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Self Explaining Roads and situation awareness

Guy H. Walker, Neville A. Stanton, Ipshita Chowdhury

Abstract

This paper places theories of SA into contact with the issue of Self Explaining Roads. Twelve drivers took part in an on-road study and performed a verbal commentary as they drove around a defined test route. The verbal transcripts were partitioned into six road types, and driver SA was modeled using semantic networks. The content and structure of these networks was analysed and cognitively salient endemic road features were extracted. These were then compared with aspects of driver behaviour. The findings highlight the systemic nature of the driver–vehicle–road interaction, and show that SA is highly contingent on road type. The findings also reveal that motorways/freeways are the most cognitively compatible road type and that incompatibilities grow rapidly as road types become increasingly minor and less overtly ‘designed’. The paper is exploratory in nature but succeeds in innovating a theoretically robust means of examining road environments under naturalistic conditions. It also succeeds in providing numerous insights and hypotheses for a developing program of work.

1. Introduction

Stanton, Chambers and Piggot provided a state of the art review for this journal in 2004 detailing what was then considered a relatively new and important concept for Safety Science: Situational Awareness (SA). Since then, the range of applications to which SA has been applied has expanded, and so too has the sophistication of the concept itself. In this paper we revisit some of the themes outlined in Stanton et al.’s paper. We will place a long-standing and popular model of SA in contact with the issue of driving and road infrastructure design, and leverage our maturing understanding of SA to guide us towards new forms of data collection and new safety related insights.

1.1. Self Explaining Roads

It is true to say that the design and construction of road infrastructure is foremost the concern of civil engineers, but it is equally true to say that certain psychological parameters have been embedded in design guidance for a considerable number of years (AASHTO, 2004; Highways Agency, 2011). As a result, the most modern form of road, the high speed, multi-lane, limited access motorway (the UK term for freeway, autostrada, autobahn, etc.), provides drivers with what Vanderbilt (2008) describes rather fancifully as a ‘toddler’s view of the world’:

“we make the driving environment as simple as possible, with smooth, wide roads marked by enormous signs and white lines that are purposely placed far apart to trick us into thinking we are not moving as fast as we are... a landscape of outsized, brightly coloured objects and flashing lights, with harnesses and safety barriers that protect us as we exceed our own underdeveloped capabilities” (p. 90).

Motorways represent an unusual form of ‘total environment’ yet the behavioural outcomes of this environment are undeniable. In most countries in the world motorways are the safest types of road to travel on despite carrying by far the largest volumes of traffic at the greatest speeds (e.g. DfT, 2008). Motorways, therefore, are an excellent example of a Self Explaining Road, one that does not “need any additional explanation or learning process to know what it means and what to expect” (Stelling-Konczak et al., 2011). This suggests that a powerful mapping exists between the objective state of the built environment and the perceived state of that environment on the part of the individual within it. This concept is a familiar one. Norman (1990) refers to affordances and ‘gulfs of evaluation’, both of which describe a person’s attempts to make sense of their context and how it matches their expectations and intentions. Because it is not possible to create motorway-like ‘total environments’ in all situations, significant gulfs of evaluation can begin to occur on other, non-motorway types of road. This is a challenge that has long been identified within this journal (e.g. Van Uden and Heijkamp, 1995; Wegman et al., 2008 and more recently Salmon et al., 2010). SER research is about reducing such gulfs (Theeuwes and Godthelp, 1995), and the results so far are...
encouraging. For example, Charlton et al. (2010) present a study in which SER derived changes to road infrastructure, most notably changes to the visual environment, resulted in significant reductions in speed. For the purposes of this paper it is interesting to note that while the SER approach makes reference to a number of cognitive antecedents as explanations for these desirable behavioural adaptations, including affordances (e.g. Weller et al., 2008), schemas (e.g. Charlton et al., 2010), expectation and prediction (e.g. Stelling-Konczak et al., 2011), one concept that is not cited, and which could serve to unify a number of ideas already in use, is SA.

1.2. Situation awareness and safety

The concept of SA explains how drivers use information from the world to combine long-term goals (such as reaching a destination) with short-term goals (such as avoiding collisions) in real time (Sukthankar, 1997). Drivers are required to keep track of a number of critical variables in a dynamic and changeable environment, such as their route, their position, their speed, the position and speed of other vehicles, road and weather conditions and the behaviour of their own vehicle. Drivers also need to be able to predict how these variables will change in the near future in order to anticipate how to adapt their own driving (Gugerty, 1997). SA is an important factor in driving safety. Indeed, Gugerty (1997, 1998) points out that “errors in maintaining situation awareness are the most frequent cause of errors in real-time tasks such as driving” (p. 498) and that poor SA can be attributed to more accidents than improper speed or technique. This is one of the reasons behind SA’s rapid maturation and diffusion among the safety community. The other reason is its tractability in the face of practical problems. Stanton et al. illustrated this in 2004 with a set of SA design guidelines (derived from Endsley (1995)) which now appear highly relevant to the topic of Self Explaining Roads. These principles are:

1. Reduce the requirement for [drivers] to make calculations.
2. Present data in a manner that makes understanding and prediction easier.
3. Organise information in a manner that is consistent with the [driver’s] goals.
4. Indicators of the current mode or status of the [driver–vehicle–road] system can help to cue the appropriate situational awareness.
5. Critical cues should be provided to capture attention during critical events.
6. Global situational awareness is supported by providing an overview of the situation across the goals of the [driver].
7. [driver–vehicle–road] system-generated support for projection of future events and states will support SA.
8. [driver–vehicle–road] system design should be multi-modal and present data from different sources together rather than individually.

In order to enact these principles a more detailed understanding of SA is required. In the next section we will place the concept of SA in contact with the problem of driving and road infrastructure design, and use it to reveal certain safety related paradoxes and limitations of existing views of the concept.

1.3. Situation focus versus cognitive focus

As mentioned above, part of the appeal of SA as a concept is its tractability and face value logic. This is amply demonstrated with the use of methods such as the Situation Awareness Global Assessment Technique (SAGAT; 1988), a partner to the dominant theoretical model of SA proposed by Endsley (1995). SAGAT, and the underlying three level model of SA, require some form of ‘ground truth’ representation of a situation, one that contains all relevant elements. A participant then experiences the same situation and their score on various probe questions derived: the higher the score, the better the person’s SA. The implication of this is that the mental representation should contain all the relevant information identified earlier in order for it to be regarded as ‘good’ awareness. There are two potential problems with this view. Firstly, the term ‘mental representation’ implies that information elements are structured in some way, meaning that SA is not merely about the presence or absence of discrete elements but also their interconnection. Secondly, the idea of a mental representation reflects the “hypothetical nature of perceptual experience” (Bryant et al., 2004, p. 110) and the notion that the mental representation is a model (e.g. Banbury et al., 2004), “a representation that mirrors, duplicates, imitates or in some way illustrates a pattern of relationships observed in data or in nature […]” (Reber, 1995, pp. 465, 793). According to the varied literature in bounded rationality and systems thinking, if situation ‘awareness’ is a form of model then it does not necessarily need to be a particularly rich or detailed model in order for it to perform effectively (e.g. Gobet, 1998; Chase and Simon, 1973). Endsley refers to ‘relevant information’ and to the abstract nature of expert SA but the paradox, one that is often overlooked, is that the better the driver’s awareness or ‘mental theory’ of their situation the ‘less’ likely it is to mirror exactly the objectively defined properties of the situation. Put another way, the goal directed task analysis that is often used as the basis for defining the situation to be assessed is highly reductionist and ‘atomistic’ in nature, and likely to be contrary to how people perceive real-world situations. This is because expert drivers have extracted the critical multi-modal cues (as per design principle #5 and #6 above) and organised it consistent with their individual goals (as per design principle #3).

1.4. Linear versus non-linear SA

The current state of the art in SA also carries with it a certain ‘linear’ flavour. Evidence of this can be seen in the control theory logic of sequential flows and feedback embodied in Endsley’s model of SA, with the author herself stating that “humans typically operate in a closed-loop manner” (Endsley, 1995, p. 33). Whilst there can be little doubt that a large proportion of driving performance does rely on a cycle of input-processing-output-feedback, this need not be the case all of the time. In a complex well learned task such as driving a large, if not larger proportion of tasks may be performed in a predictive, feed-forward manner. This relates heavily to design principle #1 (reducing the requirement for people to make calculations), principle #2 (the presentation of data which makes understanding and prediction easier), principle #4 (indicators of current mode or status cueing appropriate SA) and principle #7 (system generated support for projection of future events). It also relates heavily to the extant literature on SER, the basis of the approach being “the use of road designs that evoke correct expectations” (Charlton et al., 2010, p. 1989).

An extreme example of this is Driving Without Attention Mode (DWAM; Kerr, 1991; May and Gale, 1998). Kerr (1991) cites the automatisation of perception due to the predictability of the environment as the cause for this. Certain cues and indications are vital in triggering this switch in cognitive control. The paradox in this case, according to Endsley’s three level model of SA, is that DWAM is Level 1 SA (perception) no longer preceding Level 2 (comprehension) or 3 (projection); rather, Levels 2 and/or 3 are developed on extremely parsimonious instances of Level 1 SA, perhaps even coming before Level 1. Despite its pejorative overtones, DWAM admits the possibility that non-linear awareness, as a phenomenon, exists. It also
suggests a somewhat troubling aspect of the ‘total environments' that we may be creating for drivers.

1.5. Normative versus formative SA

The current state of the art in SA also carries with it a ‘normative' flavour, the tacit assumption being that the ‘objective' situation provides a reference point for judging ‘goodness' or ‘badness' of SA (Endsley, 1988, p. 793). Related to design principle #6 (that global SA is supported by providing an overview of the situation across the goals of the operator) SA is created for a purpose (Patrick and James, 2004). Smith and Hancock (1995) put it that SA can be viewed as “a generative process of knowledge creation” (p. 142) in which “[...] the environment informs the agent, modifying its knowledge. Knowledge directs the agent’s activity in the environment. That activity samples and perhaps anticipates or alters the environment, which in turn informs the agent” (Smith and Hancock, 1995, p. 142) and so on in the cyclical manner shown below in Fig. 1.

Smith and Hancock refer to SA as ‘constructive', which is to say that the driver is a part of the situation they find themselves in and can influence its dynamics. This means that if risks from hazards have been successfully minimised through effective driving behaviours, then the more benign situation that the driver has created will result in fewer critical variables to be aware of. If motorways present a ‘toddlers view' of the world, then closed loop models of SA are perhaps similarly regressive? Quite often, driver SA is measured in such a way that it is compatible with novices (feedback control and an unsophisticated mental theory of a situation) rather than experts (who use more predictive control and have a highly developed and abstracted mental theory of a situation).

1.6. Endemic road features

Having reviewed the conceptual basis of SA and road design, the paper now shifts to an empirical focus. In SER literature, the goal to develop and abstract mental theory of a situation). Smith and Hancock refer to SA as ‘constructive', which is to say that the driver is a part of the situation they find themselves in and can influence its dynamics. This means that if risks from hazards have been successfully minimised through effective driving behaviours, then the more benign situation that the driver has created will result in fewer critical variables to be aware of. If motorways present a ‘toddlers view' of the world, then closed loop models of SA are perhaps similarly regressive? Quite often, driver SA is measured in such a way that it is compatible with novices (feedback control and an unsophisticated mental theory of a situation) rather than experts (who use more predictive control and have a highly developed and abstracted mental theory of a situation).

So far, then, we have argued that SA models and methods based on closed loop processing and situation focused assessment may not be fully appropriate to the task of identifying endemic road features in real-world settings. As described above, the situation focus is not an adequate proxy for the underlying cognition of drivers. Instead, we have a task that is complex, dynamic, well-learned and performed in a hazardous environment alongside other actors and agents. An underlying theoretical model that is responsive to the paradoxes raised above is one based on Smith and Hancock's (1995) generative model of SA, as shown above in Fig. 1. An approach to the measurement and representation of SA that is congruent with this underlying model, and compatible with several on-road data collection methodologies, is one based on semantic networks.

Semantic networks are an established way of representing knowledge (e.g. Collins and Loftus, 1975; Collins and Quillian, 1969, 1970). Creating networks to represent driver SA involves extracting information elements from drivers (called nodes or vertices in semantic networks) and establishing links (or edges) between them. The result is that when elements become temporally, spatially, causally or semantically interlinked they begin to form ‘concepts'. It is claimed that “one can produce dictionary-like definitions of concepts” and that a definition of any situation (or state of knowledge) can be represented (Ogden, 1987). Networks capitalise on a number of important principles of systems thinking. The first is the Aristotelian idea “that the whole is characterised not only by its parts, but by the relations [or mapping] between the parts”. SA can, therefore, exhibit the synergistic property of being more than the sum of its information elements (thus responding to the issue above concerning normative forms of SA). Networks also represent the individualistic nature of awareness, and the propagation of activity through them need not be linear. Sticking to the tractable nature of SA as a concept is the fact that methods, like concurrent verbal commentaries (Walker, 2005), exist to extract information from the working memory of drivers, and methods also exist to construct networks based on that data (e.g. Ogden, 1987; Smith, 2003). In the remainder of the paper these methods will be deployed in order to provide a theoretically robust way of exploring and extracting cognitively salient endemic road features from real-world settings.

2. Method

2.1. Design

The current experiment is based upon ‘real-world' driving in which individuals use their own vehicles around a defined course on public roads and were required to provide a verbal commentary as they drove. The commentary required drivers to 'speak out loud' about what information they were taking from the environment,
what they intended to do with it, and to explain their driving actions. The transcript of this commentary was analysed using content analysis (i.e. extracting phrases, sentences, etc.) as well as being subject to analysis with Leximancer (a tool for automatically creating semantic networks from text data; Smith, 2003). These outputs were dependant upon one independent variable: road type. This had six levels; (1) motorway (freeway), (2) major A/B classification road, (3) rural road, (4) urban road, (5) junction and (6) residential road. This is an initial study and a relatively homogenous sample was used. Driving style, speed and time to complete the course was measured and outlying participants were excluded from analysis. All experimental trials took place at defined times in order to avoid peak traffic conditions in the study area and to offer some control over traffic density. All runs took place in dry weather conditions with good visibility.

2.2. Participants

Given the discussion above regarding the individual nature of perceptual experience it is expected that different populations of drivers will experience identical road situations in different ways. The purpose of the present study is primarily to test the concept of SER, SA and semantic networks, and to do this effectively in the context of a first study is to derive a relatively homogenous initial sample. This comprised of 12 male drivers, ranging in age from 20 years to over 50. The modal age category was 21–25 and mean driving experience was 13.5 years, ranging from 3 to 44 years. All drivers held a full UK driving license with no recent major endorsements and reported that they drove approximately average mileages per year of 10–12 thousand miles. All drivers in the sample have, therefore, been exposed to many hundreds of hours of driving task performance. Participants were members of the public recruited through mail shoots and adverts but in order to ensure the degree of homogeneity sought, all drivers were screened using the Driving Style Questionnaire (DSQ; West et al., 1992). This is a 30-item questionnaire from which six driving style dimensions are extracted: speed, calmness, planning, focus, social resistance and deviance using a six point scale ($1 = never engage in this behaviour, 6 = always engage in this behaviour$). The mean DSQ score was 3.25 ($SD = 1.63$). Two of an original pool of 15 drivers were excluded for mean scores that exceeded $\pm 1$ standard deviation.

2.3. Materials

Twelve cars of mixed type (from sports coupes to people carriers/MPVs) were used in the study. Car drivers were audio recorded whilst they drove using a microphone and laptop computer. The on-road route is contained within the West London area of Surrey and Berkshire and was 14.5 miles in length not including an initial three mile stretch used to warm up participants. The route is comprised of one motorway section (70 mph speed limit for 2 miles), seven stretches of major road (50/60 mph speed limits for 6 miles), two stretches of rural road (60 mph speed limit for 3 miles), three stretches of urban roads (40 mph limit for 1 mile), one residential section (30 mph limit for 1 mile), and fifteen junctions (>30 mph speeds for 1 mile). Experimental runs took place at 10:30 in the morning and 2:30 in the afternoon (Monday–Thursday day) and 10:30 on Friday. These times avoided peak traffic hours for the area, and all runs were completed in dry weather. Fig. 2 presents a diagram of the route and road types.

2.4. Procedure

Formal ethical consent was obtained from all participants before the study commenced with particular emphasis placed on control of the vehicle and safety of other road users remaining the participants’ responsibility at all times. An instruction sheet on how to perform a verbal commentary was read by the participant, which described that they should drive as they normally would but provide a constant commentary about why they were performing current actions, what information they taking from the environment, how the vehicle is behaving and what actions they plan to take. Drivers were instructed to keep talking even if it appeared to them that what they were saying did not make obvious sense. The experimenter provided examples of the desired form and content that it should take.

There then followed a warm-up phase. A three mile approach to the start of the test route enabled the participants to be practised and advised on how to perform a suitable verbal commentary. This involved providing suggestions and guidance from the passenger seat and pulling over to review the audio transcript and advise where necessary. All participants were able to readily engage in this activity with a mean word per minute rate in excess of 30. Minimal advice was needed. The verbal commentary acted as a form of secondary task and the high rate of verbalizations seem to indicate spare capacity and little grounds to suspect interference with the primary driving task.

During the data collection phase the experimenter remained silent aside from offering route guidance and monitoring the audio capture process. The driver’s, meanwhile, provided a constant verbal commentary as previously instructed. Drivers were de-briefed upon return to the start location.

2.5. Data analysis

The verbal commentary data was then subject to a simple encoding scheme, one that coded phrases non-exclusively into four themes: ‘own behaviour’, ‘behaviour of the vehicle’, ‘road environment’ and ‘other traffic’. Two verbal transcripts, one comprising of 756 items and one of 968, which had been encoded in this way and selected at random were subject to an analysis of inter-rater reliability. Two different analysts performed a blind encoding of each transcript and achieved significant correlations at the 5% level: Rho = 0.7 for analyst one and Rho = 0.9 for analyst two. The performance of the primary analyst over time was also checked (i.e. intra-rater reliability) by an earlier encoding being undertaken again at the end of the analysis phase. A correlation of Rho = 0.95 was achieved across 756 items.

A novel development reported in this paper is the use of a sophisticated software tool called Leximancer™ which automates the creation of semantic networks, and does so with complete repeatability. Leximancer™ uses text representations of natural language in order to create themes, concepts and links. This is achieved by algorithms which refer to an in-built thesaurus on the one hand, and to features of text such as word proximity, quantity and salience on the other. Leximancer™ has been used extensively in previous studies. It has provided insight into organisational change (Rooney et al., 2010), intergroup communication (Hewett et al., 2009), analysis of web content (Coombs, 2010) and large scale meta-analyses of themes within scientific journals (Cretchley et al., 2010). The application of this technique to a more intensive form of analysis based on verbal commentaries of real-life transport contexts is a novel one.

3. Results and discussion

3.1. Semantic networks

The 12 drivers contributed a total of 27,225 words into the analysis ($mean = 4537; SD = 2343$, minimum word count = 1759, maximum = 7531). Across all road types the driver’s spent just over half
the time (54%) talking about factors external to themselves, such as the behaviour of their vehicle, other traffic, and elements of the road environment itself (minimum word count across these categories = 84, maximum = 369). Of these external factors, 42% of the verbalizations refer explicitly to hazards, with the external road environment accounting for 18% (min = 23, max = 130) and, largest of all, other traffic accounting for 24% (min = 59, max = 149). Fig. 3 shows how the verbalizations provided by the individual drivers fell into these categories, and the spread of responses around the mean within each category.

It is possible to view these findings from a higher conceptual level and perceive the systemic, generative nature of the driver–vehicle–road system. For example, the driver’s own behaviour, and that of their vehicle, enables them to ‘sample’ the external road environment (including other traffic), which in turn ‘modifies’ their awareness of that environment, which in turn ‘directs’ further behaviour, and so on according to Neisser’s perceptual cycle model as shown in Fig. 4.

Leximancer™ subjects this raw textual data to six main stages in order to create the semantic networks:

1. Conversion of raw text data (definition of sentence and paragraph boundaries, etc.).
2. Automatic concept identification (keyword extraction based on proximity, frequency and other grammatical parameters).
3. Thesaurus learning (the extent to which collections of concepts ‘travel together’ through the text is quantified and clusters formed).
4. Concept location (blocks of text are tagged with the names of concepts which they may contain).
5. Mapping (a visual representation of the semantic network is produced showing how concepts link to each other).
6. Network analysis (this stage is not a part of the Leximancer™ package but was carried out as an additional step to characterise the structural properties of the semantic networks).

A total of six networks are derived from this process, one for each road type. The networks provide a representation of the knowledge extant in the driver’s working memory as they encountered each environment. They have been produced automatically with complete repeatability from raw verbal transcripts: no manipulation of the data or the process of network creation was undertaken.

In Leximancer™ the nodes in the networks are extracted from the verbal transcripts and are referred to as ‘concepts’. Each one is ascribed a relevance value from 0% to 100%, which is a value derived from the number of times the concept occurs as a proportion of the most frequently occurring concept (Smith, 2003). In total, 174 concepts were extracted from the six semantic networks. In
order to reduce the data to the highest scoring concepts and to avoid the inevitable idiosyncrasies of low scoring, highly personal and infrequently occurring concepts, those which scored lower than two standard deviations of the mean in each individual road-type category were excluded. This gives rise to a high scoring subset of 25. These were used to create Table 1.

What is clear is that marked changes occur in the content of driver SA as they enter and exit different road environments, to such an extent that no concepts are common across them. Table 2 highlights this point. It presents a summary of the limited extent of overlap across all combinations of road types, with a maximum value of only 11.5% (two concepts) occurring between motorways and urban roads. Road type is thus a powerful contingency factor in subsequent driver SA, a finding which accords with the varied literature on Self Explaining Roads.

Analysis of these networks now proceeds on the basis of their structure and content. The structural analysis employs techniques from graph theory to view the semantic networks in terms of nodes \( n \) and edges \( e \). These procedures help to reveal important underlying structural properties of the semantic networks which are not readily apparent from visual inspection alone (i.e. Fig. 5).

The metrics used are: density, diameter and centrality.

Density is given by the formula:

\[
\text{Network density} = \frac{2e}{n(n-1)}
\]

where \( e \) represents the number of edges or links in the semantic network and \( n \) is the number of nodes or semantic concepts. The value of network density ranges from 0 (no concepts connected to any other concepts) to 1 (every concept connected to every other concept; Kakimoto et al., 2006). Density is a metric which refers to the semantic network as a whole and is a measure of its overall level of interconnectivity. Higher levels of interconnectivity suggest a richer set of semantic links and a well integrated set of concepts. A more dense network is also likely to have more well connected concepts and shorter average path lengths. In order to diagnose the latter, a further metric is employed: diameter.

Diameter is given by the formula:

\[
\text{Diameter} = \max_{u \neq v} d(u, v)
\]

where \( d(u, v) \) is “the largest number of [concepts] which must be traversed in order to travel from one [concept] to another when paths which backtrack, detour, or loop are excluded from consideration” (Weisstein, 2008; Harary, 1994). Diameter, like density, is another metric which refers to the network as whole. Generally speaking, the bigger the diameter the more concepts within the semantic network that exist on a particular route through it. Again, generally speaking, a more dense network will have smaller diameter (because the routes across the network are shorter and more direct) while a less dense network will have a larger diameter (as routes across the network have to traverse a number of intervening semantic concepts). This measure is related to the idea of clustering and to individual semantic concepts which are more or less well connected than other concepts. In order to diagnose this facet a further metric is deployed: centrality.

Centrality is given by the formula:

\[
\text{Centrality} = \frac{\sum_{i,j \neq i} e d_{ij}}{\sum_{j} (d_{ij} + \delta_{ij})}
\]

where \( g \) is the number of concepts in the semantic network (its size) and \( \delta_{ij} \) is the number of edges \( e \) the shortest path between concepts \( i \) and \( j \) (or geodesic distance; Houghton et al., 2006). Centrality gives an indication of the prominence that each concept has within the semantic network. Concepts with high centrality have, on average, a short distance (measured in edges) to other concepts, are likely to be well clustered and to be near the centre of the network. Concepts with low centrality are likely to be on the periphery of the network and to be semantically distant from other concepts.

Fig. 5 shows visual representations of the networks that Leximancer™ created. Fig. 6 presents the results of applying density,
diameter and centrality to these six semantic networks, helping to reveal underlying properties that are not readily apparent from Fig. 5 alone. What is evident from Fig. 6 is that the structural metrics have some contingency upon road type.

3.1.1. Motorway

Driver SA in this environment is dominated by concepts which relate to the road environment itself. The concept of ‘lane’ scored 100% and ‘road’ scored 73%. As discussed at length above, motorways represent a form of total environment and are regarded as an exemplar of a self-explaining road. Driver SA seems to mirror this in that the road environment itself seems key to the driver’s awareness. The third highest scoring concept is ‘behind’ (83%). This refers to events that are encroaching from this direction, something which the multi-lane configuration and high speeds of a motorway afford. The clustering of concepts is relatively high (i.e. mean centrality = 14.59), as is the distance across the network (i.e. diameter = 13), and overall the network is quite sparsely interconnected (i.e. density = 0.07). This would seem to suggest that a number of distinct key concepts are simultaneously active in driver’s SA.

3.1.2. Major A/B classification roads

Driver SA in this environment is dominated by one particularly high scoring concept: ‘slow’ (scoring 100%). Relatively speaking, network density is high (0.08) and diameter low (8). Here an individual concept links to most other critical concepts, which seems evident in the other high scoring concept called ‘doing’ (71%), as in “I’m doing 60 mph”. Clearly the awareness of speed, and reductions thereof, colours many other aspects of SA in this setting.

3.1.3. Urban roads

Driver SA in this environment seems to be characterised by other cars (100%) and their interactions. Indeed, a number of other concepts hint at new goals, such as ‘parked’ [car] (48%) and ‘pull’ (as in ‘pulling away’: 70%). Interestingly, the wider environment features in the concept of ‘around’ (48%), e.g. “not sure what the speed limit is around here” or “being a bit cautious around here”. The structural metrics change once more from a dense, well interconnected network influenced by a key concept (i.e. Major A/B classification roads) to a network which is less clustered (12.75) and larger (diameter = 13). Rather than a focus on a critical SA related variable, the awareness seems to widen.

3.1.4. Rural roads

Driver SA in this environment is dominated by road related features, in particular the geometry of the road such as ‘corner’ (100%), ‘hill’ (69%) and ‘bend’ (60%). Linked to this is a greater awareness of the vehicle’s behaviour in this environment, as seen in the emergence of ‘gear’ (91%) and ‘third [gear]’ (60%), along with

<table>
<thead>
<tr>
<th>Table 1</th>
<th>List of behavioural features crossed with road type.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concept</td>
<td>Example</td>
</tr>
<tr>
<td>Ahead</td>
<td>“can’t really see what’s going on ahead”</td>
</tr>
<tr>
<td>Behind</td>
<td>“that guy behind has given us some space”</td>
</tr>
<tr>
<td>Bend</td>
<td>“and just accelerating off round the bend”</td>
</tr>
<tr>
<td>Braking</td>
<td>“braking for junction”</td>
</tr>
<tr>
<td>Car</td>
<td>“noticed hazard lights on car in front”</td>
</tr>
<tr>
<td>Check</td>
<td>“[just checking my blind spot over my right shoulder]”</td>
</tr>
<tr>
<td>Clear</td>
<td>“it’s all clear ahead”</td>
</tr>
<tr>
<td>Coming</td>
<td>“am, because there’s no other cars coming”</td>
</tr>
<tr>
<td>Corner</td>
<td>“got this corner here, looks a bit narrow”</td>
</tr>
<tr>
<td>Doing</td>
<td>“speed limit here is 60, but we’re only doing 40”</td>
</tr>
<tr>
<td>Fourth</td>
<td>“into fourth, 30mph”</td>
</tr>
<tr>
<td>Front</td>
<td>“the Volvo in front isn’t gaining any road speed noticeably”</td>
</tr>
<tr>
<td>Gear</td>
<td>“so we’re in 5th gear cruising along at 45 now”</td>
</tr>
<tr>
<td>Hill</td>
<td>“accelerating more to get up hill”</td>
</tr>
<tr>
<td>Indicating</td>
<td>“indicating left”</td>
</tr>
<tr>
<td>Lane</td>
<td>“as I observe the, er, stay in lane command, or whatever it is”</td>
</tr>
<tr>
<td>Mirrors</td>
<td>“just occasionally checking the mirrors”</td>
</tr>
<tr>
<td>MPH</td>
<td>“now a 60mph limit”</td>
</tr>
<tr>
<td>Parked</td>
<td>“want to keep a good distance from the parked cars”</td>
</tr>
<tr>
<td>Pull</td>
<td>“but it pulls along quite nicely”</td>
</tr>
<tr>
<td>Road</td>
<td>“road narrows at this point”</td>
</tr>
<tr>
<td>Around</td>
<td>“not sure what the speed limit is around here”</td>
</tr>
<tr>
<td>Slow</td>
<td>“so I’ll slow down”</td>
</tr>
<tr>
<td>Take</td>
<td>“just gonna take it easy”</td>
</tr>
<tr>
<td>Third</td>
<td>“keep it in third for a minute”</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 2</th>
<th>Summary table of behavioural features and their extent of overlap across road types.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Motorway</td>
</tr>
<tr>
<td>Motorways</td>
<td>3.8</td>
</tr>
<tr>
<td>A/B roads</td>
<td>3.8</td>
</tr>
<tr>
<td>Urban roads</td>
<td>11.5</td>
</tr>
<tr>
<td>Rural roads</td>
<td>0.0</td>
</tr>
<tr>
<td>Residential roads</td>
<td>7.7</td>
</tr>
<tr>
<td>Junctions</td>
<td>0.0</td>
</tr>
<tr>
<td>Total</td>
<td>23.1</td>
</tr>
</tbody>
</table>
the compensatory behaviours required, e.g. ‘slow’ (89%). Interestingly, rural roads feature the largest number of concepts which lie two standard deviations above the mean, indicating that the content of SA is comprised of numerous highly relevant elements. This is borne out by the lowest score for mean centrality (10.82), which is indicative of a spread of equally important concepts rather than one or two highly important ones. An interesting feature of the structural measures is that this spread of important concepts is not necessarily well interconnected (i.e. density is second lowest at 0.06). This seems to indicate a more discrete set of temporal events, one’s that are not necessarily linked to each other in the same way that concepts are inter-related in other situations.

3.1.5. Residential roads

Unlike rural roads, residential roads have the fewest number of concepts two standard deviations above the mean. Unlike major A/B classification roads where a single concept is dominant and interconnected, three critical variables emerge: other cars (100%), behind (50%) and pull [out or away] (38%). The focus seems to have switched from concepts related to the road infrastructure to instead deal with interactions with other vehicles (e.g. avoiding parked cars) and aspects related to vehicle control and maneuvering. Interestingly, whilst the content is different, the structure of the network is similar to motorways (diameter = 13; density = 0.07; mean centrality = 14.11). This would also seem to suggest that a number of distinct key concepts are active in driver’s SA simultaneously.

3.1.6. Junctions

Driver SA in this context is characterised by check[ing] (100%), clear (71%), indicating (69%) and mirrors (48%). Again, whilst the road infrastructure itself is cueing these elements, driver awareness seems more focused on other traffic than on features of the junction itself. That said, throughout the verbal transcripts words and phrases like ‘t-junction’, ‘roundabout’ and ‘slip road’ occur quite frequently. The key point seems to be that it’s the behaviour of other traffic in these situations that is more important for driver SA. The distance across this network is small (9) with density (0.07) and mean centrality (12.01) both moderate. These characteristics are similar to those for major A/B classification roads, again suggesting a focus on specific critical concepts which influence the network as a whole.

3.2. Speed envelope

The on road study paradigm grants an opportunity to tentatively explore how the content and structure of driver SA relates to actual driving behaviour. In an imaginary, and implausible, case of drivers sticking rigidly to the posted speed limits (and being able

![Fig. 5. Visual representation of the semantic networks created by Leximancer™ based directly on driver’s verbal commentaries as they encountered each of the six road types present in the study. Based on visual inspection alone it is evident that not only is the content of the networks changing but also the structure. These changes are in turn associated with the evolving, generative nature of driver SA within a dynamic environment.](image)

![Fig. 6. Radar plots of network density, diameter and centrality and their contingency upon road type.](image)
to do so regardless of road and traffic conditions) then the time to complete the 14.5 mile course would be exactly 20 min. In the event, drivers completed the course in a mean time of 26 min 29 s (min = 23:10, max = 32:56, SD = 1:50) at a mean speed of 31.08 mph. A null hypothesis based on a literal interpretation of posted speed limits is too simplistic. More tenable is that the inevitable differences in posted versus actual speeds should show no marked contingency on road type. This supposition can be upheld based on the control measures taken in the study, and that no drive was significantly impeded by traffic, weather or other external factors.

Fig. 7 shows that an alternative hypothesis is required to account for the results obtained.

Table 3 shows that the biggest absolute difference in posted versus actual speeds occurs on major A/B classification roads, with a mean difference of 14.8 mph representing 32.8% of the posted speed limit for that stretch. This is followed by residential roads, which despite showing a small difference of 6.6 mph actually represents 28.3% of the posted limit. In other words, on average drivers were electing to travel at approximately 23 mph instead of the permissible 30 mph. At the opposite end of the speed scale motorways, with a posted limit of 70 mph, showed virtually no difference in posted versus actual speeds (0.8 mph/1.1%).

These findings are consistent with the discussion above on the self-explaining nature of motorways, and lend a degree of construct validity to the study. Clearly this is an environment in which the context is well matched to driver expectations and intentions, and is an effect that can be readily detected in on-road settings. The data also agrees with the extant work on SER in non-motorway situations. Here the context appears less well matched to driver expectations and intentions, and adaptations in speed seem indicative of this. As noted above, the marked drop in actual versus posted speeds for major A/B classification roads seems to be associated with SA that is also orientated around the concept of speed. Again, this lends a further degree of construct validity.

### 3.3. Hazard incident rate and density

Hazards are defined as any object or entity that has the potential to cause a driver to change direction or speed (Coyne, 2000). When drivers are asked to provide a verbal commentary they are, in effect, talking out-loud about objects or entities with the potential to cause them to change direction or speed and the decisions and behaviours they are enacting in respect to them. Hazard incident rate (HIR) is a term employed in Police and advanced driver training and is a reflection of the temporal nature and pacing of hazards. Based on the analysis above it becomes possible to calculate a crude hazard incident rate (HIR) based on individually encoded items related to the external environment. HIR can be measured in hazards per hour whilst Hazard Incident Density (HID) can be measured in hazards per mile.

Fig. 8 shows an interesting relationship between speed adaptations and hazard incident rate (HIR). Broadly speaking, the hazard incident rate increases across different non-motorway road types. Similarly, as the hazards per hour increase, speeds adapt in a downward direction. Thus for motorways (478 hazards per hour) the speed is 69.23 mph whereas for residential roads (1564 hazards per hour) the speed is 23.38 mph. The overall pattern suggests, once more, that drivers are using their SA to interpret the road context and adapt their behaviour to suit. However, whilst the overall pattern suggests a favourable downward adaptation, the speed versus hazard incident rate for the most behaviourally compatible road type, motorways, suggests that speeds should, if
of the work and build a more complete picture of how roads are interpreted by different sections of the driving population. Other limitations include the challenge of maintaining validity in the interpretation of network content and structure. Likewise, the effect of one road type priming the sorts of awareness subsequently developed in another requires further consideration in future studies. In addition to all this come the inevitable vagaries of conducting studies in on-road settings and the limitations on experimental control that this environment connotes. Clearly, the work reported in this paper is not mature enough in itself to directly inform engineering interventions on a large scale, but they are sufficiently well developed to enable new hypotheses to be developed and for further experiments to be conducted. The key insights offered by this work include a theoretically robust method of extracting cognitively salient features from road environments, one that goes beyond the current state of the art involving picture sorting tasks, questionnaires and other indirect methods to instead perform the study with high levels of ecological validity ‘on the road’. From the cognitively salient features that have been extracted it is clear that a strong systemic relationship exists not just between drivers and road environments, but also other drivers and their vehicles. It appears that road design can influence drivers both directly (in terms of how they perceive it and behave) and indirectly (in terms of how it affects other drivers, and how in turn other drivers behave in that context). Future studies will employ these results to establish whether the endemic road features detected by the current method represent a good focus for design interventions. The current study also provides a useful baseline, wherein upon it will be interesting to note the structural and content based changes in SA (via semantic networks) that result from drivers experiencing redesigned roads. Indeed, a method for undertaking such redesigns will be the SA design guidance referred to at the beginning of this paper. The long term research vision is to build on these findings and equip road safety professionals with a means to ‘analytically prototype’ a given road scheme with regard to its cognitive compatibility with drivers. A form of ‘route drivability’ tool is the ultimate goal to which this early research speaks. For the time being, a worthwhile methodological and theoretical advance has been made, with great potential for insightful safety related benefits in real world settings.

4. Conclusions

This paper has attempted to build on the maturing field of SA within the safety domain, and to put the concept in touch with the practical engineering problem of safer road infrastructure design. An argument has been put forward that SA could be a valuable adjunct to the developing strand of work in Self Explaining Roads and the results gained are broadly consistent with this. The study is exploratory in nature, but it succeeds in applying a sophisticated approach to SA in a real-world setting, unearthing cognitively salient features of road infrastructure, and tentatively exploring whether the SA that drivers develop is linked to appropriate driving behaviours. As an exploratory study it is right to reflect on some of the inherent limitations. Foremost amongst these include the efficacy of the verbal commentary method to elicit insights into cognitive processes, especially if some of those processes are implicit in nature. Further work of a more fundamental nature is planned in which it is possible to capitalise on the strengths of the network based approach in terms of inferring implicit structures from the linkages between nodes. Another strand of work is to examine the use of behavioural metrics and other data sources to complement the verbal commentary method, all of which can be combined within the network based paradigm. As it is, the role of implicit knowledge is one that is troubling for a broad swathe of SA research, but the methods proposed in the current study are by no means inconsistent with future developments in this area. Another principle limitation is the use of a small homogenous sample. Having established the sought after linkages between SA and SER, it is now possible to increase the scope and ambition anything, be more negatively adapted. For example, for the hazard incident rate for residential roads to match that of motorways, the downward adaptation in speed would have to be greater than the on-road data suggests: 7.14 mph instead of 23.38 mph. Drivers seem best able to manage this in respect to major A/B classification roads, where the difference in actual and ‘ideal’ speed is only 4.22 mph (or 9.33%). This rises dramatically as the roads reduce in status, reaching a difference between actual versus ‘ideal’ for residential roads of 69.43%. This is a very crude indicator, with many extraneous and other variables to take into consideration. There is a need, therefore, to not overstate the case. Nevertheless, when this difference between actual and ‘ideal’ speeds is plotted onto a graph (e.g. Fig. 9) a powerful trend emerges, one that looks like a progressive uncoupling of the perceived state of the situation from the actual state.

References

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