

Complex cognitive interactions in a badly designed world: Investigating the underlying causes of collisions between distinct road users

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Abstract

Collisions between distinct road users (e.g. drivers and riders, drivers and cyclists) make a substantial contribution to the road trauma burden. Although evidence suggests different road users interpret the same road situations contrarily, it is not clear how their situation awareness differs, nor is it clear which differences might lead to conflicts. This article presents the findings from an on-road study which was conducted to examine driver, cyclist and motorcyclist situation awareness in different road environments. The findings suggest that drivers, motorcyclists, and cyclists develop markedly different situational understandings even when operating in the same road environments. Examination of these differences indicate that they are likely to be compatible along arterial roads, shopping strips and at roundabouts, but that they may create conflicts between the different road users at intersections. The key role of road design in supporting compatible situation awareness and behaviour across different road users is discussed.

Introduction

Although significant reductions in road collision-related death and injury have been made over the last four decades in most motorised countries (Elvik, 2010) a number of complex intractable issues remain. One of these is collisions between different types of road user (e.g. drivers and riders, drivers and cyclists). For example, an analysis of United Kingdom (UK) motorcyclist crashes found that their most common cause was other vehicles entering motorcyclists' path when exiting side roads (Clarke et al, 2007). Similarly, a high proportion of cyclist crashes involve drivers' failing to detect cyclists and colliding with them (Wood et al, 2009).

Despite many attempts to clarify and resolve the problem of collisions between different road users, their underlying causes remain ambiguous. Recent studies have demonstrated that differences in road users' situation awareness may lie at the root of the problem. Walker et al (2011) and Salmon et al (2013), for example, both concluded from exploratory on-road studies that drivers and motorcyclists differing understandings of the same situations are likely to lead to conflicts between them. Both studies, however, were exploratory in nature and involved small sample sizes. The aim of this paper is to examine the issue further based on a larger sample of road users. To do so we present the findings from an on-road study of driver, rider, and cyclist situation awareness in different road environments. The aims of the study were to model road user situation awareness in different road environments, to identify the key differences in situation awareness between different road user groups, and to identify potential conflicts that arise when road users engaged in the same road situations experience them differently.

Situation awareness as a causal factor in collisions between different types of road user

Road user situation awareness is defined as activated knowledge, regarding road user tasks, at a specific point in time (Salmon et al, 2012). This knowledge encompasses the relationships between road user goals and behaviours, vehicles, other road users, and the road environment and infrastructure. Recent accounts of situation awareness emphasise the key role that schema, or mental templates, play in the development and upkeep of situation awareness. Underpinned by

Neisser's perceptual cycle model (Neisser, 1976), these emphasise the schema driven nature of situation awareness, arguing that individuals possess schemata for different contexts and that it is these schemata that drive, and determine the content of, situation awareness. For example, in the road traffic context, drivers possess 'intersection' schema that direct and guide their interaction with the intersection and perception of it (what their expectations are, where they look, how they interpret information) and how they behave (whether they brake, change lanes, or accelerate through the intersection). The resulting interaction then modifies or confirms their intersection schema which in turn influences behaviour at the next intersection and so on.

It is argued that different road users' situation awareness will be different even when engaged in the same road situations (Salmon et al, 2013; Walker et al, 2011). That is, different road users, operating with their own personal schemata, vehicle, and goals, interact with and sample the environment differently and perceive and interpret the same road situations differently (Salmon et al, 2013; Walker et al, 2011). Many different actors operating together with varying situational understandings is a normal and indeed requisite feature of complex sociotechnical systems; however, problems arise when these distinct portions of situation awareness become incompatible (Stanton et al, 2006). In the road safety context, Salmon et al (2013) and Walker et al (2011) argue that incompatibilities between situation awareness across road users lie at the root of conflicts between them. For example, Salmon et al (2013) found that, at intersections, motorcyclist situation awareness was heavily underpinned by information related to avoiding other traffic and the opportunity to filter between traffic queues, whereas driver situation awareness was underpinned by the traffic ahead of the vehicle and the intersection infrastructure (e.g. traffic lights). They argued that these differences are incompatible in that they increase the potential of conflict between drivers and riders at intersections.

The schema driven nature of situation awareness ensures that road design has a key role to play in creating appropriate situation awareness and behaviour in road users; using the intersection example above, the road environment on approach to the intersection should be designed to trigger specific intersection schemata within different road users and then serve to support their situation awareness development. For example, Walker et al (2013) demonstrated the key role that road type and road design has on driver situation awareness and behaviour. The downsides of inappropriately designed intersections are thus twofold in that they may not trigger appropriate schema in road users and then may not support situation awareness across the different road users operating within them, which in turn can lead to collisions.

Designing road environments that facilitate the 'connection' of different road users' situation awareness therefore seems to provide an appropriate way to reduce collisions between them. Notably, from a schemata-driven situation awareness viewpoint, focussing on factors such as increasing motorcyclist conspicuity is not appropriate since there will be instances where drivers with inappropriate schema (i.e. not directing search and perception of motorcyclists) will still not perceive the motorcyclists, regardless of how conspicuous they may be. There are therefore three pressing lines of inquiry for road safety researchers interested in supporting safe interactions between distinct road users. First, exactly how situation awareness differs across road users requires clarification. Second, the extent to which these differences are compatible or incompatible requires investigation. Third, whether road design supports compatibility in situation awareness across all of its users is also of interest.

Assessing situation awareness during on-road studies

The present study used a network analysis-based approach to describe and assess road user situation awareness. Using this approach, situation awareness networks are constructed using data derived from the Verbal Protocol Analysis (VPA) method, which involves participants 'thinking aloud' as they drive/ride/cycle. Based on content analysis of the VPA transcripts, situation awareness

networks are constructed. These depict the information or concepts underlying awareness (nodes) and the relationships between the different concepts (links between nodes). For example, from the verbal transcript line 'The traffic light is green', the resulting network would include the node 'Traffic light' related to the concept 'Green' since the traffic light 'is' green. This provides a representation of situation awareness since the driver is aware of the traffic light and its current status. Once the networks are constructed, qualitative and quantitative analysis procedures are used to interrogate the content and structure of the networks. This enables comparison of situation awareness across different participants and scenarios.

Method

Design

The study was an on-road study in which participants drove an instrumented vehicle around a pre-defined urban route in the South East suburbs of Melbourne, Victoria. All participants provided concurrent 'think aloud' verbal protocols as they negotiated the route. For each participant, situation awareness networks were constructed for four distinct road environments along the route: intersections (15 in total), arterial roads (approximately 6.2kms), a shopping strip (approximately 0.5kms), and three roundabouts.

Participants

Fifty eight participants (32 male, 16 female) aged 21-64 years (mean = 37.31, SD = 13.02) took part in the study. An overview of the participants in each road user group is presented in Table 1.

Table 1. Participant demographic characteristics

| Road user group | Mean age (SD) | Gender | Hours drove/rode/cycled/walked per week (SD) |
|-----------------|-----------------|------------------------|--|
| Drivers | 34.9yrs (12.53) | 10 males 10 females | 11.5 hours (5.05) |
| Motorcyclists | 45.5yrs (12.87) | 17 males 1 female | 7 hours (5.19) |
| Cyclists | 32.4yrs (10.42) | 15 males 5 females | 6.85 hours (5.23) |

Participants were recruited through a weekly on-line university newsletter and were compensated for their time and expenses. Prior to commencing the study ethics approval was formally granted by the Monash Human Ethics Committee.

Materials

A demographic questionnaire was completed using pen and paper. A desktop driving simulator was used to train participants in providing concurrent verbal protocols. A 15km urban route was used for the on-road study component. The route comprised a mix of arterial roads (50, 60 and 80km/h speed limits), residential roads (50km/h speed limit), and university campus private roads (40km/h speed limit). Drivers drove the route in an instrumented 2004 Holden Calais sedan equipped to collect various vehicle and driver-related data. A Dictaphone was used to record drivers' verbal protocols. Motorcyclists rode the route using their own motorcycle. Each motorcycle was fitted with an Oregon ScientificTM ATC9K portable camera, which, depending on motorcycle model was fixed either to the handlebars or front headlight assembly. The ATC9K camera records the visual scene, speed and distance travelled (via GPS). A microphone was fitted inside each rider's motorcycle helmet to record their verbal protocols. Cyclists cycled the route using their own bicycles. To record

the cycling visual scene and the cyclist verbal protocols, the ATC9K portable camera was fitted to the cyclists' helmets, and cyclists wore ImgingTM HD video cycling glasses. All verbal protocols were transcribed using Microsoft Word. For data analysis, the LeximancerTM content analysis software and AgnaTM network analysis software were used.

Procedure

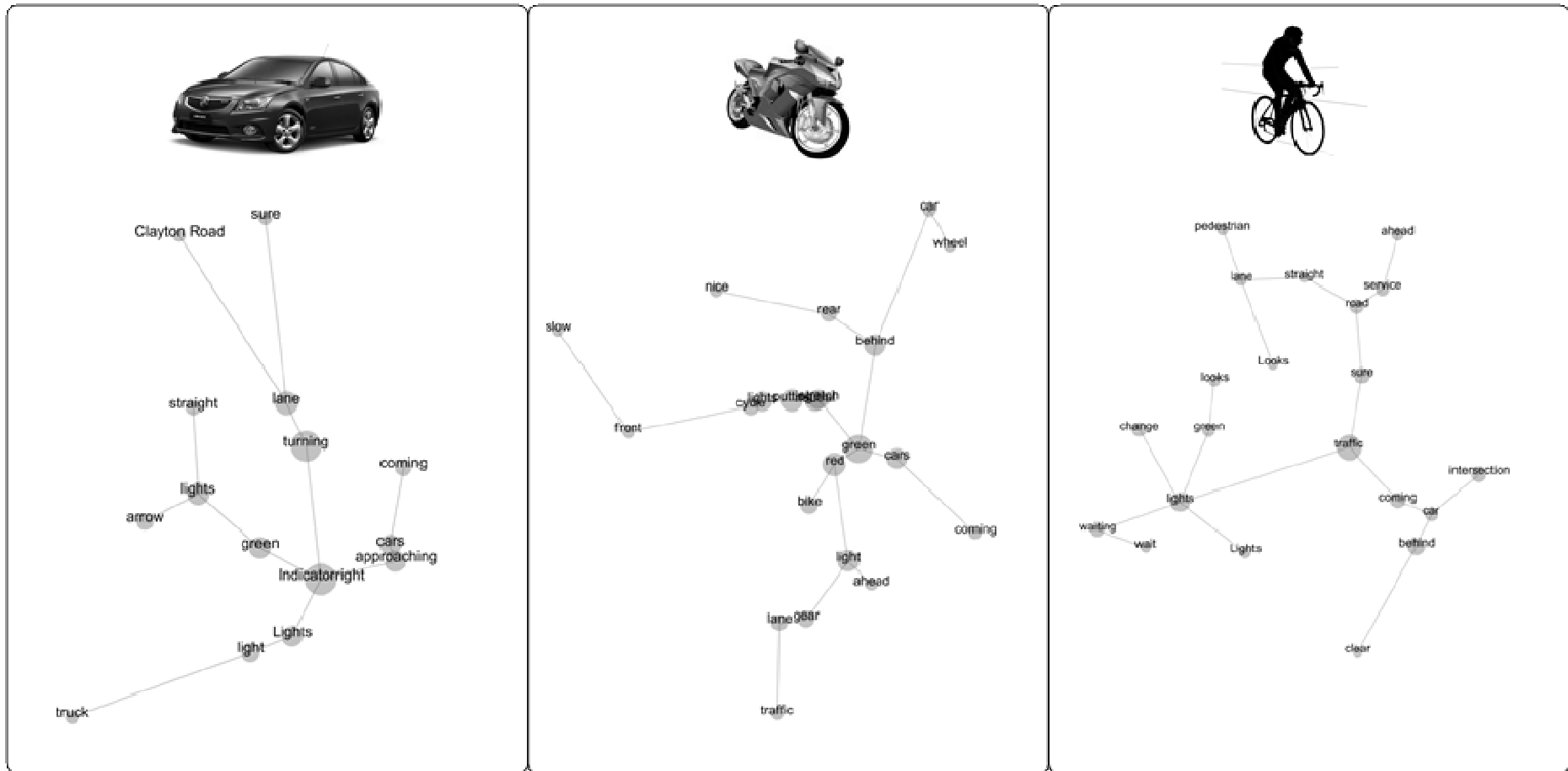
In order to control for traffic conditions, all trials took place at the same pre-defined times on weekdays (10am or 2pm Monday to Friday). These times were subject to pilot testing prior to the study in order to confirm the presence of similar traffic conditions. Upon completion of an informed consent form and demographic questionnaire, participants were briefed on the research and its aims. Following this they were given VPA training in which they received a description of the VPA method and instructions on how to provide concurrent verbal protocols. They were then asked to complete a test drive on a desktop driving simulator whilst providing a verbal protocol and practiced with feedback until an experimenter felt that they were capable of providing an appropriate verbal protocol. Participants were then shown the study route and were given time to memorise it. At this point a technician fitted the camera equipment to the motorcycle or cycling helmet. Participants were then taken to their vehicle and asked to prepare themselves for the test. Following this, the experimenter instructed the participant to begin negotiating the study route. For the drivers, an experimenter was located in the vehicle and provided route directions if necessary. For the motorcyclists and cyclists, an experimenter followed behind (in a car for the motorcyclists, on a bicycle for the cyclists) ready to intervene if the participants strayed off route.

Participants' verbal protocols were transcribed verbatim using Microsoft Word. For data reduction purposes, extracts of each participant's verbal transcript for each route section (intersections, arterial roads, shopping strip, roundabouts) were taken from the overall transcript. The extracts were taken based on the video data and pre-defined points in the road environment (e.g. beginning and end of arterial roads). The verbal transcripts were then analysed using the Leximancer content analysis software which auto creates situation awareness networks. The networks were then entered into the Agna network analysis software program for content and structural analysis purposes.

Results

A selection of the qualitative and quantitative network analyses are presented in this paper (the full analysis will be presented at the conference). Example situation awareness networks for drivers, cyclists, and motorcyclists are presented in Figure 1.

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Figure 1. Example driver, cyclist, and motorcyclist situation awareness networks

The content of participant situation awareness at the different road environments was examined by looking at the concepts (i.e. network nodes) underpinning road user situation awareness in two ways. First, all of the concepts across all participants and road environments were organised into the following categories and then summed using frequency counts:

1. *Traffic lights*. Includes concepts related to the traffic lights and their status, such as 'Lights', 'Green', 'Red', 'Amber', 'Arrow', 'Turning Arrow' etc;
2. *Traffic*. Includes concepts related to other traffic in the surrounding environment, such as 'Traffic', 'Cyclist' etc;
3. *Locations*. Includes concepts referring to a location on the road, such as 'ahead', 'behind', 'side' etc;
4. *Physical actions*. Includes concepts relating to physical actions being made by participants or other road users, such as 'change', 'move' 'turn', 'overtake' 'slowing' etc;
5. *Cognitive actions*. Includes concepts relating to the visual and cognitive activities undertaken by the participants, such as 'checking', 'thinking', 'looking', 'assuming' etc;
6. *Communications*. Includes concepts relating to communications between road users, such as 'indicating', 'telling' etc;
7. *Conditions*. Includes concepts that refer to the current road and traffic conditions, such as 'wet', 'slippy', 'debris', 'quiet', 'busy' etc;
8. *Speed*. Includes concepts relating to the participants and other road users' speed, such as 'speed', 'fast' 'slow' etc; and
9. *Other*. Includes other concepts not covered by the categories above, such as 'stupid', 'tired' etc.

This enabled a comparison of the content of the different road users' situation awareness across the road environments studied. Second, the sociometric status network analysis metric was used to identify the key concepts underpinning situation awareness for each participant. The sociometric status metric provides a measure of how 'busy' a concept is relative to the total number of concepts within the network under analysis (Houghton et al, 2006). Concepts with high sociometric status values represent key concepts since they are highly connected to other concepts within the situation awareness network. This gives an indication of the concepts that are central to a participant's situation awareness. Those concepts with a sociometric status value above the mean plus one standard deviation value for the network are taken to be key concepts (Salmon et al, 2009). The key concepts identified for each participant were placed into the categories above, enabling a comparison of the key concepts across road users and road environments.

Situation awareness concepts

In Figure 2 the situation awareness concepts in each category are expressed as a percentage of the total number of concepts for each road user group in each road environment.

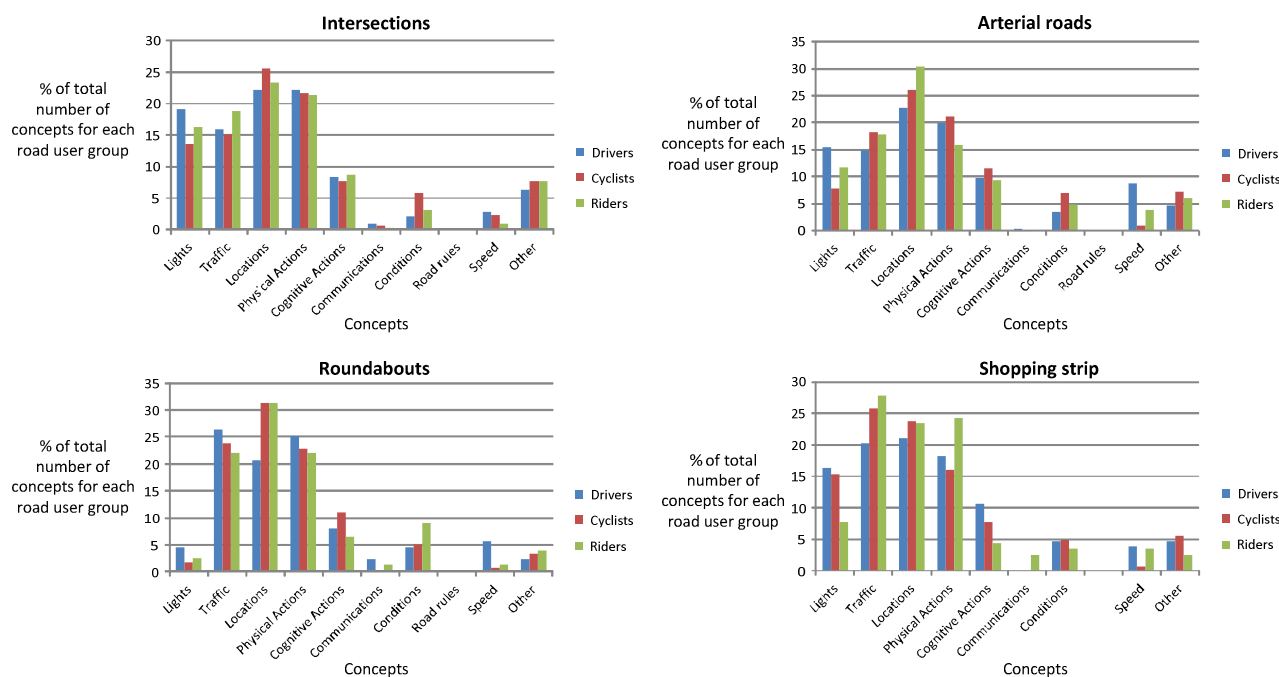


Figure 2. Road users' situation awareness concepts at intersections, arterial roads, roundabouts and the shopping strip.

At the intersections, the composition of situation awareness was similar across the three road user groups, with the majority of concepts relating to locations (e.g. 'ahead', 'behind') followed by physical actions (e.g. 'turning', 'stopping', 'going'). With the locations category, the most frequent concept for the drivers was 'ahead', whereas the motorcyclists and cyclists also had other frequent location concepts such as 'behind', 'side', 'lane' and 'service lane'. After physical actions, for the drivers, the next most frequent category of concepts related to the traffic lights (19.17% of all driver intersection concepts), whereas for the riders and cyclists the next most frequent was concepts relating to the surrounding traffic.

Along the arterial roads, all road users had a strong focus on locations, physical actions, and the traffic, however, whilst the most frequent category of concept for all three road user groups was locations, the next most frequent for motorcyclists was the surrounding traffic, whereas for drivers and cyclists it was concepts relating to physical actions. In addition, drivers maintained a higher focus on concepts relating to traffic lights along the arterial roads. Cyclists and motorcyclists had a greater focus on locations, which reflects their increased focus on the locations of other road users in proximity to them.

At the roundabouts, almost a third of all cyclist and motorcyclist concepts related to locations ('ahead', 'straight'), whereas these concepts represented only around 20% of the drivers overall concepts. Other notable differences included that drivers focussed more on other traffic than motorcyclists and cyclists and also more on speed-related concepts. Finally, motorcyclists had a greater percentage of concepts relating to the conditions (e.g. 'clear', 'busy').

At the shopping strips, the majority of all three road user groups' concepts were related to other traffic, locations, and physical actions; however, motorcyclists had a greater percentage of concepts concerned with other traffic and physical actions whereas drivers had a greater percentage of concepts related to cognitive actions and the traffic lights along the shopping strip. This likely reflects the motorcyclists own manoeuvrability and their increased focus on the actions of other

road users in close proximity to them. In addition, both drivers and cyclists had more concepts relating to the traffic lights along the shopping strip.

Key situation awareness concepts

'Key' situation awareness concepts reflect those concepts central to situation awareness and provide an indication of the main focus of participant situation awareness. In Figure 3 the key situation awareness concepts in each category are expressed as a percentage of the total number of key situation awareness concepts for each road user group in each road environment.

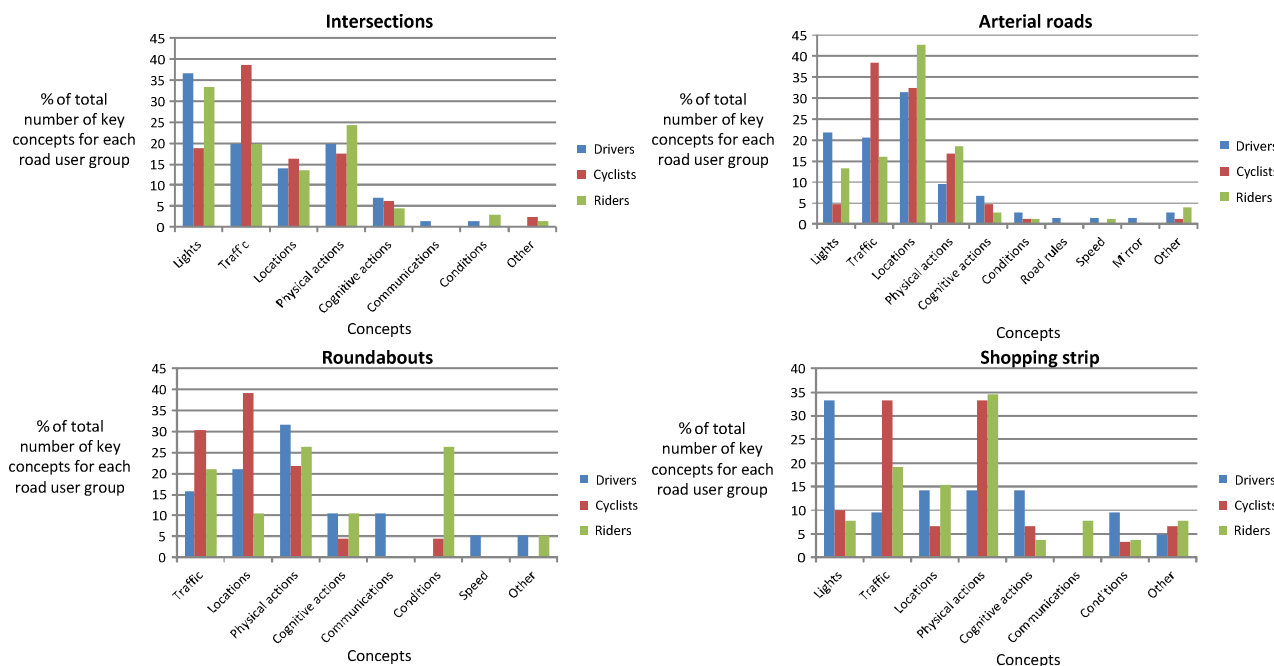


Figure 3. Key situation awareness concepts at intersections, arterial roads, roundabouts and the shopping strip.

The analysis of key concepts shows important differences. Overall, regardless of road environment, cyclist situation awareness is underpinned by a high focus on other traffic. For the drivers, the presence of traffic lights shapes their situation awareness significantly, since it becomes their key focus. Motorcyclists are the group most influenced by road environment type, with their key concepts changing markedly across the four road environments studied.

At the intersections, the traffic lights and their status made up over one third of drivers' key concepts, followed by the other traffic (20%), the drivers' and other road users' physical actions (20%), locations in and around the intersection (14%), the drivers' own cognitive actions (7%), communications and the road conditions (both 1.4%). The spread of cyclist key concepts was markedly different, with almost 40% of their key concepts relating to other traffic in and around the intersection and only 18.75% relating to the traffic lights and their status. Concepts relating to cyclists and other road users' physical actions made up 17.5% of cyclists' key concepts, followed by locations (16.25%), and their own cognitive actions (6.25%). The motorcyclists' key concepts were more closely aligned to the drivers; however, there were still notable differences. Concepts relating to the lights comprised around a third of their key concepts, followed by physical actions (24.24%), other traffic (19.69%), locations (13.63%), cognitive actions (4.54%) and the conditions of the road (3.03%).

Along the arterial roads, the majority of drivers' key concepts were related to locations (31.5%), traffic lights along the arterial roads (21.9%), and other traffic (20.54%). Other common key

concepts were related to the drivers' and other road users' physical actions (9.58%), and the drivers' own cognitive actions (6.84%). For the cyclists, the majority of their key concepts were concerned with other traffic on the road (38.55%) and almost a third were related to locations on the arterial roads (32.53%). The next most common were concepts related to the cyclists' own physical actions (16.87%) followed by the concepts concerning the traffic lights and cognitive actions (4.81%) and the conditions (1.2%). For the motorcyclists, close to half of all key concepts concerned locations (42.66%), followed by almost a fifth relating to physical actions (18.66%). Other motorcyclists key concepts included concepts relating to the traffic (16%), the traffic lights (13.33%), riders' cognitive actions (2.66%), the conditions (1.33%) and travelling speeds (1.33%).

At the roundabouts some notable differences in the key concepts across road users were revealed. Almost 40% of the cyclists' key concepts related to locations, whereas only a fifth of drivers and just over 10% of riders did. Almost a third of cyclists' key concepts concerned other traffic at the roundabout whereas these concepts only made up around a fifth of the riders key concepts and just over 15% of the drivers key concepts. Finally, a quarter of the riders' key concepts concerned the conditions (e.g. road layout) at the roundabout, whereas these concepts made up just under 5% of cyclists key concepts. Drivers had no key concepts related to the conditions at roundabouts.

Finally the key concepts were again different across the road users when negotiating the shopping strip. The most frequent for drivers were concepts related to the traffic lights (33.33%), whereas light-related key concepts made up only 10% and 7.69% for cyclists and riders respectively. A third of cyclists key concepts were related to the traffic, and another third to physical actions. The most frequent key concepts for the motorcyclists were related to physical actions. The drivers had the most key concepts relating to cognitive actions (14.28% compared to 6.66% for cyclists and 3.84% for riders).

It is also pertinent to examine the differences in key concepts across the four road environments. Cyclist key concepts remained the most stable, with a consistently high number of key concepts relating to other traffic regardless of road environment. Drivers' key concepts also remained stable, with a high focus on the traffic lights (when present), however, changes were also brought about by the characteristics of the different road environments. For example, along the shopping strip the percentage of key concepts related to cognitive actions (i.e. checking, looking) increased markedly. Of the three road users groups, the motorcyclists were influenced the most by road type, having a variety of prominent key concepts across the four road environments studied. For example, at the roundabouts the majority of key concepts concerned the conditions (i.e. road surface condition), whereas at the intersections the majority concerned the traffic lights, and along the arterial route the majority concerned locations (e.g. in front, behind, to the side).

Discussion

First and foremost the analysis presented confirms the notion that situation awareness differs across different road users even when they are operating in the same road environments. The analysis, confirms Salmon et al (2013) and Walker et al's (2011) exploratory study findings that situation awareness is different across road users. It is concluded then that drivers, riders, and cyclists experience the same road environments differently and that situation awareness is heavily influenced by transport mode and the nature of the road environment (e.g. intersection versus arterial road).

Examination of the networks enables judgement to be made on the extent to which the differences in situation awareness are compatible. That is, do the differences in situation awareness across road users enable them to interact together safely, or do they lead to conflicts? The findings indicate that the level of compatibility may vary across different kinds of road environment. At intersections, driver situation awareness seems to be strongly oriented to the lights and the status of the lights,

along with a prominent focus on the intersection itself and the area in front of the vehicle. Although the cyclists and motorcyclists have a strong focus on other traffic and their behaviour, this is not the prominent focus for drivers. This could become problematic when cyclists and motorcyclists are manoeuvring around the intersection in areas that drivers do not focus on, such as the left and right hand sides of the vehicle. It also suggests that drivers may not become aware of cyclists and motorcyclists until they are ahead of the vehicle and in very close proximity. This finding is in line with Salmon et al (2013) and provides further evidence that drivers' limited exploration of the intersection environment is likely to create conflicts with more manoeuvrable and unpredictable road users such as motorcyclists and cyclists.

For the other three road environments studied, the differences in situation awareness appear to be compatible. Along the arterial roads, for example, the major differences identified were that motorcyclists seem to focus more on the surrounding locations (e.g. 'front', 'behind', 'side'), drivers focus on speed whilst cyclists and riders do not, and that cyclist situation awareness is underpinned by a strong focus on other traffic. Drivers did, however, have a strong focus on other traffic and surrounding locations on the road. These differences seem compatible, since the vulnerable road users are on the lookout for drivers, and the drivers are on the lookout for the vulnerable road users. Similarly, the findings provide an indication of compatibility at the roundabouts and shopping strip studied.

The differences found in the content of situation awareness across the different road environments leads us to conclude that situation awareness is heavily related to the road environment in which road users are operating. This is in line with Walker et al (2013), who concluded that both road type and the way in which road environments are designed both influence driver situation awareness and behaviour. This emphasises the critical role of road design in supporting situation awareness across different road users and in 'connecting' road users. Moreover, these findings suggest that the increased manoeuvrability of cyclists and motorcyclists engendered by intersection environments is an issue that requires further examination.

Design induced incompatibility?

The potential intersection conflict between drivers and cyclists and motorcyclists is overlaid onto Neisser's perceptual cycle model in Figure 4. Here the schemata, perceptual action, and environmental factors creating the conflict are mapped onto the appropriate component of the perceptual cycle.

As shown in Figure 4 the key factors driving this conflict appear to be the relatively low numbers of cyclists and motorcyclists on our roads, road design, and road user experience. The role of road design is important, since simple modifications could potentially remove the problem. Currently at intersections cyclists and motorcyclists have a significant level of flexibility, since they can proceed through the intersection in a variety of ways (e.g. cyclists can pass through in the flow of traffic, via filtering, via hook turn, or via the pedestrian crossings). This is reflective of emergence and is design induced; as they are vulnerable road users and the intersection is not geared towards supporting their safe passage through, they have developed a variety of ways through the intersection that they perceive to be safer. The present study suggests that drivers do not appear to be expecting this flexibility and are either not on the lookout for cyclists and motorcyclists, or are not looking for this variance in behaviour. Their situation awareness was focussed on the road ahead, their own behaviour, and the lights, and not on the areas of intersections in which unpredictable motorcyclists and cyclists might be operating (e.g. filtering through the traffic queue). Further, the intersections studied do not support the interaction between different road users. For example, none currently alert drivers to the presence of unpredictable motorcyclists and cyclists, nor does do they offer any protection to the motorcyclists and cyclists as they pass through the intersection (e.g. dedicated cyclist lanes stop prior to the intersection, absence of filtering lanes). In addition, the road rules prohibit cyclists from cycling on footpaths and motorcyclists from filtering

up the traffic queue. Coupled with the relatively low numbers of cyclists and motorcyclists, the effect of this is that drivers and pedestrians have limited experience of the range of behaviours and often may not be expecting them. Here flexibility, an often sought for characteristic in complex sociotechnical systems, coupled with poor intersection design, is creating conflicts between distinct road users at intersections.

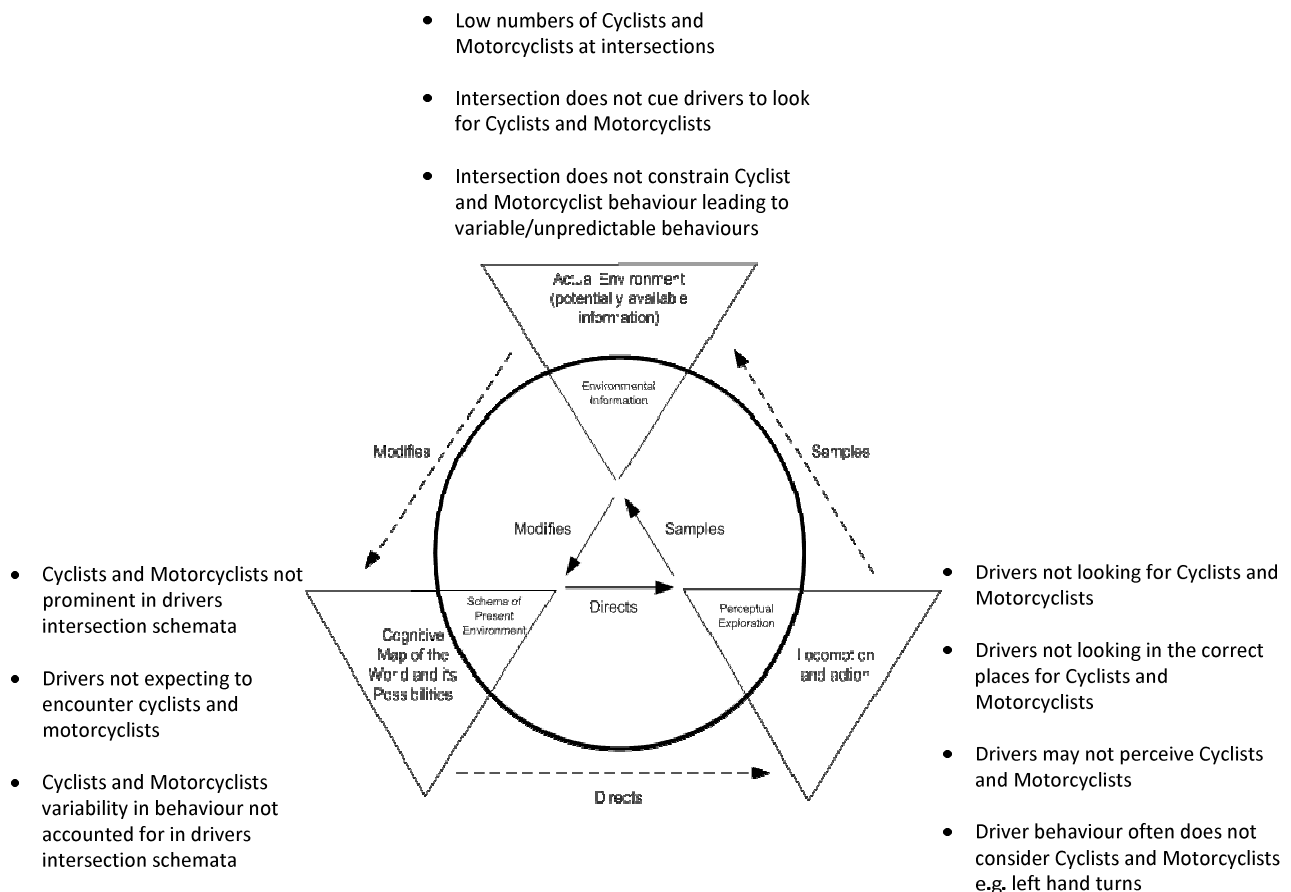


Figure 4. Intersection conflict mapped onto the Perceptual Cycle model.

Consideration of different road user situation awareness during the road design process is therefore proposed as an important step in reducing conflicts between different road users. Currently road designs are assessed through a conflict point analysis that focuses on physical pathways through road environments and the potential for road users to come into physical conflict with one another. It is these authors' opinion that a failure to consider cognitive conflict points will prevent conflicts between different road users from being solved through road design. Considering both cognitive and physical conflict points between different road users and the role of road design in creating cognitive conflicts during the road design process will provide a way of tailoring road designs to both the cognitive and physical needs of all road users. For example, there are a number of simple road design-based interventions that could prevent the potential for conflicts at intersections. Signage warning drivers to be on the lookout for riders and cyclists will be beneficial, as will dedicated motorcycle and cycle lanes which will protect them whilst negotiating the intersection and in turn reduce variance in behaviour and make them more predictable to drivers.

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