speed, with most participants correctly responding that the speed of both themselves and the other was 'normal' (Z-score based), with no significant differences in the proportion of correct awareness to one's own vs. the other driver's speed.
- *Speed change.* There was a high social situation awareness agreement to speed change, with both participants correctly responding they were slowing down, $x^2 1,\ N = 904{=}112.5$, $p{<}.001$. No significant differences existed in the proportion of correct awareness to one's own vs. the other driver's speed change. In examining each of the countries separately (Israel & New York), the agreement of slowing down was statistically significant, $x^2\ (1,\ N = 390) = 48.248,\ p < .001$ only in New York.
- *Vehicle heading.* There was more variance in the social situation awareness agreement of vehicle heading, with both correctly perceiving each other, particularly when the other driver continued straight while they themselves turned left, $x^2\ (4,\ N = 348) = 45.09,\ p < .001$.Both participants had a significant agreement when they were both pointing straight, $x^2\ (4,\ N = 500) = 500,\ p < .001$.
- *Signaling.* There was a high social situation awareness agreement to signaling, particularly when both drivers signaled, $x^2\ (1,\ N = 636) = 31.51,\ p < .001$.
- *First to enter the intersection.* There was a significant social situation awareness agreement to who entered first the intersection, $x^2\ (1,\ N = 444) = 217.997,\ p < .001$, with the highest agreement that the driver that continued straight entered the intersection first (in 4 scenarios).

4.2 Social Situation Awareness Models

A model for the social situation awareness during the driving encounter represents the inter-connected sequence of the perceptions and understandings of the self and the other in the situation. The driving encounter is dynamic, the drivers continuously perceive and understand the social situation, respond and act accordingly, and the encounter unfolds towards its resolution of both drivers crossing the intersection safely and successfully. Thus, the fundamental premise in understanding the social situation awareness in the driving encounter is that the perception of the self and the other evolves as well. We constructed several "prototype" models to represent the evolution of the social situation awareness during the encounter. Specifically, we focused on the correct agreement in the perceptions and understandings of the other driver and examined associations within sequences of correct responses to questions addressing the key situational elements: approach direction, speed and speed change, heading, signaling, and the right-of-way. To visualize the sequential and inter-connected nature of the social situation awareness evolution, the "prototype" models are presented as Sankey diagrams. Each node in the diagram represents a given question about the other driver and its proportion of correct responses, and the links between the nodes represent the frequency of correct responses to both answers.

4.2.1 Approach Model. The first model represents the relationship between a driver's perception of the other driver's direction of

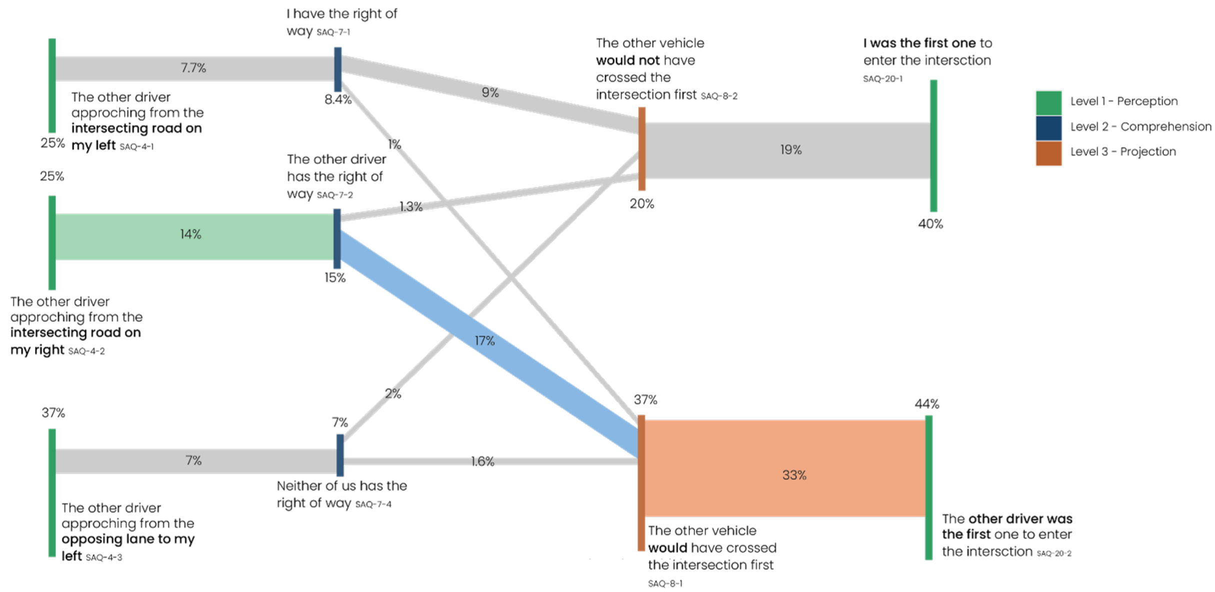

Figure 2: Model of approaching and perceiving the other driver when approaching from the side

approach to the intersection, their evaluation of the right-of-way, and their projection of the other driver's next action – whether they will cross first or stop before the intersection.

The model is based on four distinct situation awareness questions. Using the chi-squared test of independence, we analyzed the relationship between each pair of questions comprising the following model:

- *Direction of approach.* The relation between one's perception of the other driver's direction of approach with evaluating the *right-of-way* was statistically significant, $x^2 4, N =$ 396=536, p<.001.
- *Right-of-way.* The relation between one's evaluation of the right-of-way and projection of what could have happened next based on the location of the other driver and the right-of-way was statistically significant, $x^2\ (2,\ N = 258) = 82.8,\ p < .001$
- *First to enter.* The relation between projection of what could have happened next based on the location of the other driver, the right of way and the perception of who entered the intersection first was statistically significant, $x^2\ (1,\ N = 702) = 346.69,\ p < .001$

Whereas 87% (25%+25%+23%) of the participants correctly perceived the direction of the other driver's approach to the intersection, there were other differences expressed in two distinct social situation awareness models shown in Figure 2.

In scenarios in which participants approached the intersection from the side of the other driver, the most common correct set of answers corresponded with the other driver approaching from the right, the other driver having right-of-way, the other driver projected to cross the intersection first, and the other driver being first to enter the intersection (see Figure 2). One thing the model shows is that people are likely to correctly perceive when other drivers are approaching in the oncoming lane (37%) as opposed to the cross-traffic (25% for from the left or 25% from the right).

The model also shows participants were not very sensitive to right-of-way; only 8.4% correctly noted when they had the right-of-way, 15% corrected noted when the other driver had the right-of-way, and 7% correctly noted when neither driver had the right-of-way. In contrast, 20% of participants correctly projected that the other vehicle would not have crossed into the intersection first, 37% correctly noted that the other vehicle would have crossed into the intersection first, and an even larger percentage (40% and 44%) correctly perceived when they or the other driver was first to enter the intersection. In scenarios where participants approached from the opposite direction (see Figure 2 on the left), 37% correctly perceived the driver's approach, while only 7% understood that neither driver has the right-of-way in this scenario.

4.2.2 *Speed and Speed Change Models.*

The second social situation awareness model represents the relationship between the other driver's speed as they approach the intersection, the comprehension of the speed change over time, and assessing the collision risk and projecting who will enter the intersection first based on that information (see Figure 3).

Only a few participants (39%) correctly perceived the other driver's speed approaching the intersection was 'Normal'. Of these, 72% correctly noticed the other driver's subsequent speed, 22% correctly noted the other driver was accelerating, and 26% correctly noted that the other driver was slowing down. 27% of the participants correctly predicted that the driver would slow down and move into the intersection; a larger percentage correctly predicted that the other driver would come to a complete stop.

Interestingly, when people correctly noted that they were the first to enter the intersection (40%), they were mostly likely to correctly predict that the other driver would come to a complete stop (21%).

4.2.3 Heading Model. The third model represents the relationship between the levels of situation awareness based on the situational element of the other driver's heading direction (perception, comprehension & projection) with the perception of who entered the intersection first. (See Figure 4 (a)).

As the participants' driving directions differ in each scenario, the model begins with three distinct starting points for each possible answer. Drivers were perceived to be pointing straight 22% of the time, left 11% of the time, and right 7% of the time. The comprehension and projection of the heading direction from each point are the same as the perception. The relationship between the perception and comprehension of the heading and the projection to which direction the other driver will take was statistically significant, x^2 $(4,\ N = 542) = 542,\ p < .001$ with high frequency to heading straight.

4.2.4 Signaling Model. The fourth model attempts to represent the relationship between signaling and the projection to which direction the other driver was about to go, concluding with the perception of who entered the intersection first. (See Figure 4 (b)). The relationship between the frequency of perception the other driver's signaling and the projection that they were about to turn left was statistically significant, x^2 $(2,\ N = 452) = 195.97, p < .001$.

The signaling situation awareness model illustrates the various situation awareness flows based on the perception of the other driver's signaling. 46% correctly perceived the other driver signaling, and 12% correctly perceived the other driver not signaling. Participants who did not see the other driver signaling predicted that the other driver would go straight. When participants perceived the other driver signaling, 8% predicted the other driver would turn right, while 16% predicted the other driver would turn left.

5 DISCUSSION

5.1 Mutual and Social Situation Awareness between Drivers

Given the definition of an encounter between drivers, that both intended to occupy the same un-signalized intersection at the same time and within a short time, the effective and safe resolution of such encounter required communication, negotiation, and mutually acceptable resolution. Taken together, the findings suggest that the social situation awareness, composed of the agreed-upon perception and understanding of various situational elements in the interaction, emerges and unfolds as a synthesis of the communication between the drivers, explicit and implicit.

5.2 Social Situation Awareness Models of the Encounters

We formulated several models providing different perspectives of the encounters based on the social situation awareness of the main situational elements. These models aggregate the responses of both participants, thus capturing the social situation awareness agreement between the drivers. These models provide implications and insights as to the communications and negotiations that might have taken place.

We distinguish between awareness due to explicit communication, primarily the signaling act, and awareness due to implicit cues, consisting of spatial aspects of the approach to the intersection (direction), pointing/heading of the vehicles, understanding the right-of-way in the given intersection, and speed and speed change during the approach. All models follow a similar generic structure: the perception and understanding of the elements, the formulation of an anticipation or expectation as to the acts and behaviors of the other driver, leading to a decision and action (primarily entering the intersection). Another important commonality across the models is the direct or indirect awareness of spatial factors in the encounter, as outlined next.

Approaching model. The approaching model reflects the initial awareness that there would be an encounter. The model suggests that drivers not only perceived the other driver approaching the intersection but were also aware of the direction they came from. Together with understanding the right-of-way in the intersection, they could formulate an expectation as to whether the other driver will enter the intersection first. This supported drivers in framing the initial nature of the encounter, and the expectation significantly matched the correctly perceived end outcome of who entered the intersection first. Moreover, this mutual agreement in perception and understanding of the approach to the intersection may have helped drivers to perceive and understand other important aspects of the encounter.

Signaling and Heading models. A critical part of formulating the expectations was perceiving and understanding how drivers would enter the intersection, continuing straight or turning either right or left. This was communicated explicitly via signaling and implicitly via the pointing and heading of the vehicles. This brings us to the signaling and heading situation awareness models. The explicit communication of signaling was particularly effective when they conveyed intentions to turn right or left. A lack of signaling conveyed continuing straight, however, there were many cases where participants signaled even though they both intended and in fact continued straight. This may have rendered the explicit communication of signaling less effective. We can speculate that some of the signaling while continuing straight was potentially due to some imitation behaviors, which are often observed in drivers' actions. In this study, they are associated with one of the drivers signaling to turn, whereas the other driver continues straight. The awareness and expectation of a possible turn of the other driver or continuing straight was complemented by the implicit cue reflected in the heading situation awareness model. There seems to have been better awareness when the heading cue implicitly suggested continuing straight. There was less awareness and understanding of other headings that were associated with turning.

Overall, when considering the awareness and expectations of the directional aspects of the other vehicle's travel, as reflected by the situation awareness models, it seems that both the explicit communication of signaling and the implicit cues of heading were not particularly effective (as is found in the weaker associations and lower frequencies of correct responses). This may be due to the spatial skills and understanding required of the drivers. Specifically,

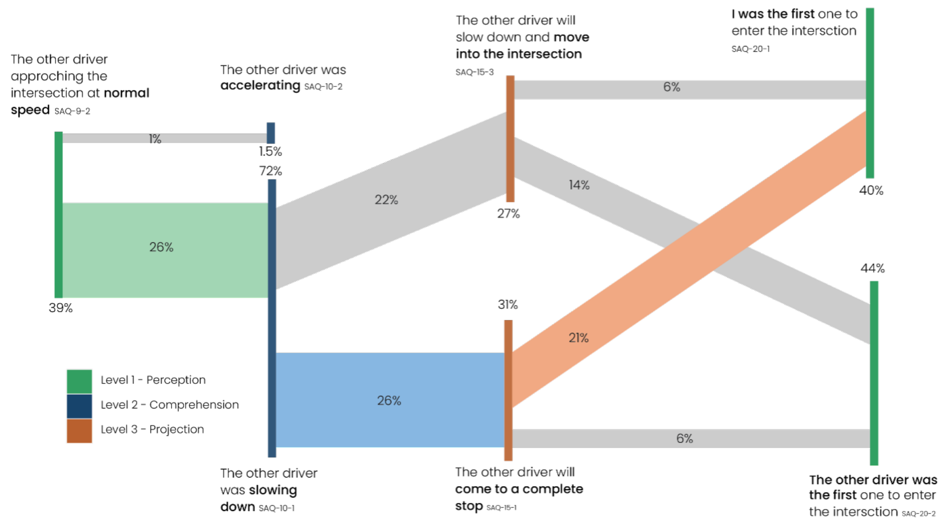

Figure 3: Model of encounter based on the other driver's speed

perceiving and understanding the movement direction of another object and reporting its direction requires using a different spatial frame of reference, allocentric rather than egocentric. This may have been more challenging to participants in the short and few VR driving scenarios they participated in.

Change of speed model. The strongest implicit cue was the change of speed of the other driver as they approached the intersection, as reflected by the speed change social situation awareness model. Participants were aware of the other driver's slowing down behavior, which led to formulating the expectation regarding the entry to the intersection. The finding that the change of speed was a rather strong implicit cue for formulating expectations can be explained by the manner with which humans perceive speed and speed change. Such perception is also associated with spatial understanding, particularly depth, distance, and size perception of other moving objects (the other vehicle in our case). This perception does not require a change in the spatial frame of reference, and an egocentric FOR can be utilized, which makes the task easier. In addition, the perceived distance and size are better in shorter distances, such as those in the intersection encounter, and thus make the speed change judgment easier. All these aspects can point to speed change being a strong implicit cue.

Implications to communications and AV design. In the social encounters between drivers in un-signaled intersections that were examined in this study, the findings show that explicit communication and implicit communicative cues played a role in the situation awareness that can be associated with driving behaviors. The findings particularly highlight the role and significance of implicit communication in negotiating and resolving vague encounters. With a possible lack of clarity or lack of explicit communication, drivers tend to look for and be aware of implicit cues embodied in the behavior of the other vehicle.

In the design of AVs, especially in the design of interactions between AVs and other human-driven vehicles or other road users, particular attention should be directed to the design of implicit communications. Thus, in addition to all the work done on explicit communication with human-vehicle interfaces, implicit cues such as the heading of the vehicle or its speed should be designed into the system to augment the explicit communication modes.

5.3 Limitations

One fundamental limitation of this study is that the model is built on driving simulator study data; this allowed us to control the scenarios carefully but not to capture the complexity and variability of real-world driving scenarios fully. Additionally, we focused on a limited set of driving scenarios. We did not consider other factors influencing drivers' social situation awareness, such as weather conditions or time of day. Another limitation is the participant study population–we considered ourselves to be increasing generalizability through stimulus sampling by running our study across two sites. Still, future studies would need to be run in other places to capture what we know are regional differences in driving interaction. The social situation awareness instrument we developed may not fully capture all aspects of social situation awareness in driving interactions and suggests that further research is needed to develop more comprehensive measures of this construct. Order and learning effects may have impacted the driving behavior as people drove in the same environment over multiple scenarios. We also cannot rule out that other small non-symmetric features of the environment and driving simulator may have influenced driving behavior; examples of this are the different directions of the sun depending on where the drivers were spawned and the uncommon positioning of the right blinker.

6 CONCLUSION

The contribution of this research is the development of *social situation awareness* as a key concept toward understanding everyday driving interaction. As part of this contribution, we (a) developed

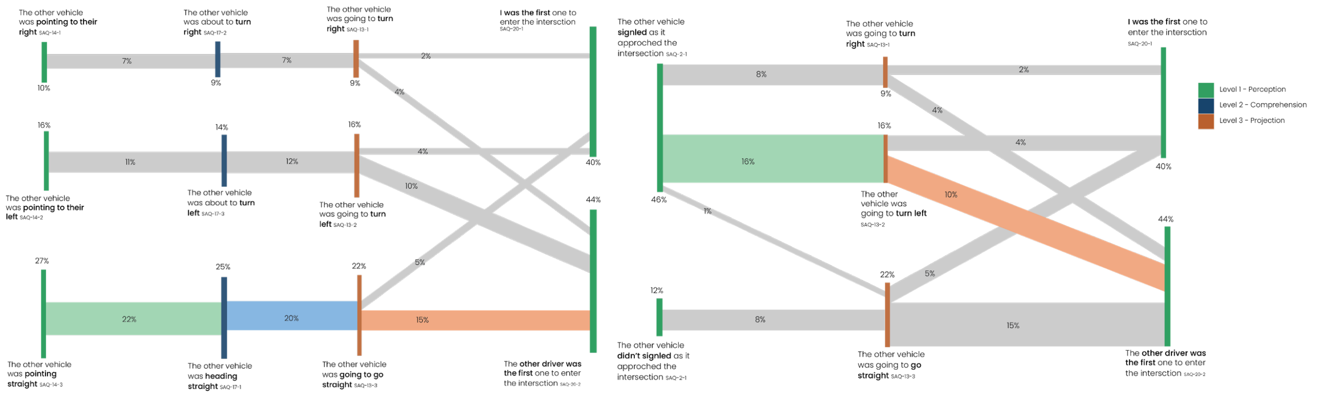

Figure 4: Models of encounter based on situational elements: (a) other driver's heading direction, and (b) other driver's signaling

a social situation awareness questionnaire to understand what aspects of their and other people's driving behavior participants were aware of, (b) ran a multi-driver virtual reality driving simulation at two sites. We then (c) scored the questionnaire results with empirical "ground truth" driving behavior from the simulator. From the statistically significant relations in these study results, we (d) constructed a theoretical model for social situation awareness.

This model suggests that key aspects of social situation awareness lie in the *approach*, where drivers have an awareness of their and the other driver's respective direction of approach, right of way, and order of entry into the intersection; in the awareness of the *speed* and *change of speed* in the intersection; in the *heading* of the vehicles; and the *explicit signaling* from the drivers. Of these, the perception of the *change of speed* seemed to have the highest mutual awareness from both drivers. This model proposes key aspects of driving interaction that can be tested in future research; this will help us understand how drivers implicitly and explicitly communicate and help us avoid social accidents with one another and with autonomous vehicles.

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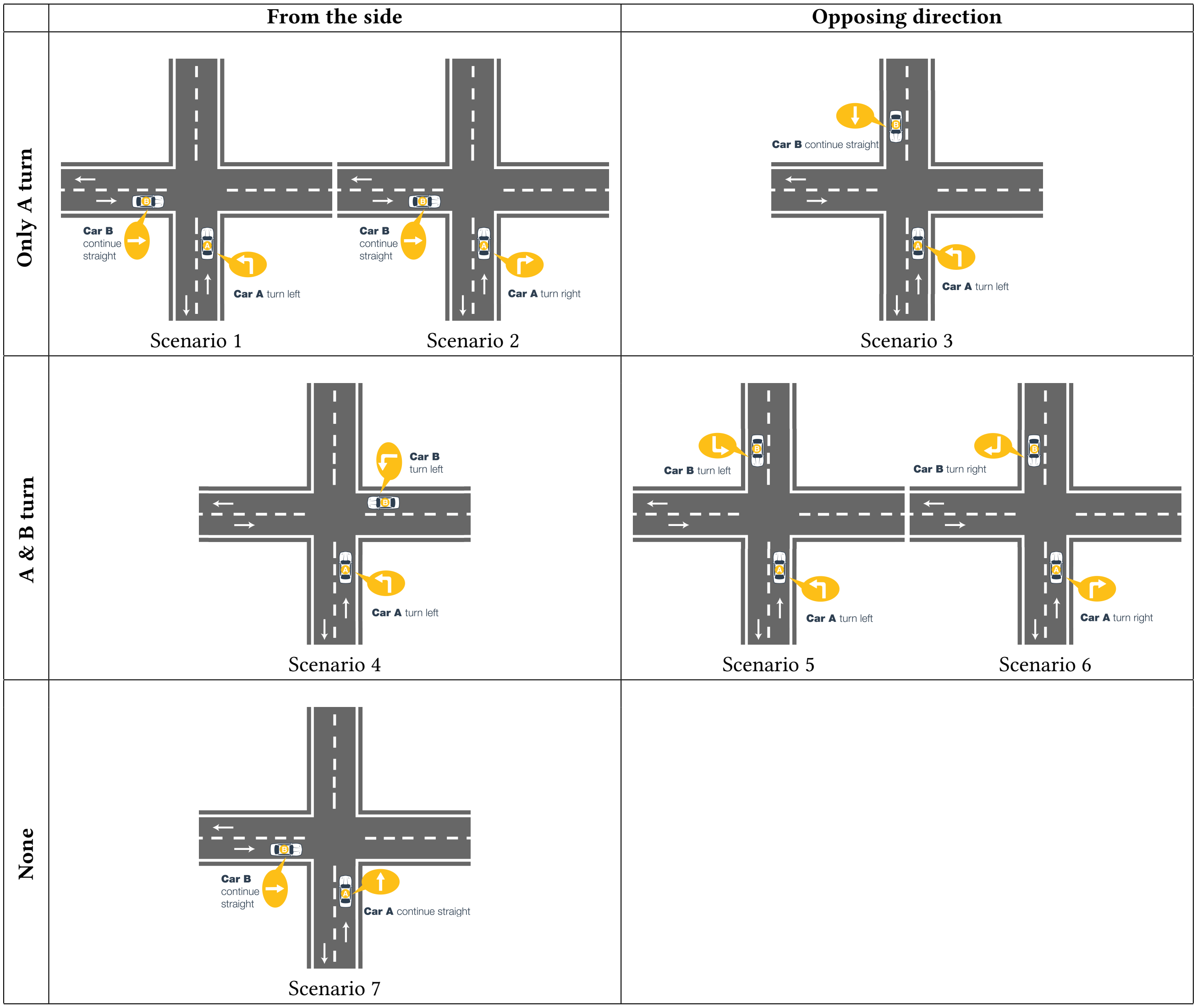
A INTERSECTION SCENARIOS

Our study features 7 interaction scenarios; the drivers in each car are given directions in the in-vehicle GPS about where they should go. In scenarios 1 and 2, the two drivers approach the intersection from the side, as cross-traffic; in S1, car A turns left and in S2, car A turns right. In scenario 3, the cars approach from opposing directions; car A is to turn left, while car B is continues straight. In scenario 4, both vehicles turn left, but from the side. In scenario 5, both vehicles turn left, but from opposing directions. In S6, both cars turn right from opposing directions. Finally, in S7, both vehicles continue straight but from the side.



B SOCIAL SITUATION AWARENESS QUESTIONNAIRE

To develop the Social Situation Awareness Questionnaire, we used Endsley's model of situation awareness as a guide to develop questions about the three levels of social situation awareness required to complete the task at hand, crossing an intersection while following the traffic rules. We followed a systematic methodology that involved identifying the critical situational elements required for participants' social situational assessment, creating a hypothetical sequence of events that could lead to the completion of the task or a near-accident, and developing questions based on the situational elements identified for each level of social situation awareness.

We first identified the situational elements required for each level of social situation awareness based on Endsley's model. For level 1 (perception), the social situational elements were the location, speed, and heading of the other driver. For level 2 (comprehension), the social situational elements were the location of the other driver relative to the participant's location, the changing speed of the other driver, and the heading direction of the other driver. For level 3 (projection), the social situational elements were the projected tactics and maneuvers of the other driver that could inform the participant's decision-making. Next, we created a hypothetical sequence of events that involved the interaction between the two participants and the situational elements identified. This hypothetical scenario allowed us to identify any critical elements that were missing and to determine the appropriate questions for each situational element at each level of social situation awareness.

B.1 Final list of SSA-Questions

Table 1: Final list of SSA-Questions

ID	Question	Answer choices	Awareness to / SSA elements/ Ground truth/ SSA level
1	While approaching the intersection, how fast were you driving?	· High speed · Normal speed · Slow speed · I'm not sure	Awareness to: Myself SSA elements: Speed Ground truth: Speed SSA level: Perception
2	Did the other vehicle signal as it approached the intersection?	· Yes · No · I'm not sure	Awareness to: Myself SSA elements: Speed Ground truth: Speed SSA level: Perception
3	As you entered the intersection, what was the location of the other vehicle?	· I didn't notice / can't remember · In the middle of the intersection · Before the intersection · After the intersection · I didn't have a chance to get into the intersection	Awareness to: Other driver SSA elements: Location Ground truth: Zone of the other driver SSA level: Perception
4	What direction was the other vehicle coming from?	· From the intersecting road on my left · From the intersecting road on my right · From the opposing lane to my left · I'm not sure	Awareness to: Other driver SSA elements: Location Ground truth: Location SSA level: Perception
5	At the intersection, how did you interpret the other vehicle's location?	· It was approaching the intersection · I am not sure it was approaching the intersection · I didn't see it	Awareness to: Other driver SSA elements: Location Ground truth: N/A SSA level: Comprehension
6	At the intersection who had the right of way?	· Me · The other vehicle · Both of us · Neither of us · I'm not sure	Awareness to: Both SSA elements: Location Ground truth: Right-of-way SSA level: Comprehension
7	Given the location of the other vehicle and the right-of-way, what did you think could have happened next?	· The other vehicle would have crossed the intersection first · The other vehicle would not have crossed the intersection first · Both of us would enter the intersection at the same time · I'm not sure	Awareness to: Both SSA elements: Location Ground truth: First to enter intersection SSA level: Projection
8	While the other vehicle was approaching the intersection what was their speed?	· High speed · Normal speed · Slow speed · I'm not sure	Awareness to: Other driver SSA elements: Speed Ground truth: Speed SSA level: Perception
9	As you approached the intersection, how did you interpret the other vehicle's speed change?	· It was slowing down · It was accelerating · It didn't change its speed · I'm not sure	Awareness to: Other driver SSA elements: Speed Ground truth: Speed change SSA level: Comprehension
10	As you approached the intersection, how was your speed changing?	· I was slowing down · I was accelerating · I didn't changed my speed · I'm not sure	Awareness to: Myself SSA elements: Speed Ground truth: Speed change SSA level: Comprehension
11	While the other vehicle was approaching the intersection, I could tell that:	· I was slowing down · I was accelerating · I didn't changed my speed · I'm not sure	Awareness to: Other driver SSA elements: Heading Ground truth: Car rotation SSA level: Projection

Table 1: Final list of SSA-Questions

ID	Question	Answer choices	Awareness to / SSA elements/ Ground truth/ SSA level
12	While going into the intersection, which direction was the other vehicle pointing?	· To their right · To their left · Straight · I‘m not sure	Awareness to: Other driver SSA elements: Heading Ground truth: Car rotation SSA level: Perception
13	Based on the other vehicle's speed while approaching the intersection, what did you expect the other driver to do?	· Come to a complete stop · Continue at the same pace and enter the intersection · Slow down and move into the intersection · I'm not sure	Awareness to: Other driver SSA elements: Speed Ground truth: Speed SSA level: Projection
14	As you approached the intersection, did you feel there was a risk of a collision?	· Yes · No · I'm not sure	Awareness to: Other driver SSA elements: Heading Ground truth: N/A SSA level: Projection
15	Before crossing the intersection, which direction did you think the other vehicle was pointing (In its perspective)?	· Heading straight · Turning to its right · Turning to its left · I'm not sure	Awareness to: Other driver SSA elements: Signaling Ground truth: Car rotation SSA level: Comprehension
16	As you approached the intersection, did you signal?	· Yes · No · I‘m not sure	Awareness to: Myself SSA elements: Signaling Ground truth: Signaling SSA level: Perception
17	As you approached the intersection, what direction was your car pointing?	· To my right · To my left · Straight · I‘m not sure	Awareness to: Myself SSA elements: Heading Ground truth: Car rotation SSA level: Perception
18	Who was the first one to enter the intersection?	· I was · The other vehicle · Both of us · I‘m not sure	Awareness to: Other driver SSA elements: Heading Ground truth: First to enter intersection SSA level: Perception
19	As you approached the intersection, did you notice another vehicle?	· Yes · No · I‘m not sure	Awareness to: Other driver SSA elements: Environment Ground truth: Encounter SSA level: Perception