Validating Sociotechnical Systems' Requirements through Immersion

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Abstract: One of the most critical phases in complex socio-technical system development is the validation of non-functional requirements (NFR). During this phase, system designers need to verify that the proposed system's NFRs will be satisfied. A special type of NFRs which is often ignored regards the Human Factors (HF) NFRs. These requirements are of vital importance to socio-technical systems since they affect the safety and reliability of human agents within such systems. This paper presents a scenario-based approach for validating HF NFRs using VR CAVE simulation. A case study is used to demonstrate the application of the method in the validation of the situation awareness NFR of an in-vehicle Smart driver assistive technology (SDAT). Such systems aim to alleviate accident risks by improving the driver's situation awareness by drawing their attention on critical information cues that improve decision making. The assessment of the HF NFR is achieved through an experiment with users in a virtual environment. This work describes and demonstrates a method that utilizes a custom-made, modular 3D simulator that uses a number of hazardous scenarios, for the validation of the HF NFRs of prospective systems.

1 INTRODUCTION

Requirements validation constitutes an important facet of a successful system development. Unlike functional requirements, which can be deterministically validated, non-functional requirements (NFRs) are considered as soft/latent variables not directly observed or implemented; instead, they are satisfied (Zhu et al., 2012) by functional requirements. Despite their importance, NFRs are usually addressed at a late stage of system development, whilst functional requirements are considered at the early phase of software development (Marew, 2009). Therefore, the initial stages of a system's specification may not address the NFRs adequately, which could lead to system failure once the system has been commissioned (Adams et al., 2015). NFR analysis approaches range from unstructured and informal, to highly formal and mathematically-driven. The former include approaches such as KAOS (Nwokeji et al., 2014), a goal-oriented software requirements capturing approach. In the same vein, i* approach (Chung et al., 2000) uses goals and enables the quantification of requirements from goal diagrams. The latter category includes formal methods based on model checking such as Z, Markov, and queuing models (Matoussi, 2008).

This paper introduces a Human Factors (HF) requirements validation method that exploits scenario-based testing through immersion. The application of the methodology is demonstrated through a case study on the analysis of the situation awareness NFR of a future smart driver assistive technology (SDAT). The uses a custom made virtual reality (VR) simulator that mimics the environment and models prototype SDATs using 3D visualizations that simulate the candidate designs.

The paper next reviews the literature in NFR assessment, HF and situation awareness (SA). This is followed by the NFR validation methodology. Next a case study demonstrates the application of the HF NFR validation method, followed by analysis of the data from the experiment and presentation of the emerging results. The paper concludes with a brief discussion of methodological and substantial implications.

2 LITERATURE REVIEW

The majority of NFRs in complex socio-technical systems address system properties such as performance, reliability and security. However, there is an additional dimension that needs to be analysed,

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which is the human dimension. By definition a socio-technical system exhibits both technical and social complexity. These systems are composed of human and machine entities that work together to accomplish a common goal. Transportation systems belong to this category of complex systems since they incorporate vehicles, drivers, road infrastructure and intelligent systems in vehicles. The technical aspects of these in-vehicle systems refer to the functional requirements of machine agents and the human-machine interaction metaphors. The social facet of the system relates to human factors and the associated human performance constraints. Thus, designing such complex systems requires the investigation of all facets. The technical dimension is addressed by the functional requirements and the system NFRs, while the human dimension is influenced by HF NFRs. These are defined by human agent limitations affected by the diverse nature of human characteristics, such as ability, stress, concentration, SA etc. However, despite their importance as a critical cause of systems failure, human factors have not been adequately considered by practitioners during the design, development, and testing of systems (Gregoriades, 2004).

Moreover, even though human factors and requirements have a lot to share, only a few studies apply human factors knowledge to requirements engineering. While NFR such as performance, security and maintainability are considered for software functions, NFRs for people, such as SA and workload, have received less attention. Such requirements have been proven very significant in preventing system failure, articulated in the form of accidents in complex systems such as transportation (Gregoriades, 2010). Therefore, the systematic analysis of this type of NFRs prior to any system implementation is considered vital. The main problem in validating these requirements is the need for a detailed specification of the envisioned system or the implementation of a prototype system. Both of these activities are time consuming and expensive. The former requires formal methods which are hard to comprehend by stakeholders and the latter requires time effort and cost. Once either of the two is realised it is possible to perform an analysis of system behaviour under a number of test scenarios. Formal methods, though, suffer from being too specific, hence their application in validating NFRs is constrained. Prototyping, on the other hand, provides a more generic model based on which different facets of the system can be tested such as people, technology and tasks. This, however, is expensive and risky. Therefore, the use of a simulated environment for requirements analysis saves the costs of prototypes, especially for complex systems (Sutcliffe et al., 2004) and makes the process safe. This approach, employed in this study, enables testing technological solutions and the evaluation of their effect prior to implementation.

Designing complex systems such as the smart in-vehicle information systems requires the effective and efficient management of requirements. The inappropriate specification of functional and non-functional requirements increase dramatically the risk of failing to meet customer needs (Peng, 2012). Functional requirements have received much attention in this process, while, NFRs have been more or less deliberately ignored (Illa, 2000). This led to a lot of systems failing due to improper management of NFRs. Past research addressed extensively different sets of NFRs along with frameworks of NFR such as Softgoal Interdependency Graphs (SIGs) (Zhu, 2012).

NFR validation has attracted significant attention in recent years due to the importance of NFRs in overall system acceptance. Traditional approaches to NFR validation include prototyping and inspection. Recent approaches focus on the quantitative analysis of NFRs. In our previous work we used a Bayesian Networks (BN) approach to model NFRs using knowledge elicited from the domain (Gregoriades, 2005). NFRs are assessed based on a scenario generation and evaluation algorithm that runs the BN with different input. The output is a quantitative estimation of the satisfiability of the NFR. Other groups (Zayaraz et al., 2005; Sadana et al., 2007) also used a quantitative model to analyze conflicts among NFRs. This approach, however, is limited to high level architectural requirements. In the same vein, Marew and colleagues (Marew et al., 2009) used Quantified Softgoal Interdependency Graphs (QSIGs) to assess the degree of softgoal satisfaction. However, the assessment of QSIGs is based on subjective estimates of the degree of interdependencies among softgoals. Similarly, Zhu et al. (2012) apply fuzzy qualitative and quantitative softgoal interdependency graphs for NFRs tradeoff analysis. Based on the above, it is evident that NFRs assessment is an ongoing research issue. The growing ubiquity of complex sociotechnical systems led to more NFRs to be analysed during systems' design phase. One example of such NFRs is safety which is addressed in this study and expressed in terms of accidents.

2.1 Human Factors & Requirements

NFRs such as performance and maintainability are specified for software or hardware systems. NFRs for people, such as SA and workload, have received less attention. These requirements, however, have been proven very crucial in preventing system failure. Specifically, in transportation, road accidents are usually attributed to human error (Fuller, 2002; Theeuwes et al., 2012) that is induced from low SA caused by increased workload. Humans, as information processing systems, have a number of information flow channels (visual, auditory, tactile) processing various information sources (e.g. a navigation system display, the forward view through the windscreen) of varied bandwidths (e.g. high-density traffic will require a higher sampling rate than low-density traffic). Our cognitive capacity is limited, and consequently there is an upper threshold to the amount of information we can process per second and channel (Endlsey, 2000; Fuller, 2002; Holohan et al., 1978). Therefore, we tend to share our attention among a few information sources. An overloaded driver is less likely to deal effectively with an unexpected event (Konstantopoulos et al., 2010). Fuller (2012) also expresses accident risk as a function of the driver's cognitive resources and task-demand in the driver-road system.

Therefore, the systematic analysis of these HF NFRs prior to any system implementation is considered vital. The main problem in evaluating these requirements is the need to implement a prototype design of a hardware-software system, which is expensive (Stone et al., 2001). Hence, the use of virtual reality (VR) settings is becoming very popular. One of the most important applications of VR technology has been the use of virtual prototypes for functional requirements analysis (Sutcliffe et al., 2004). However, the use of VR for HF requirements analysis has not been addressed. Essentially, HF requirements can be expressed in terms of a threshold value that defines their minimum quantification or satisfaction level. These define the cognitive and physical capabilities of humans. These capabilities are put to the test when processing dynamically changing information during driving. If these capabilities are reached then this in effect increases the likelihood of committing an error due to high workload. Workload, however, is directly related to SA; the link between the two has been previously established (Gregoriades et al., 2007). When the perceived information increases people tend to prioritise which increases the risk of an incorrect comprehension. In traffic safety, SA constitutes a major critical factor, since it provides the driver with the ability to anticipate events given perceived driving and environmental conditions.

Validating HF requirements for such systems makes the use of VR simulators inevitable due to the complexity, effort and cost associated with the development of prototypes. In the same vein, controlling infrastructural parameters in the real world is unethical. Moreover, ruling out confounding effects to examine the influence of control measures on HF is very difficult in field experiments. Driving simulators provide the researcher with a powerful tool to test driving behaviour under controlled settings. Apart from the usually high cost of the simulator, outsourcing of experiments to analyse driving behaviour using native users is difficult, if not impossible in some cases, due to the large number of subjects needed for reliable results. On the other hand, low cost driving simulators do not provide a sufficient level of realism to analyse human factors. Unrealistic conditions may affect the driving behaviour which effectively could influence the validity of the experimental study. The method proposed herein demonstrates the design of a driving simulator that exploits 3D modelling tools in a scenario-based approach to promote realism and interactive representation of road networks. The approach simplifies the process of implementing 3D road infrastructure models through the utilization of reusable modules that represent different in-vehicle technologies or infrastructural components. This simplifies the process of designing/modifying the simulation model by reusing model constructs in a plug and play fashion, which enables the analyst to easily design a range of experimental conditions (i.e. scenarios), to evaluate assumptions and hypotheses from different perspectives.

2.2 Situation Awareness

SA constitutes a major critical factor in complex socio-technical systems. In transportation, it provides the driver with the ability to anticipate events given perceived driving and environmental conditions. SA defines the process of perceiving information from the environment (level 1), comprehending its meaning (level 2) and projecting it into the future (level 3). SDAT have been developed to alleviate accident risk by either reducing driver workload or assessing driver attentiveness. Examples include adaptive cruise control, collision notification, driver monitoring, traffic signal recognition, night vision, lane departure warning systems and blind spot monitoring. Such systems aim to draw drivers' attention on critical cues that improve their decision making. However, they only provide limited support to SA since they address isolated factors and in some cases with negative effect due to the extra information load they incur to the driver. The first step in improving drivers' SA is to enhance their capability of perceiving and interpreting traffic and environmental conditions (i.e. level 1 and 2 of the aforementioned SA model). However, such smart systems facilitate level 3 SA for navigation, which might decrease drivers' attention, due to secondary task execution, that could lead to reduced level 1 SA. This could undermine attention to operational or tactical driving activities (e.g. braking, lane changing, gap acceptance etc.). To that end, three important issues need to be addressed prior to any SDAT development: (i) identification of drivers' information needs that could enhance SA, (ii) the specification of a SDAT feedback metaphor (feedback type and appropriate time for issuing warnings) to support those needs without impairing driver attention, and (iii) the evaluation of the effect of a prospective SDAT on traffic safety. This is a complex process and in most cases is only feasible once a prototype of the system is available.

Endlsey et al. (2012) warn socio-technical system designers of the importance of maintaining SA in complex systems and draw attention on the issues that could inhibit SA. One of the most important strains of SA is information overload. Too much information at any point in time hinders human operators' adequate SA. Overloading divides the decision maker's attention among numerous stimuli resulting in increased demand for cognitive resources. This is known as attentional tunnelling (Endlsey, 2012) and results in reduced information scanning capability.

3 NFR VALIDATION METHOD

The proposed NFR validation method is based on the design science (Hevner et al., 2010) paradigm, and in particular its evaluation phase which investigates the effectiveness of an artefact and guides its re-design through changes in specification. Design science synthesises the sciences of the artificial, engineering design, information systems development, system development as a research methodology, and executive information system design theory for the building and evaluating of IT artefacts for specific problems (Hevner et al., 2010). The design and development of new artefacts such as the SDAT, described herein, requires a systematic approach towards artefact design, development and evaluation. This aims to assure that the artefact contributes towards resolving a particular problem.

The method is composed of a number of steps that are executed both in sequence and in parallel at certain stages. Initially, the problem needs to be expressed in terms of human factors specification. This could be articulated in terms of human performance and human reliability, and in particular, as the acceptable SA and workload levels of human agents in a system. These are conditions that could incur high likelihood of human error (Gregoriades, 2010). Once the problem to be analysed is clearly stated and the critical HF NFRs are identified, then the minimum level NFR satisfiability needs to be set. The refinement of HF NFRs into functional specifications which when realised will guarantee the satisfaction of the NFR comes next. This is achieved using a combination of domain knowledge and input from subject matter experts. For instance, guidelines for enhanced SA, as specified by Endlsey (2012), are expressed in terms of information requirements, visualisation metaphors and interaction styles which are functional requirements that the SDAT should have. The next step in the process is the specification of the test scenarios, based on which the artefact is going to be evaluated. Grounded within the problem to be analysed, the goals of the desired virtual environment are set. Accordingly, specifications of the virtual environment to be used for the evaluation of the artefact are also set. During this stage a generic VR simulator is customized based on the above goals, to model the problems in question. The customization of the simulator is composed of three steps: 1) the development of the test environment in terms of buildings, infrastructure and traffic conditions. 2) The modelling of the scenarios, as described by the domain experts; these include atypical events in the simulation that would stress test the subjects in the experiment. 3) The modelling of the virtual version of the artefacts under scrutiny. Prior to its use, the VR simulator needs to be validated against a number of factors such as realism, to guarantee the correctness of the NFR assessment. NFRs quantification is achieved through an experiment with users in the VR environment. The specification of the experiment is defined by an HF expert. The assessment of NFR is then refined into phenotype behaviours that can be monitored in a driving simulator. Phenotype driving behaviours are monitored and logged into the systems database. The logged observations from the simulation are pre-processed, analysed and subsequently collated into a single metric that corresponds to the assessed NFR. The NFR assessment is compared against the desired NFR level. If the minimum level of NFR is not satisfied then the virtual artefact under scrutiny needs to be redesigned. The process is repeated until the NFR is satisfied.

4 CASE STUDY

To demonstrate the application of the method, a case study was conducted for the validation of the SA NFRs of a future SDAT. The NFR evaluation method is based on the paradigm of scenario-based testing. In each scenario, participants were required to drive through a pre-specified path on a road network. Throughout the driving task, participants had to respond to emerging hazardous situations. Situational cues were visualised through the SDAT in the form of a virtual augmented reality head-up display (HUD) interface within the virtual vehicle. The SDAT interface was designed based on identified driver information requirements and domain knowledge (Endlsey, 2012). SDAT designs aimed to address drivers' information needs for better SA. Specifically, vehicle's peripheral traffic, road works, road signs and approaching traffic jam were projected through the virtual SDAT. The goal was to assess the effect of each SDAT design on drivers' SA. Satisfiability of SA NFR is specified as an improvement in drivers' SA using SDAT compared to no SDAT use, and is specified as a threshold value. Two SDAT designs were developed using Endlsey's (2012) design principles for SA support. The functional requirements of the SDAT systems have been implemented using the guidelines of: information prioritization, timeliness and relevance of information, information filtering, familiarity of the visual metaphors, and presentation of information in the right context. These aim to alleviate information overload, reduce display density, enhance driver's ability to comprehend the meaning of information and finally assist in developing projections of the situation into the future. The SDATs utilise the above through fusion of vast amount of information from the environment into meaningful attentional directives/cues that describe the driving situation in real-time.

Figure 1: The driving simulator in the VR CAVE. A participant doing the experiment while being observed by researchers.

As part of the NFR validation method, the first step is the design and implementation of the driving simulator. Figure 1 illustrates the developed simulator in VR CAVE that enables the stereoscopic interaction of participants with the experimental conditions.

Participants are immersed with the experimental scenarios through a combination of augmented reality and tangible interaction styles, for a more realistic experience. The second step in the method is the design of the virtual prototype SDAT systems in the virtual environment. The development of the virtual SDATs is realized using a scripting language. The virtual SDAT had to abide to the functional requirements specified in previous steps. The third step is the specification of the hazardous scenarios.

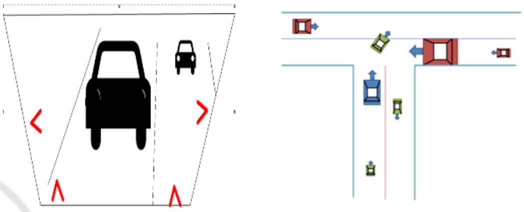

Figure 2: The radar design (right) and information prioritisation –arrow design (left).

The user interface of SDAT systems is of paramount importance in improving SA. Hence, it was designed to provide blind-spot information and to alert drivers of unseen imminent threats. The system uses a combination of HUD with augmented reality capabilities, so that the direction of the threat is clearly comprehended by drivers. The information architecture of the UI aimed to provide the driver with enhanced peripheral vision with a dynamic assessment of the most critical entities within the immediate periphery of the vehicle. The blue print designs of the candidate systems are depicted in Figure 2. In the first design (radar), the host vehicle is shown in a circle (in blue) surrounded by red and green vehicles of different sizes. The size and colour of surrounding vehicles denotes the level of risk. Hence, vehicles that are in the driver's blind spot are considered high risk and are represented by big red icons. Low risk cars are depicted with small green icons. High proximity or hidden vehicles at intersections are also high risk and hence are shown as big and red. Surrounding vehicles' positions and speeds can be obtained from on-board vehicle sensors. Vehicles at intersections can be obtained through vehicle-to-vehicle communication protocol. The prototype visualization metaphor presented in Figure 2 is depicted on the vehicles windshield. The second design (arrows) of the system is based on the need to prioritize information based on risk level and aims to warn drivers of vehicles that are expected to emerge from side roads and are not yet visible or vehicles that are in driver's blind spot. This, as illustrated in Figure 2, is expressed using arrows, on the augmented reality windscreen, pointing to the direction of the imminent threat, and is depicted on the vehicle's smart windshield. The most critical threat is depicted on the screen so as not to split the attention of the drivers among competing risks. This gives extra time to drivers to react to critical situations

The assessment of SA is achieved through an experiment with subjects using the developed driving simulator and virtual SDAT in a 3D CAVE facility. During this stage, 17 participants were involved, each spending on average of 90 min to complete the experiment in the VR CAVE lab. The analysis of the data collected from the experiments aimed to assess the SA NFR for the two candidate SDAT designs.

Data was collected in three phases: before, during and after the experiment. During the pre-experimental phase, the Manchester Driving Style questionnaire (Reason et al., 1990) was used to elicit the driving style of participants along with their demographic information. At the post experimental phase, data collection focused on the evaluation of the two candidate designs using a series of questions on four constructs: functionality, information visualization, usability and usefulness. During the experiment, participants' SA was measured while they were driving in a pre-specified route in the artificial road network within the 3D driving simulator (Figure 1), both with and without the SDATs. In particular, participants were asked to consult the HUD SDAT as during the driving simulation surrounding vehicles engaged the host vehicle by either pulling in or stopping in front of the driver. During the drivers' engagement with the experimental conditions, phenotype behavioural data related to driver workload and SA was recorded. Driver related data was recorded in a log-file on a simulation time-step basis. Specifically, manifestations of workload, such as lateral deviations (Montella et al., 2011), attention level through an electroencephalography (EEG) measurement, lane change, headway, speed, acceleration, deceleration, breaking patterns and steering wheel angle, were recorded on a time-location log-file. Collected data was automatically assigned to road sections that were specified in advance by the analysts, based on infrastructural properties. The assessment of the drivers' SA was achieved using the SAGAT (Situation awareness global assessment technique) method, which uses objective measures of SA gathered during an interruption in task performance. Hence, during each scenario with the participant, the simulation was stopped (freeze) three times, at points on the road network where the three dangerous scenarios were unfolding (car pulling in from the left, car stopping in front, car pulling in from the right). At each simulation freeze, participants were asked to complete a questionnaire that inquired their understanding of the situation. During the freeze, the simulators screens were blank. The simulator saved several screenshot of the situation just before the freeze to enable the comparison between the 'actual' event and the subjects' perceived situation.

5 RESULTS

Data collected from the simulations were pre-processed and analysed to identify differences between the actual situation and the participants' perceptions of the situation under the three conditions and the three interventions (phases). Analysis was conducted on both the post-experiment and the experiment data. Results from the post experiment data revealed that both SA enhancement systems were perceived by the users as improvements over the control condition (i.e. without any enhancement). Specifically, the post-experiment questionnaire addressed the following dimensions of each candidate design: features, user interface, ease of learning, system capabilities, usefulness, ease of use, and SA. Each dimension was supported on average by 5 questions, on a 7 point response scale from 1 (negative effect) to 7 (positive effect). To increase the discrimination in the evaluators' judgment, participants' were asked to report the reasons for their choices and any interaction problems they had experienced under the relevant heuristic. Figure 3 shows the percentages of positive responses (i.e. >4, or <4 for negatively worded statements) for each of the measured dimension on which the two designs were evaluated. Based on this analysis, there do not seem to be noticeable differences in regards to user interface and ease of use. However, overall the radar design seems to have been perceived more positively than the arrows, especially in relation to learning, system capabilities, and usefulness. This might be attributed to the small size of the arrows that were popping up on the smart windshield. Among the two designs the radar design was also considered more appropriate to support driver SA. Moreover, based on open responses from participants, in certain occasions, the number of arrows that were present on the windshield were more than two. Hence, the cues were becoming destructing rather than informative. On the other hand, the Radar design also had its shortcoming in terms of visualization of the threats. Specifically, the colouring and size of threats were considered insufficient.

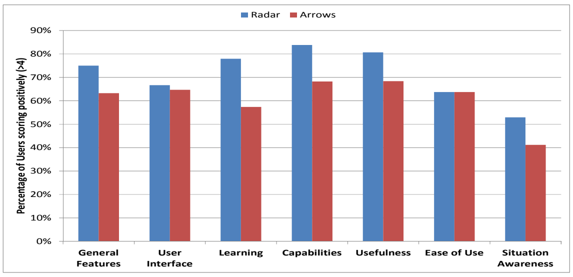

Figure 3: Percentages of positive responses in each of the measured dimensions, by design.

Results from data during the experiment aimed to assess the SA NFR using a combination of the SAGAT data and the driver behaviour data from the simulation log files. Initially the SAGAT and the driver behaviour data were integrated into one dataset for each participant. Subsequently the data that represented the actual situation was compared with the data that represented the perceived situation for each participant at each phase of the experiment. The similarity assessment between actual and perceived was estimated using the Euclidian distance metric. Analysis of the SA data was then performed using ANOVA in a within-subjects model. Based on the results, the use of both SDAT designs in an augmented reality overhead display demonstrated a superior performance to no-design. Results from the SAGAT analysis also revealed that design 1 (radar) was superior to design 2(arrows) and no design. This was identified as significant based on figure 4. In the same vein, the phase of the simulation freeze, denoting the sequence of the freeze, was also identified as a significant factor with phase 3 in the radar design having on average a SA metric of 85% compared to 63% in the control condition (no design).

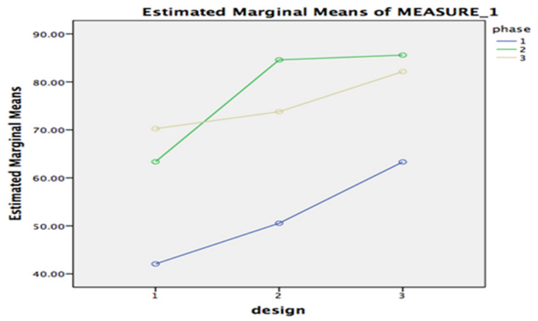

Figure 4: Estimated marginal mean for the 3 designs (radar -1, arrows-2, no-design-3) and the three phases of the simulation (freeze1-3).

6 CONCLUSIONS

The HF NFR validation method presented herein provides a novel cost effective solution to validating HF NFRs of prospective complex sociotechnical systems. It enables the evaluation of NFRs through experimentation in VR settings under an envelope of test scenarios. The developed driving simulator is component-based and hence enables the requirements engineer to easily customize it to the problem in hand. Requirements are realised in virtual settings and this provides designers with the flexibility of customizing the functionality of the SDAT in an attempt to satisfy the HF NFR under consideration. Results from the application of this method in the validation of the SA NFR of an in-vehicle SDAT revealed the method's practicality. The method is based on design science and encourages the redesign of the artefact until it satisfies the NFR. Results indicate that what the users experience during their interaction with the artefact and what they perceived of this experience as reported in the post-test questionnaire point to the same conclusion. Specifically, statistical analysis of the data collected indicated that the radar design is superior to arrows and no design. Similarly, subjective evaluation of the candidate designs also revealed the same results. Hence, this agreement is a good indication that the NFR validation method is producing accurate estimations. Limitations of this work concentrate on the simulator's level of realism and immersion factors that laboratory methods suffer from. Simulated settings do not currently offer the resolution of the real world, and so they may affect driving behavior. Future work will include the improvement of the realism factor which in turn will improve observational accuracy. Moreover, the experimental design for the evaluation of the SA was very time consuming. This could be optimized though the use of a cut down version of the SAGAT questionnaire.

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