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# The application of a systems thinking design toolkit to improve situation awareness and safety at road intersections

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**Abstract**

Incompatibility in situation awareness at intersections has been identified as playing a role in road crashes. One of the key factors underpinning these incompatibilities is the design of the road environment. In this study, findings from the analysis of road user situation awareness using schema theory, event analysis of systemic teamwork and cognitive work analysis were used within a participatory design process involving the Cognitive Work Analysis Design Toolkit (CWA-DT) to generate new design concepts. This paper provides a summary of the design process and outcomes as well as findings from an evaluation of the CWA-DT based on participants' subjective experience of the process.


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*Keywords:*Situation awareness; Road intersections; Design; Cognitive work analysis; Event analysis of systemic teamwork; Schema theory

## 1. Introduction

Incompatibilities between different road users (i.e. drivers, cyclists, motorcyclists and pedestrians) continues to be a key factor in road traffic accidents [1]. Road users' awareness of other types of road users and their behaviorcan be an important aspect of this problem, especially at road intersections where incompatibilities amongst road user situation awareness can lead to conflicts and injuries [2]. Situation awareness incompatibilities need to be considered from a systems perspective,rather than being viewed as a failing of individual road users. An important

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aspect of this is applying systems thinking in the design of the road environment. Salmon and colleagues [2], for example, found that inappropriately designed intersections can create the kinds of incompatibilities in awareness that might lead to collisions between different forms of road user. Notably, the current approach to road design is underpinned by engineering and efficiency concerns, rather than systems thinking.To design compatible and safe intersections, for all road users, we need a design process that promotes system thinking in road design. A candidate process, the cognitive work analysis design toolkit (CWA-DT) [3] has been developed for use with the outputs of cognitive work analysis [4]. It has the flexibility, however, to also be applied based on the use of other systems-based analysis methods and approaches. This paper will describe the application of the CWA-DT in the context of road intersection design, to deal with the issue of incompatible situation awareness amongst road user groups. The aim is to showcase the CWA-DT in a design application area outside of rail safety, the area in which it was developed. The application built on an understanding of the system interactions gained from an analysis of road user situation awareness using the Neisser's[5] perceptual cycle model [2], the event analysis of systemic teamwork (EAST) methodology [6] and the work domain analysis (WDA) phase of CWA.

### *1.1. Situation awareness at intersections – findings from the application of systems-based methods*

Initially, verbal protocol data collected from an on-road study involving drivers, motorcyclists and cyclists was used to understand situation awareness in different road environments including shopping strips, roundabouts, arterial roads and intersections[2]. The concepts present in road users' situation awareness networks were mapped onto the perceptual cycle model. This model is based on the notion that that humans possess mental templates (schemata) that, when triggered by contextual conditions, direct perception and behaviour, and ultimately our interaction with the world. The mapping of findings from the verbal protocol data resulted in a number of insights relating to incompatible situation awareness, particularly between drivers and two-wheelers (cyclists and motorcyclists). For example, as there are low numbers of cyclists and motorcyclists present at intersections,drivers have limited experience of these users. Therefore, cyclists and motorcyclists are not prominent in drivers' intersection schemata leading to drivers not looking for cyclists and motorcyclists. Consequently, drivers are unaware of the presence of cyclists or motorcyclists when they are filtering to the front of a traffic queue, leading to potential for conflict.

In another study, the EAST methodology was applied to better understand the interactions between road user groups [6]. EAST uses a network of networks approach where task networks provide a summary of the goals and subsequent tasks being performed at the intersection, social networks analyse the organisation of the system and the communications between 'agents' (both human, such as drivers and cyclists; and non-human, such as traffic lights and vehicles), and knowledge networks describe situation awareness in terms of concepts and relationships between concepts. Networks were generated for drivers, cyclists, motorcyclists and pedestrians based on their verbal protocols when making right-hand turns at intersections. The networks were analysed to understand the similarities and differences across groups. Insights derived from this analysis included that as cyclists do not have a formal, safe path available to make a right hand turn and thus engage in flexible, emergent behaviour which can make their behaviour unpredictable and unexpected for other road users, particularly drivers, resulting in poor situation awareness and increased risk of conflict.

Further, the WDA phase of CWA [4] was applied to create an actor- and event-independent description of the intersection domain. The WDAdescribed the intersection system at five levels of abstraction beginning with the purpose of the system at the top (i.e. optimize multi-directional traffic flow), to the values and priority measures used to gauge the effectiveness of the system (i.e. minimize collisions and trauma), the functions performed within the system (i.e. control road users), to the object-related processes that enable those functions (i.e. provide physical barrier) and the physical objects in the system itself (i.e.bollards). Links between the levels identify how the system purposes are supported through the different levels. The WDA providedinsights about the functioning of the system such as where there are high levels of redundancy, or where there are vulnerabilities due to lack of support for a function.

### *1.2. The Cognitive Work Analysis Design Toolkit*

The CWA-DT was developed to meet the need to extend CWA to better inform the design of sociotechnical systems [3]. It links the outputs of CWA with the design principles offered by sociotechnical systems theory and provides guidance and tools for participatory design processes. The toolkit includes guidance for ten stages of a design process including: analysis planning, the analysis process, requirements specification, design planning, concept design, high level evaluation & concept selection, detailed design, evaluation & design refinement, implementation and testing & verification.However, the toolkit is intended to be flexible and users are encouraged to apply those aspects they consider will add value to their particular design aims.

As noted above, the CWA-DT has its basis in the sociotechnical systems theory approach. This approach provides values and principles for the design of systems that can display adaptive capacity (i.e. has sufficient flexibility and resilience to continue to meet its goals in the face of external disturbances and unanticipated events) while concurrently supporting worker or user wellbeing [7, 8 & 9]. The values include notions such as the need to view humans as assets, rather than liabilities within a system, and the need to consider individual differences in design. The principles of sociotechnical design include that tasks are allocated appropriately between and amongst humans and technology; that useful, meaningful and whole tasks are designed; and that problems are controlled at their source (see Read et al [10] for a full list).

Evaluation criteria to evaluate the utility of the CWA-DT were identified prior to its development[10]. They include the extent to which: it facilitates creativity and / or innovation; it provides a structured design process; it supports the coordinated design of all system elements; it provides an efficient and cost effective process; it can integrate with existing systems engineering processes; it facilitates an iterative design process;and it provides a valid design process (i.e. produces effective designs). These criteria are used to evaluate the performance of the toolkit in this application. Previous applications have provided emerging evidence of the toolkit's effectiveness [3].

## 2. Applying the CWA-DT to intersection design

As part of a wider program of research aiming to develop new intersection design concepts that support safer interactions between different forms of road user, the CWA-DT was used in conjunction with the analyses described above to support the creation of novel intersection design concepts. The process followed is shown in Figure 1. The figure shows how the analysis outputs were used to inform the design planning activities. Further, insights from the development of the analysis artefacts contributed to these documents and also to the development of materials for use in two consecutive participatory design workshops. The outcome of the process was a shortlisted set of design concepts to improve situation awareness and safety at intersections.

### *2.1. Pre-workshop design planning*

As shown in Figure 1, the analysis findings and insights from the research team fed directly into the design planning documents. The Design Brief documented the aim of the design process as being *to develop an intersection design that promotes compatible situation awareness amongst road users*. The context for the design was identified as an urban environment in Australia, with mixed residential, retail / business land use around the intersection. The scope of the design process was design of the roadway or road infrastructure rather than considering the design of vehicles, in-vehicle devices, training and licensing, etc. Both blue sky designs and designs appropriate for retrofit to existing intersections were within the scope.

Secondly, evaluation criteria for determining the success of the design concepts were identified and recorded in the Design Criteria document. The first set of criteria was the target behaviors that were identified from the previous research [2 & 6] as being desirable to encourage through design to promote situation awareness. These criteria were: the design influences drivers to look for cyclists, motorcyclists and pedestrians; the design influences drivers to look where cyclists, motorcyclists and pedestrians may be; the design ensures that drivers perceive cyclists, motorcyclists and pedestrians; the design influences cyclists and motorcyclists to engage in predictable behavior; and the design ensures that drivers experience cyclists, motorcyclists and pedestrians.

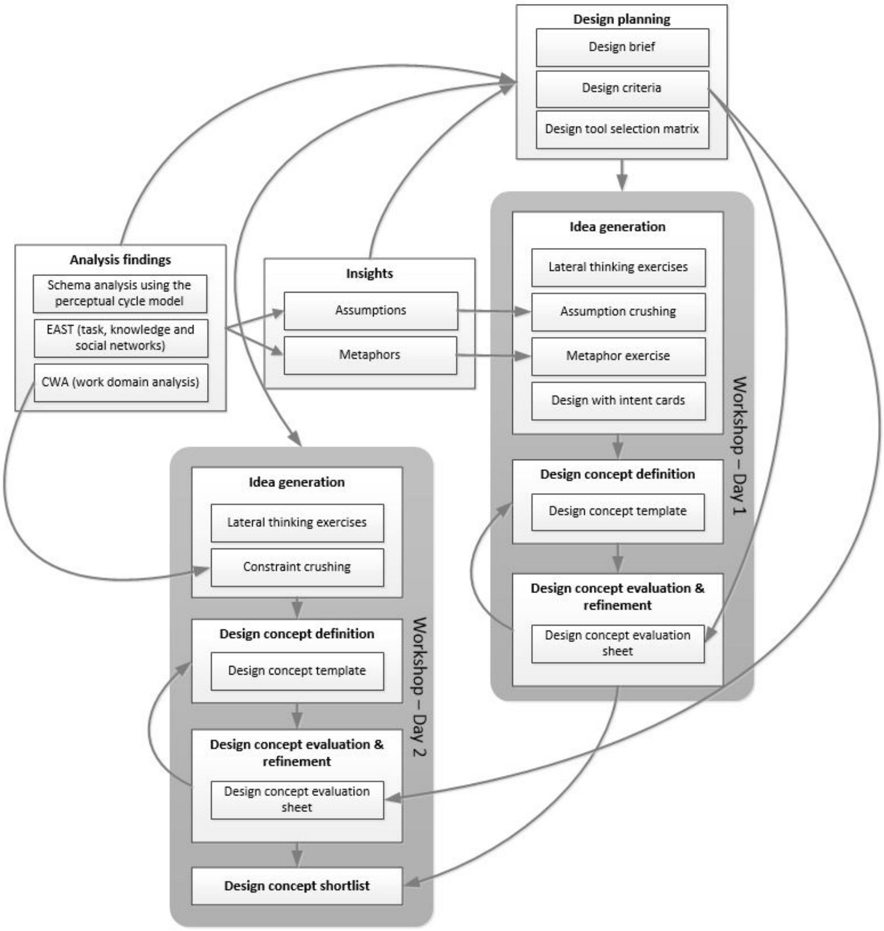


Fig. 1.Process of applying the CWA-DT to intersection design.

The second set of criteria were drawn from the WDA model. These were:Safety (minimize collisions, injuries, fatalities, minimize risk); Compliance (minimize violations); Efficiency (minimize time taken to traverse intersection, flow through); Optimize flexibility; and Maximize reliability.It was noted that the safety-related measures should be considered more important due to their importance in relation to the overall project.

The final set of evaluation criteria were drawn from sociotechnical systems theory and consisted of the principles derived from the sociotechnical systems theory literature [e.g. 7, 8 & 9].

The design team used the Design Tool Selection Matrix to select appropriate design tools for the participatory workshop which involved consideration of the design aims and constraints as well as they type of insights generated.

## 2.2. The workshop

### 2.2.1. Participants

Eleven subject matter experts participated inthe workshops. The participant group comprised seven males and four females and the mean age of participants was 34 years (range 23-44). Participants' disciplinary backgrounds included human factors, psychology, sociology, traffic engineering, urban planning and safety science. The majority of participants held academic positions however there were representatives from industry / government (including the road authority) and a number of the academic participants had previous industry experience. Within the participant group,there were experienced users representing a range of road user types (driver, pedestrian, cyclist, motorcyclist and heavy vehicle driver).

*2.2.2. Materials*

Participants were provided with a handout that contained a description of each of the five sociotechnical values and indicators that could be applied to determine if the value was met. For example, for the value *humans as assets*, an indicator was *the design doesn't remove user control / the opportunity for users to make decisions*. Participants were also given a similar summary of the sociotechnical principles with descriptions of each principle provided along with indicators to evaluate their presence.

Practical tools and exercises were included to facilitate a creative design process. For example,LEGO was available for participants to use as it has been recommended to assist idea generation and design through providing an engaging and playful medium to discuss and share ideas within teams [e.g. 11]. Specific exercises for idea generation includedthe use of a selection of Design with Intent cards [12] to prompt ideas. The Design with Intent toolkit aims to assist design for behavior change by codifying a range of design strategies. Each design with intent card contains a behavior change technique or principle which can be used to inspire ideas. For example, the *Provoke empathy* card asks: *Can you help users see other people's perspectives and thought processes, by revealing them through the design of your system?*

A large printed copy of the intersection WDA was provided to participants as part of the constraint crushing exercise. A template for the constraint crushing activity was also used to prompt participants to consider, for each key constraint for each road user group: the effect of removing the constraint, the effect of strengthening the constraint, and how the constraint could be made visible to users.

Design concept templates were used for documenting design concepts. These A3-sized sheets incorporated prompts to give the concept a name, provide a drawing or sketch of the design, indicate which sociotechnical systems theory values were incorporated in the design and describe the design hypothesis (i.e. how the design will improve situation awareness and compatibility between road users, and ultimatelyminimize collisions / injuries). It also prompted participants to identify other system changes that would be required for the concept to be successful and to consider any potential unintentional consequences of the design.

A design concept evaluation sheet was used to assist participants to consider the likely effectiveness of each design concept against the design criteria specified in the design planning phase.

A demographic questionnaire was used to gather information about participants and their expertise. Further, an evaluation questionnaire was provided to participants to gain their feedback and comments on the process. The questionnaire contained statements about the design process and a Likert-type scale where participants were asked to select the category that best described the extent to which they agreed with the statement given, with the categories of: strongly agree, agree, neutral, disagree, strongly disagree, and unsure / don't know. The statements were aligned to the evaluation criteria for the CWA-DT.

*2.2.3. Procedure*

The workshop washeld over two consecutive days and involved a number of activities which are described in Table 1. These activities were undertaken with participants working in small groups. To encourage maximum collaboration across groups, some participants moved groups at the beginning of the second day.

## 3. Results

The application of the CWA-DT produced three shortlisted design concepts and also provided evaluation results, based on the experiences of participants in the workshop, regarding the effectiveness of the CWA-DT.

*3.1. Outcomes of the workshop*

Table 2 provides a short description of the design concepts shortlisted for further testing and evaluation.

Table 1.Descriptions of design activities used in the workshop.

| Activity | Description |
|---|---|
| Lateral thinking exercises | A lateral thinking exercise was used at the beginning of each day to encourage participants to think laterally rather than in a rational, analytical manner. |
| Assumption crushing exercise | Assumptions underlie the current design of the world and may unconsciously affect the breadth of the design space being explored. The assumption crushing exercise takes assumptions identified during the analysis and crushes them to enable novel idea generation. One assumption uncovered by the analysis and presented to participants was that *Roads should be built for cars, as they are the most common mode of transport*. Participants generated alternative assumptions including that roads should be designed for demand, that they should be designed to discourage car use, or that they should be designed for the most vulnerable user group. |
| Metaphor exercise | Metaphors can assist designers to take inspiration from an area or domain that is similar but has some difference, and apply this in design. The metaphor of 'team'was identified in the insight generation process. That is, similar to road users, teams (e.g. sports teams, research teams) need to maintain awareness of what team members are doing to ensure they achieve common goals. Participants brainstormed ways that team members maintain awareness of each other's activities and how these methods or approaches could be used at intersections. Participants then shared their ideas with the larger group, and built on one others ideas. |
| Design with intent cards | In this exercise, participants were asked to think about the desired behaviours and to use the Design with Intent cards to consider how these behaviours could be encouraged through design. |
| Constraint crushing exercise | The WDA, which identifies the constraints on behaviour in the system, was presented to participants as part of this activity. The aim is to expand design thinking beyond the existing system constraints, thus encouraging novel ideas. Further, constraints restrict flexibility and variability which may be desirable in some circumstances or undesirable in others. For example, in a safety context, strengthening constraints, or making their presence more visible, could be beneficial. In the constraint crushing activity the large group were introduced to the WDA and were asked to identify the key constraints for each user group (e.g. drivers, cyclists and motorcyclists, and pedestrians). For example, a key constraint identified for drivers was the road markings. A template was used by participants to consider and discuss how behaviour could be influenced by removing each key constraint, or by strengthening it or making it more salient to road users. |
| Design concept definition | Following the design activities, participants were asked to generate one or two design concepts based on the ideas they had discussed. These were documented on design concept templates. |
| Design concept evaluation & refinement | Towards the end of each day, participants were asked to consider all of the design concepts they had generated and use the design concept evaluation sheet to consider how the different designs compared against the design criteria. They then selected and refined the most promising concept and presented it to the larger group. |
| Design concept shortlisting | At the end of the workshop group discussion was held to determine a short list of design concepts, from those generated over both days. |

### *3.2. Evaluation of the design process*

The design process was evaluated based on the participant responses to the evaluation form. Only the responses of participants present for the entire workshop (10 participants in total) were included in the analysis. The results are provided in Figure 2 for each of the evaluation statements (paraphrased from the statements on the questionnaire). These are grouped by the evaluation categories of creative, structured, holistic, integrated, iterative, valid and useable.

It can be seen in Figure 2 that there were some ratings of 'neutral' or 'unsure' for the efficiency criteria possibly suggesting that participants may not have sufficient experience in design processes to be in a position to compare the CWA-DT process with others. In relation to the validity criterion, there were some ratings of 'neutral', 'disagree' and 'unsure' provided, particularly in response to the statement '*The design approach produced practical solutions that have a good chance of being implemented*'. Potentially some participants felt that the designs were so innovative that they might not be easily implemented. This is not necessarily a drawback of the design process at this point, as the intention was to create novel designs. Later stages of the design process would involve discussions around what needs to occur for successful implementation of these concepts. Finally, one participant did not agree with the statement that '*the workshop activities were easy to understand*'. Potentially, this related to the use of the WDA model within the workshop which, on first introduction, can be difficult to understand.

Table 2. Key features of the shortlisted design concepts.

| Concept name | Description / key features |
|---|---|
| Turning teams | In this intersection concept, traffic lights would be brought back further from the intersection than usual, to match pedestrian desire lines based on the location of buildings and adjoining pedestrian paths. The pedestrian crossing path would be wide enough to enable cyclists not comfortable to traverse the intersection with the motorized traffic to have an official alternative of crossing with pedestrians. The intersection would have a separate bus lane, shared with cyclists, then lanes for cars and motorcyclists to proceed straight ahead and a right hand turn lane for cars and motorcyclists. A filtering box for motorcyclists and for cyclists would be provided. Lights are phased based on road user type and direction of travel. So the team is not just the road user group, but the direction of travel. So buses and cyclists will in some cases be part of the same team. Allowing all those not in conflict to proceed simultaneously, and clearing cyclists from the intersection prior to allowing motorized traffic to enter. For example, in one traffic cycle, traffic in the right hand turn lane would turn right, cyclists would go straight ahead and to the right, and the bus could proceed straight ahead. Next, once the cyclists will have cleared, motorized traffic could proceed straight ahead. Pedestrian phases would also be activated where there are no conflicts. |
| Self-regulating intersection | This intersection design is based on the principles of a roundabout. However, rather than being a traditional roundabout, it involves the placement of a large oval shapedmedian strip in the center of the intersection so that motorized traffic cannot perform a standard right-hand turn. Instead, when traffic from each intersecting road is given priority to enter the intersection, they move around the median strip in the same direction, and exit where they wish. Cyclists have the option to either move with the motorized traffic or to 'cut through' via dedicated lanes available through the central median strip. Within the intersection, there are no lane markings to promote connectedness between road users and require them to negotiate their way through with other road users. Filtering lights would allow vehicles to enter the intersection in a steady stream and once in the intersection the traffic stream would self-regulate the speed of the intersection which would be expected to be slow (i.e. 20km/h). The central concept is about maintaining flow and it is expected that users would give way to one another to maintain flow. |
| Circular concept | In this design concept, motorized and non-motorized traffic would have more obvious separation with pedestrian crossing zones provided further back from the intersection that usual but footpaths linked in a circular pathway that could also be used by cyclists wanting to turn left or right. This circular pathway would link with cycle lanes on the road that would be provided down the center of the intersection. Pedestrians would be encouraged to use the separate pathway as the areas adjacent to the path would be made attractive for them with cafes, gardens, BBQ areas, seating, etc. So while pedestrians and cyclists would need to travel further distances to get across the intersection, this would be compensated by making their environment more pleasant. In addition, a separate bus lane would be provided and a motorcycle zone would be provided at the front of the intersection to encourage motorcyclists to filter to the front. There would also be a sign for motorists that would alert drivers to watch for motorcyclists filtering from behind. |

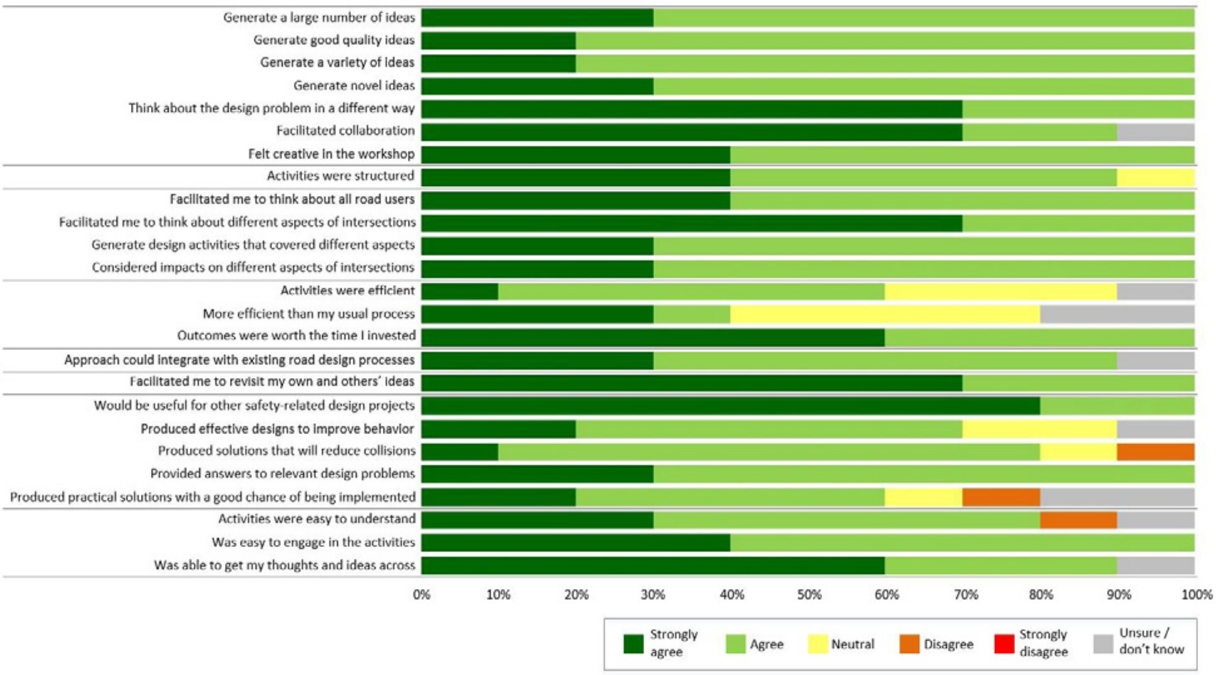


Fig. 2.Responses to evaluation statements by workshop participants.

## 4. Discussion and conclusions

The workshop was successful in that it produced three design concepts for intersections that aimed to better support compatible road user situation awareness and consequently reduce conflicts between road users at intersections. Subsequent testing and evaluation of the designs using empirical methods is planned to determine their efficacy. The evaluations provided by participants indicated strong evidence that the CWA-DT is a useful design process, from a participant perspective. In particular, participants commented positively on aspects such as metaphorical thinking, the level of collaboration achieved during the workshop and the focus on designing for all road user groups.

This application of the CWA-DT provided evidence of its utility for design within the road transport context. It has also demonstrated that the toolkit can be used with system-based analysis frameworks other than CWA, expanding its potential utility for human factors practitioners designing sociotechnical systems. With ever increasing calls for a systems approach to road safety, it is proposed that the CWA-DT can support practitioners to use systems-based analysis approaches to generate practical design interventions.

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