MODELING SOCIAL SITUATION AWARENESS IN DRIVING INTERACTIONS

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ABSTRACT

The design of self-driving vehicles requires 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 assess the participants' awareness of other driver's direction of approach to the intersection, signaling, speed and speed change, and heading of the vehicle were measured. Drawing upon the statistically significant relations observed in our data, we propose a collection of Social Situation Awareness models. Those models integrate various elements such as approach direction, speed, change of speed, heading, and explicit signaling from drivers.

Keywords: Situational Awareness, Driving Simulation, Driver Interactions

INTRODUCTION

The public acceptance of self-driving vehicles is contingent on their safety and effectiveness on the road. Unless such vehicles are given their own roads or own lanes, they must manage the routine driving task of coordinating movement with other drivers and pedestrians, just as every driver does. Therefore autonomous vehicle (AV) designers must understand at a fine-grained level of detail what it is that drivers are doing when they interact with one another at every stop sign, down every road. What do drivers do when they see another vehicle? When do they decide to go? When do they slow or yield? When and how do they coordinate what they will do? Only with a firm grasp on these interaction fundamentals can we proceed to provide design guidelines based on driving behaviors that humans can anticipate, comprehend, and respond to.

Endsley (1) famously defined situation 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 the case for *social situation awareness* as a model for understanding everyday driving interaction. Towards this goal, 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 that we developed to assess their situation awareness, particularly with respect to the other vehicle and driver. This study was conducted in two locations, Israel and New York, to avoid generalizing about behavior that might be specific to drivers at one locale (aka stimulus sampling (*2*)). The data of the intersection encounters from this study were then used to understand statistically significant relations between measures to model social situation awareness.

The primary contribution of this work is the development of the concept of social situation awareness, which will help researchers to understand on-road interaction. Secondary contributions of this work are the methodological components towards this endeavor: the social situation awareness questionnaire, the multi-driver interaction study protocol, and key measures for establishing driving interaction performance and awareness.

RELATED WORK

This project is premised on the importance of understanding the way drivers interact with one another. Effective social communication is crucial for safe and efficient driving, as it helps to prevent collisions, reduce congestion, and promote smooth traffic flow. 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.” (*3*) Factor et al. (4) 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. In this section, we address the need to gauge the degree to which drivers are attending to and cognizant of one another in driving interactions, which we call *social situation awareness* .

Driving Encounters

Swan and Owen described driving interaction as “the presentation of action, a request for reaction,” and noted that “the very nature of driving behavior dictates that driving public are embedded in a social situation created by the actions of others.” (*5*) Over the years, numerous studies have proposed a wide range of theoretical perspectives on road traffic interactions, including safety perspectives (*6*), game-theoretic perspectives (*7*), sociological perspectives(*8*), and communication and linguistics perspectives(*9*). Markkula et al. (10) 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."

Measuring and Modelling Driving Interaction

To date, research on driving interaction has largely focused on "driving style." For example, Sagberg et al. (11)'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).

Markkula et al. (10)'s definition of driving interactions significantly reframes driving to focus 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. They differentiate this from explicit communication, where "a road user behavior which does not affect own movement or perception, but which can be interpreted as signaling something to or requesting something from another road user;" for example, the use of hand gestures, signaling lights or horns.

What is still missing from the field of automotive interaction, even from Markkula et al. (10)'s model, are ways to model the interaction behaviors, so that we might identify causes of and prevent issues with the "social accidents" noted by Factor and Juhlin (*3, 4*). To address this, we need to account not only for the interaction behaviors, but the perception, awareness and planning drivers perform around each other's behaviors.

Situation Awareness

For this research, we put forward a concept for *social situation awareness* in driving interaction.

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. The cognitive model of situation awareness put forward by Baumann and Krems (12) distills situation awareness as essentially a comprehension process within the working memory. In the driving sub-task, Gugerty (13) contextualized the theoretical models of comprehension, focal attention, and multitasking. Similarly, Matthews et al. (14) contextualized situation awareness into the strategic, tactical, and operation goals of driving. However, there is a research gap in terms of *social situation awareness*, i.e., the way situation awareness is affected in inter-driver interactions. These models, however, do not capture the perception, planning and operation that Markkula et al. (10) note are required to interact with other drivers on the road.

We believe that a situation awareness model improves upon communication models, which would focus just on what people notice about the social context; it helps to account for the different functional ways the observations people make get used, and how that drives the subsequent interaction outcomes. Parush et al. (15) have made similar models of communication and team situation awareness in medical teams and have examined how differences in these models affect team performance (*16*). Social situation awareness can model what participants are perceiving, comprehending, and projecting about the actions of other actors in the multi-person studies, and how each actor uses that awareness to decide to communicate or elicit a response from the other parties.

Interaction Studies

Although driving studies commonly feature driving interaction scenarios, driving interaction studies, wherein multiple drivers have the ability to respond dynamically to the presence and behavior of one another, are still quite rare. This is due in part to the scarcity of multi-driver simulation platforms for research.

Multi-driver interaction was first performed in simulation by Hancock and De Ridder in 2003 (*17*); 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 (*18*). 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 (*19*), cooperative lane change maneuvers (*20*), and traffic-light assistance (*21*). 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. (*22*)

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. (23) 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 (*24*). Goedicke et al. (25)'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 from this prior 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.

STUDY

The primary purpose of this study is to better understand drivers' behavior during encounters, specifically the communication used by participants and its relations with their behavior. The study is intended to elicit how pairs of drivers behave in situations when 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 are that the first vehicle to arrive at the intersection can cross or the driver on the right side has the legal right-of-way.

Method

We analyzed the interaction behavior of drivers in our study by replaying 3D recordings of pairs of participants as they drove, each in their own virtual cars, in the virtual reality simulation environment. The study uses a repeated measures design, with both participants driving in each scenario. The independent variable consists of the various driving scenarios; the dependent variables are participants' implicit and explicit communications, driving behaviors, and their situation awareness.

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). And most participants did not report any known condition of motion sickness during VR games (42%). Since the study was conducted in pairs, the participants were asked about their acquaintance with their partner, and 47% of them reported not knowing each other.

Apparatus

For the scenario deployment and data gathering, we used Goedicke et al. (25)'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.

FIGURE 1 Physical layout of the laboratory in Israel, *left*. Driver perspective of SA questions in the VR world at the end of a scenario, *right*. See also supplementary video.

The simulator was situated in a laboratory, and participants sat next to one another, unaware that they were in the same world (see Figure 1). Each driver observed partial representations (captured by the VR headsets 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 in the other vehicle when they encountered one another in the scenarios.

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)(*26, 27*) around multi-vehicle incidents to select 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.

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 Figure 2) 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 (*17*)(*28*), and dynamic route length change, these were not ultimately used in our study."

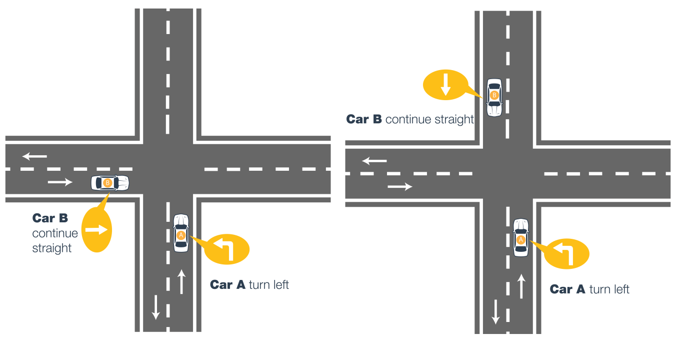

FIGURE 2 Two of the seven scenarios: Scenario 1, *left* and Scenario 3, *right*

Dependent Variables

Social Situation awareness questionnaire. Endsley (29) Situation Awareness (SA) model was adapted to assess and compose objective Social Situation Awareness measures and formulate Social Situation Awareness questions for the three levels of situation awareness in social driving encounters. These questions were embedded as part of the VR simulation.

Baumann and Krems (12) 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, in our opinion, can influence a driver’s situational awareness—objective driving scenario facts that a participant can perceive about themselves or the other driver. These elements were referred to as situational elements. The situational elements are {*location, right-of-way, speed, signaling, and car’s heading*} for each vehicle. Each element requires situational awareness in order to be perceived by the driver, 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.

Driving Behavior. Using time-stamped data and vehicle position, we were able to analyze 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.

Procedure

After being informed and instructed on how to put on the VR headset, the participants entered the VR world and drove for approximately 40 minutes in 12 different driving scenarios. The driving instructions were displayed on the dashboard of the vehicle (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 at the same time. 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 a series of situation awareness questions about the environment, the other driver, and themselves. 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. 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). If a participant answered that they did not perceive the other driver during a scenario, they were only asked about themselves and the environment. After answering all questions, both participants were advanced to the next scenario. The order of scenarios were randomized for each pair of participants using a Latin Square design. Finally, at the conclusion of the study, and after the removal of the VR headsets, participants were asked to complete a demographic questionnaire that included questions about their driving experience.

Data analysis

Here, we describe the methods we used to analyze the study data and provide a summary of our findings along with a quantitative analysis. To have a comparable sample for our repeated measures design, we first impose an inclusion criterion.

Inclusion criteria

For this analysis, we did not include the five non-intersection driving encounter scenarios from the study. 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.

Social Situational awareness scoring

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 the social situation awareness in each scenario for each participant.

RESULTS

The analysis of the driving simulation data focused on the mutual awareness of what they and the other driver did, and calculated several competing models of the social situation awareness, which we detail here.

Mutual Awareness

Mutual awareness metrics determine the degree to which a driver's perceptions and understandings match or differ from those of the other driver. Specifically, in mutual awareness we addressed two questions: 1. Is there a difference between awareness to oneself 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 questions on these six situational elements: right-of-way, speed, speed change, vehicle heading, signaling, and who entered the intersection first.

- *Overall Mutual Awareness.* 90% of the participants agree and are correct about the other driver's speed change, whereas the least number of participants are correct about who had the right of way (22%). Additional tests were conducted to determine which of the situational elements they agreed upon, and the results are presented below.
- *Right of way (ROW).* The Chi-square test assessing the overall agreement on the right of way (ROW) across all scenarios, yielded a statistically significant result $x^2(1, N=60) = 24.67,\ p = 6.8^{-07}$. This overall agreement was particularly evident in the subset of three scenarios where one driver was positioned to the right of the other. When conducting the same test on each of the countries separately (Israel & NY), we got that only for Israel it was statistically significant $x^2(1, N=36) = 13.78,\ p = 0.0002$.
- *Speed.* There was a high mutual awareness to speed, with most 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 oneself vs. the other driver's speed.
- *Speed change.* There was a high mutual awareness to speed change, with both participants correctly responding they were slowing down, $x^2(1, N=904) = 112.5,\ p = 2.777^{-26}$. There were no significant differences in the proportion of correct awareness to oneself 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, $x^2(1, N=390) = 48.248,\ p = 3.754^{-12}$ only in New York.
- *Heading direction.* There was more variance in the mutual awareness of vehicle heading, with both correctly perceiving each other, particularly when the other driver continued straight while they themselves turned left, $x^2(4, N=348) = 45.09,\ p = 3.79^{-09}$. Both participants had a significant agreement when they were both pointing straight, $x^2(4, N=500) = 500,\ p = 6.7^{-107}$.
- *Signaling.* There was a high mutual awareness to signaling, particularly when both drivers signaled, $x^2(1, N=636) = 31.51,\ p = 1.98^{-08}$.
- *First to enter the intersection.* There was a significant mutual awareness to who entered first the intersection, $x^2(1, N=444) = 217.997,\ p = 2.473^{-49}$, with the highest agreement that the driver that continued straight entered the intersection first (in 4 scenarios).

Social Situation Awareness models

As we are seeking to understand the factors which influence social situation awareness, we constructed several "prototype" models, based on the combination of driving encounter scenarios, situational elements, and answers regarding those elements in our study. Each stage in the model is represented based on the participants' answers to the situation awareness questions and their proportion scoring. The models attempt to represent the associations between the three levels of situational awareness, perception, comprehension, and finally projection.

All models are presented in the form of a Sankey diagram, where on each level the nodes represent the various answers to a specific question and the correct frequency for those answers. The links between each pair of nodes represent the frequency of answering both answers correctly with regard to ground truth. The most frequent flow is highlighted in the diagrams.

Approach models

The first model represents the relationship between a driver's perception of the other driver's direction of approach, 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-square test of independence, we analyzed the relationship between each pair of questions comprising the following model:

- *Direction of approach* the relations between one's perception of the other driver's direction of approach with evaluating the *right-of-way* was statistically significant, $x^2(4, N=396)=536$, $p=2.03^{-84}$.
- *Right-of-way* the relations 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, $x^2(2, N=258)=82.8$, $p=1.01^{-18}$.
- *First to enter* the relations 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, $x^2(1, N=702)=346.69$, $p=2.22^{-77}$.

Whereas 87% of the participants correctly perceived the other driver approaching the intersection, there were other differences expressed in two distinct social situation awareness models shown in Figure 3.

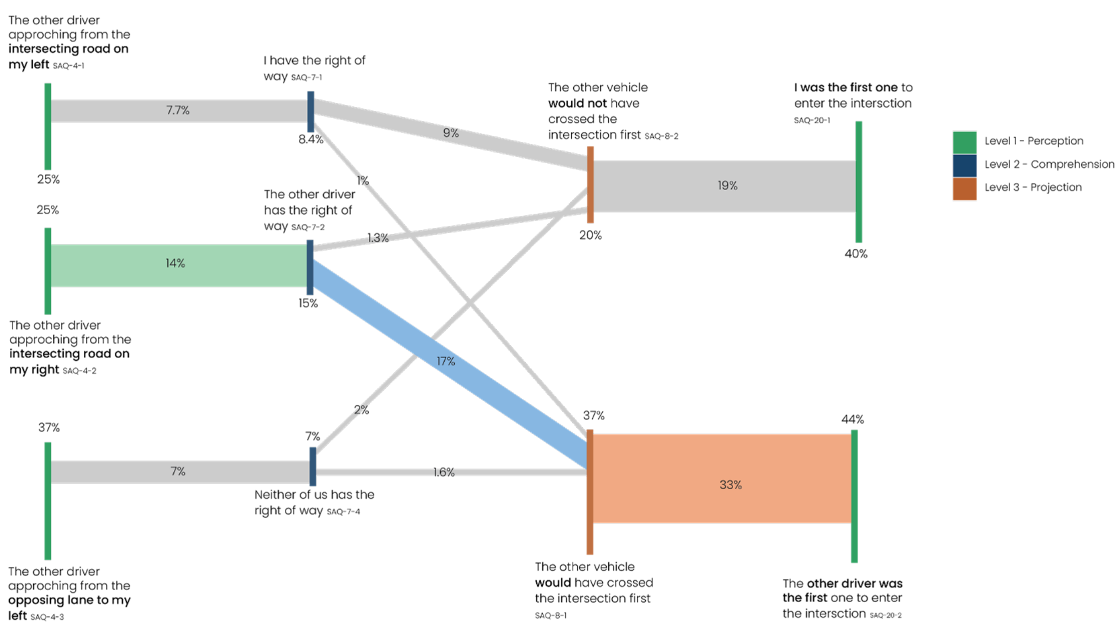

FIGURE 3 Model of approaching and perceiving the other driver when approaching from the side

In scenarios in which participants approached the intersection from the side of the other driver, they perceived the other approaching from both sides, right and left, (see Figure 3 on the right) . Only

14% of those who perceived the other driver coming from the right understood that the other had the right of way, and 17% projected that the other driver would cross the intersection first, which corresponded to the real outcome (correctly perceived by 37% of participants). 8.4% of those who saw the other driver approaching from the left realized they had the right of way, while 9% predicted the other driver would not enter the intersection first.

In scenarios where participants approached from the opposite direction (see Figure 3 on the left), 37% correctly perceived the driver from the opposite lane to their left, while only 7% correctly perceived the right-of-way. At this point, the projections of the participants are divided into two possibilities: the other driver would have crossed the intersection with 1.6% accuracy and stopped before the intersection with 2% accuracy. The projections are then aligned with the actual outcome, indicating who entered the intersection first. Only 29% correctly perceived the other driver entering the intersection first, while 18% correctly remembered entering the intersection first.

Speed and speed change models

The second social situation awareness model attempts to represent 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 4).

The perception of the other driver's speed as 'Normal' had a low proportion of correct responses 39%, whereas the comprehension of the speed change as 'slowing down' had a high proportion of correct responses (72%). 26% of the participants who perceived the other driver's normal speed understood they were slowing down. Of the participants who perceived the other driver is slowing down, 26% projected that the other driver would stop, while 22% projected that the other driver would enter the intersection first. There is a split in the perception of the final outcome, the entering of the intersection, based on each of the other driver's possible actions. 14% remembered the other driver entering first, while 6% remembered they entered first of the 21% who projected the other driver to move into the intersection. 6% of those who predicted the other driver would stop remembered the other driver entering first, while 21% remembered they entered first.

Heading model

The third model attempts to represent the relationship between the 3 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 5 on the left).

As the participants' driving directions differ in each scenario, the model begins with three distinct starting points for each of the possible answers. 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, $x^2(4, N=542)=542$, $p=5.5^{-116}$ with high frequency to heading straight.

Signalling 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 5 on the right). The relations between high frequency of perceiving the other driver's signaling and projection that they were about to turn left was statistically significant,

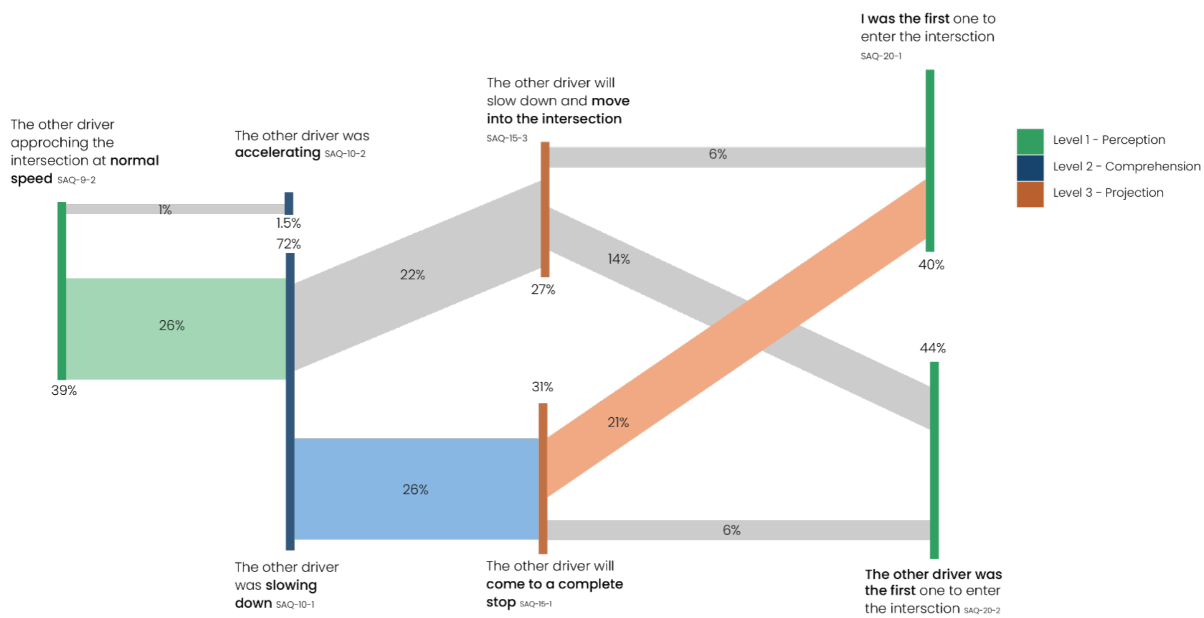

FIGURE 4 Model of encounter based on situational element - other driver speed

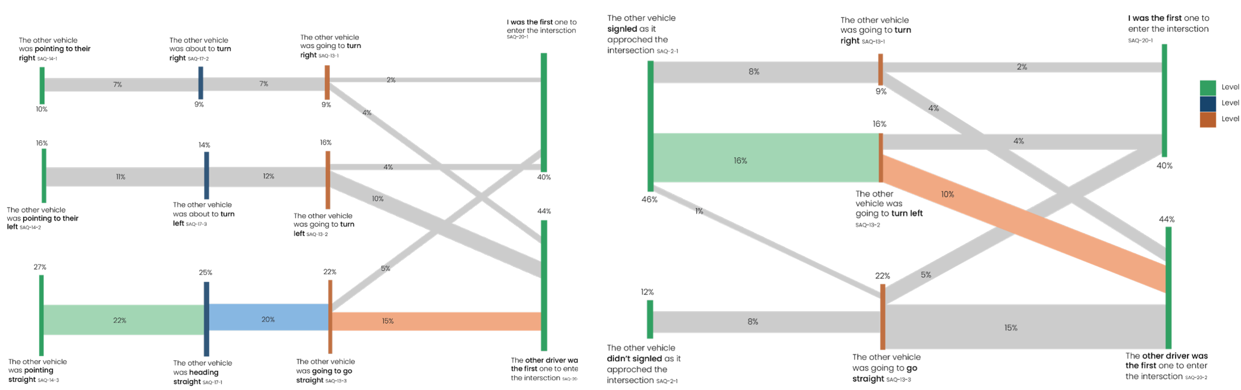

FIGURE 5 Model of encounter based on situational element - *left* other driver heading direction, and *right* other driver signaling

$x^2(2, N=452)=195.97$, $p=2.78^{-43}$.

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.

DISCUSSION

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 mutual and social situation awareness in the encounter unfolds as a synthesis of the communication between the drivers, explicit and implicit, with mutual awareness to situational and spatial factors in the encounter context.

Social situation awareness Models of the Encounters

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

We distinguish between awareness that reflects explicit communication, primarily the signaling act, and awareness of 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 was going to 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 basically supported drivers in framing the initial nature of the encounter, and the expectation matched significantly the correctly perceived end outcome of who indeed entered the intersection first. Moreover, this mutual awareness and understanding may have helped drivers to perceive and understand other important spatial 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 kind of imitation behaviors, which are often observed in drivers' actions, and in this study are associated with one of the drivers signaling to turn whereas the other driver continuing 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, perceiving and understanding the movement direction of another object and reporting its direction requires the use of 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 final and strongest implicit cue was the change of speed of the other driver as they approached the intersection, as reflected by the speed change situation awareness model. Participants were aware of the other driver's slowing down behavior which lead 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 account for the implicit cue of speed change being a strong one and most agreed upon by both participants.

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 situational 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 unclarity 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, in particular in designing manners 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.

Limitations

As this study is the first of its kind, assessing social situation awareness, it is unsurprising that it has some limitations. One fundamental limitation 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 that may influence drivers' social situational 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, but 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 direction of the sun depending on where the drivers were spawned, and the uncommon positioning of the right blinker.

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 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 to understand how drivers implicitly and explicitly communicate and help us avoid social accidents with one another and with autonomous vehicles.

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