Using cognitive work analysis and the sociotechnical systems approach to improve pedestrian safety at rail level crossings

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The sociotechnical systems approach argues that systems with adaptive capacity will be safer. However, this approach may conflict with current practice in safety management. We applied cognitive work analysis to understand the problem of pedestrian safety at rail level crossings and used the findings to evaluate the current design against the values of sociotechnical systems theory. The evaluation was conducted against indicators developed based on the sociotechnical literature and it is concluded that the existing design of rail level crossings does not align with the values. Recommendations for improving the design of rail level crossings are identified and discussed.

Practitioner Summary: Cognitive work analysis and criteria adopted from sociotechnical systems theory can be used to evaluate existing systems and provide insights into design improvements to support adaptive and resilient systems.

Keywords: Rail level crossing safety, pedestrian behaviour, system-based analysis, sociotechnical systems theory, cognitive work analysis

1. Introduction

Across Australia, over ten years between June 2002 and July 2012, there were 92 collisions between trains and pedestrians at rail level crossings (RLXs; Australian Transport Safety Bureau, 2012). In the state of Victoria, 17 fatalities and six serious injuries resulted from train-pedestrian collisions between 2009 and 2013 (Transport Safety Victoria, 2014). RLX design has historically tended to be engineering-led with minimal consideration of human factors issues. Further, human factors literature on the topic of pedestrian behaviour at RLXs is sparse. In this paper, we focus on RLX design in Victoria, Australia however it should be noted that the principles of RLX design applied are similar to those in the United States, the United Kingdom and Europe and the current Australian design standards would be considered good practice internationally.

Human factors approaches based in systems theory, such as cognitive work analysis (CWA) and the sociotechnical systems theory approach, argue that systems which facilitate adaptive human behaviour will have more capacity to operate within their safety boundary and demonstrate better safety performance (e.g. Badham, Clegg, & Wall, 2006; Vicente, 1999). This philosophy is beginning to be applied in the RLX context through the application of CWA (e.g. Mulvihill, Salmon, Lenné, Beanland, & Stanton, 2014; Salmon, Lenné, Read, Walker, & Stanton, 2014). This paper will add to this emerging knowledge base by conducting an evaluation of the current RLX system design against indicators derived from sociotechnical systems theory. This will assist to provide insights and recommendations for improving safety.

The aim of this paper then is to take an innovative perspective on the issue of pedestrian safety at RLXs by applying the findings of cognitive work analysis (Vicente, 1999) to inform a review of the extent to which the existing RLX design aligns with the sociotechnical systems theory approach (Clegg, 2000).

2. Method

CWA, a framework of methods that supports the analysis of complex sociotechnical systems with the aim of improving system design (Vicente, 1999), was applied to understand pedestrian behaviour at RLXs. The framework provides a formative approach to the analysis of human activity in complex systems by identifying and analysing the constraints that shape behaviour. The framework encompasses five phases of analysis. The first phase, work domain analysis (WDA), describes the environmental constraints on behaviour within the domain. Secondly, control task analysis, through the use of decision ladders and the contextual activity template, considers the tasks that need to be achieved. Thirdly, strategies analysis identifies the various strategies that can be used to fulfil the tasks. The fourth phase, social organisation and cooperation analysis is used to allocate functions amongst human and technology and identify communication and collaboration requirements. Finally, the competencies required by actors operating within the domain are identified through the final phase, worker competencies analysis (Vicente, 1999).

The CWA was informed by a number of data collection activities. The RLXs in the studies were located in metropolitan Melbourne and incorporated separated pedestrian paths adjacent to road RLXs. They had automatic gates which block the pedestrian path when warnings activate, emergency exit gates to enable exit from the RLX, and / or bells and flashing lights to warn of approaching trains. The data collection included covert observations of pedestrian behaviour, walk-throughs by participants who provided verbal protocols, use of the critical decision method interview, review of incident data and review of the findings of inquests into RLX deaths involving pedestrians conducted by the Coroner's Court of Victoria. All activities had approval from relevant human ethics committees. Aspects of the analysis were validated in workshops involving road and rail subject matter experts.

The qualitative evaluation of RLX design was conducted against indicators drawn from the sociotechnical systems theory literature. The sociotechnical systems approach is strongly aligned with systems theory and underpinned by notions of industrial democracy, participative design and humanistic values. Key principles and values of sociotechnical design have evolved over many years of action research implementing innovations in organisations (e.g. Cherns, 1976; Clegg, 2000; Davis, 1982). The principles and values aim to support the design of organisations and systems that have the capacity to adapt and respond to changes and disturbances in the environment. The indicators used in the review were developed for the values of sociotechnical system theory. The evaluation is based on the findings of the CWA and associated data collection activities, with the key actors considered being pedestrians and train drivers.

3. Results

3.1 Cognitive work analysis

A key finding of the CWA was the high latitude for behaviour provided by the RLX environment. The strategies analysis outputs showed that pedestrians had many options in terms of the strategies they can use to cross the RLX. They also showed that certain strategies were more likely to be used in particular situations (for example, bypassing the pedestrian gate is more likely in situations when the pedestrian intends to catch the approaching train). Further, the WDA and decision ladder outputs show that there are many cues in the environment that pedestrians can use to determine whether or not a train is approaching. For example, the closing of the pedestrian gate, the sound of bells activating, or the movement of people waiting on the train station platform are cues used to identify an approaching train. Interestingly, not all of these are intentionally made available to pedestrians in the formal design of the system.

Overall, the CWA outputs confirmed the complexity of the RLX system and validated the decision to apply systems-based methods and approaches to its evaluation. The results provided evidence of key systems principles such as emergence, individual and system performance variability, dynamicism and incorporating hierarchical structures.

3.2 Sociotechnical systems evaluation

3.2.1 Humans as assets

Rather than characterising humans as unpredictable, error-prone and the cause of problems in an otherwise well-designed technological system, this value argues that technical systems are not perfect and cannot cope with the demands of the changing environments in which they are situated. The people in the system should be viewed as assets as they are capable of identifying the need for change and of learning and adapting; making them effective problem solvers (Clegg, 2000; Norros, 2014). In short, humans are the glue that hold sociotechnical systems together.

Indicator 1: The design supports performance variability / flexibility in the means by which tasks can be undertaken by users ~ The current design of RLXs allows pedestrians to exhibit considerable variability in their behaviour. For example, pedestrians can cross the RLX via the roadway and can move in-between the formal fencing and the road when crossing. However, this variability is not designed in to the system and is not supported. Pedestrians who choose to cross in a way not expected by designers may find themselves in a dangerous position, such as being on the road when the warning bells begin to sound without being sure of where is a safe place to stand. In contrast to flexibility, the underlying aim of the design is to constrain users to only cross when the technical system allows (e.g. when the gates are opened for pedestrian traffic).

Indicator 2: The design doesn't involve removing humans from the system ~ While pedestrians are part of the RLX system, rather than being decision makers, they are generally treated as entities to be controlled. Interestingly, even some researchers have categorised pedestrians / road users as 'external intrusions', rather than a legitimate part of the system (Kim & Yoon, 2013). Train drivers, on the other hand, are able to make decisions. However, due to the technical constraints associated with train braking resulting in long stopping distances, they are generally not in a position to take any meaningful action to avoid a collision.

Indicator 3: The design doesn't remove user control / the opportunity for users to make decisions ~ As suggested previously, the design intention is specifically to remove user control and decision making with the aim of protecting users from being in the path of a train through engineering separation. However, the CWA outputs showed that users still need to make decisions about how they will act on the warnings provided. Further, they can choose to be in control of their activities if they avoid the formal pedestrian infrastructure and cross via the road. So while the RLX does not completely remove user decision making, it allows users to make undesirable decisions that often end in safe outcomes but occasionally lead to tragedy.

Conclusion: The value of *humans as assets* appears to be only somewhat embraced in the existing design.

3.1.2 Technology as a tool to assist humans

This value asserts that technology should be viewed as a tool to assist people to meet their goals, rather than an end in its own right (Clegg 2000). It aims to discourage the common scenario where a technical solution is implemented as a panacea to a problem, with little or no consideration of the goals of people's work or the social system required to make the technology work within an open system (Clegg 2000).

Indicator 1: Any technology included in the design is matched to a human need for that function ~ The technology installed at RLXs has evolved from a time when a flagman present at the crossing would swing a red lantern to warn traffic and pedestrians to stop for the train. Often the flagman also operated gates to close across the RLX. The automatic flashing lights and automatic gates are the modern versions of these warnings (Wigglesworth, 1978). There is a legitimate need for users to know of an approaching train, however, it is questionable whether or not the current design is the most effective means to achieve this in modern era. Further, there is little technology available to support train drivers in traversing the RLX. For example, trains may be approaching on a curve with no advanced vision of the RLX and drivers can rely only on their view of the warning devices and gates to know if they are operating correctly.

Indicator 2: The design process ensures that technologies are considered only in relation to human needs ~ RLX design processes in Australia are based on technical standards such as *Australian Standard 1742.7-2007* and the *Victorian Rail Industry Operators Group (VRIOG) Standard 003.2 – 2006*. The requirements in such standards tend to be based on convention rather than contemporary human factors research. Further, the requirements codified in standards are applied without specific consideration of human need in the particular location. For example, there are examples of RLXs where formal pedestrian footpaths and gates are provided on one side of the RLX only, even though there are surrounding land uses that would draw pedestrians to use that side of the RLX (e.g. shops, schools, parking, public transport connections).

Indicator 3: Technology is easily accepted by users, as it meets a need they have identified and is designed to fit into their goals / tasks / ways of working, etc. ~ It is apparent that technology at RLXs may not be explicitly designed to fit the goals of users and, in fact, a conflict between the user and wider RLX system goals can be associated with collisions (for example, where the pedestrian's goal is to catch the approaching train). While pedestrians have goals relating to safety, our decision ladders and strategies analysis outputs identified that this will be traded-off for efficiency in certain situations in line with the efficiency-thoroughness trade off (Hollnagel, 2009). The RLX doesn't support users to make those trade-offs appropriately. Further, as the RLX does not assist pedestrians to achieve their goals, the technology is not easily accepted by all users. For example, it is not accepted by those who use emergency exit gates to access the RLX, or those who push gates as they opening.

Conclusion: The value of *technology as a tool to assist humans* does not appear to be embraced in the existing design.

3.1.3 Promote quality of life

This value advocates that people cannot be considered as simply machines or extensions of machines (Robinson, 1982). Therefore, there must be consideration of the human need for quality of working life and tasks should be designed to have meaning for people. In the RLX context we are considering pedestrians (non-employees) as well as employees such as train drivers. Quality work or activity can be conceptualised as that which is challenging, has variety, includes scope for decision making and choice, facilitates ongoing learning, incorporates social support and recognition, has social relevance to life outside work and provides a feeling that the work leads to some sort of desirable future (Cherns, 1976, 1987). Instead of allocating humans those tasks that cannot be performed by technology, humans should only be allocated tasks that justify the use of humans and that utilise human skill and judgement. Technology should then be used to fulfil the remaining functions (Hendrick, 1995).

Indicator 1: The design gives people a reasonable challenge (e.g. task demands match people's competency) ~ Whether a reasonable challenge is provided will depend upon the individual user. For some users, the task demand of stopping when the bells begin to sound may be appropriate. However, for others, the task is too simple, and people, being problem solvers, will make their own decision based on the threat they perceive and taking into account their personal goals and intentions. People may try to increase the challenge by bypassing the formal RLX infrastructure or by finding ways to avoid being constrained by the gate (e.g. using the emergency gate).

Indicator 2: The design gives users control over decisions that affect them, and choice over which actions to take ~ Control and choice is generally removed from pedestrians who are expected to comply with warnings and barriers. Train drivers also have little control over the situation and their choices about evasive action are limited to sounding of the horn and applying the emergency brake. These actions may have no bearing on the outcome meaning that drivers may experience a sense of helplessness about the situation with consequential negative psychological effects and impacts on their wellbeing. For example, a study conducted by Mehnert and colleagues (2012) found that in male train drivers who had experienced a 'person under the train' incident, measures such as anxiety, depression, distress, mental quality of life, lack of meaning in life, loss of control and sense of safety, and sense of guilt were significantly associated with the development of posttraumatic stress (Mehnert, Nanninga, Fauth, & Schäfer, 2012). In Australia, train drivers and assistants as an occupational group had the highest number of mental stress claims for the years 2008-09 and 2010-11 (Safe Work Australia, 2013). Thus, it appears that the current design is part of a system that does not provide pedestrians or train drivers with a sense of control and choice which has the potential to have considerable negative effects on compliance and on wellbeing.

Indicator 3: The design facilitates ongoing learning ~ While pedestrians may learn from their actions if they are involved in a near miss with a train, there is no other designed-in feedback to enable pedestrians to learn about the consequences or potential consequences of their actions. For example, pedestrians do not receive feedback about the impact of their actions to bypass automatic gates on train drivers, with no way for this to be easily communicated. There are no railway personnel located at RLXs to warn of dangers and provide feedback about behaviour. Further, there is limited opportunity for pedestrians to share their experiences with authorities to enable the system to learn about safety issues at particular RLXs.

Train drivers may learn from experience or from colleagues that particular areas are dangerous and use strategies such as sounding their whistle earlier or for a longer period at such locations. However, being required to meet a timetable, they may not be in a position to slow down at such RLXs to increase their chances of taking evasive action if required.

Indicator 4: The design incorporates social interaction and social support ~ The design does not incorporate facilities to support social interaction between pedestrians or between pedestrians and train drivers. In fact, it arguably attempts to remove this by attempting to control pedestrians through the crossing safely. However, examples of social interaction were observed such as pedestrians providing others with advice on route guidance and holding open gates for others following. Potentially, improvements could be made to facilitate better social interaction at the RLX and also to encourage pedestrians to assist and support one another in the case of an issue or emergency.

Indicator 5: The design has a broader social relevance ~ The social relevance of RLXs as providing access across a rail line that otherwise would disconnect a community is not emphasised by the crossing design itself. Further, the protective function of the RLX may not be communicated to pedestrians in a way that there is recognition and appreciation of this. However, it should be noted that the majority of the participants in our studies spoke positively of the RLX warnings and many had no suggestions for how they could be improved.

Indicator 6: The design provides users with the sense that they are contributing to a greater goal / desirable future ~ As noted above, the design does not appear to connect pedestrians with the goals of the RLX system to provide access or to protect from injury. For example, the decision ladder analysis found that while a number of people stated, when prompted, that they were concerned for their safety during the RLX encounter, others reported different goals. For example, many referred to getting to the other side of the RLX quickly, not endangering others and ensuring they took action that was in line with social norms. Previous work has also found that pedestrians who crossed in a compliant manner reported a safety goal 44.2% of the time, while other goals included efficiency, compliance and positive subjective experience. The majority of those who crossed in a non-compliant manner (68.5%) reported an efficiency goal (Mulvihill, et al., 2014). So the goals of pedestrians are personal and immediate and their concerns are around how reaching their destination will be affected. With a small number of exceptions, pedestrians in our research did not refer to 'bigger picture' goals or impacts on other such as train drivers.

Indicator 7: The design incorporates recognition for what the user has contributed ~ There is no recognition or feedback provided by the RLX system for behaviour that is considered desirable or that contributes to safe outcomes. In fact, considering how (informal) reinforcement processes operate within the system, the most common positive reinforcement occurs when a pedestrian traverses the RLX at an optimal time to catch the approaching train. This optimal time is a point where they are not waiting on the train station platform for an extended period waiting for the train (time wasted) but are not so late that they must wait behind a closed pedestrian gate and watch their train pass. Therefore, pedestrians may be rewarded for rushing through the RLX as the train is approaching and punished (by missing their train) where they stop and wait.

Indicator 8: Humans are provided with appropriate tasks, i.e. not monotonous tasks that can be performed by technology with human supervision, but those that provide appropriate challenge ~ In the existing design, humans have the task of stopping at the RLX when the warnings activate. As noted above, this task of stopping is not challenging for the majority of users and users may add challenge to avoid the monotony and sense of loss of control over their situation. Technology performs the task of detecting a train approaching and activating warnings. This is somewhat monotonous and thus could be seen as appropriate for technology to perform. However, the uncertainties involved in providing an optimal warning time may make this an inappropriate task for technology to perform. An optimum warning time would take into account the type of train, its current and future (predicted) speed, its stopping pattern, as well as the road / pedestrian traffic situation and pedestrians' individual capabilities to cross without being struck by the train. This task is highly complex and is beyond the capability of the existing technology. It may also not be achievable by humans but potentially at least some human supervision of the automated system would provide some improvement.

Conclusion: The value of *promote quality of life* does not appear to be embraced in the existing design.

3.1.4 Respect for individual differences

This value relates to the fact that people have different needs and wants. For example, some people may prefer high levels of autonomy and control, while others may not. The design process should recognise and respect these differences and should aim to achieve a flexible design that incorporates different preferences, acknowledging that meeting all needs may not always be possible (Cherns 1976, Cherns, 1987).

Indicator 1: The impact of the design on each type of user is considered ~ The existing RLX design does not appear to support the needs of the diverse range of users that will encounter them. For example, young children may not have the cognitive ability to understand the risks associated with being on the track while a train is approaching and those with mobility impairments or those using wheelchairs may have difficulty traversing the tracks due to the gap between the footpath and the rails. This is particularly problematic with children, older pedestrians and pedestrians with disabilities being identified as over represented in pedestrian-train incidents (Freeman, Rakotonirainy, Stefanova, & McMaster, 2013).

The legal requirement for RLX authorities to comply with the *Disability Discrimination Act (1992)* and disability standards for accessible public transport is stated in the VRIOG standard. This is very important and the right of people with disabilities to be provided with equal access to public transport should be given priority. However, it appears to only consider physical impairment, rather than also ensuring that people with intellectual disabilities can use the RLX safely. Further, this appears to be the only area where user needs are given consideration in the standards. For example, there is nothing in the standard acknowledging the needs of children, people who are accessing the station platform versus those crossing directly over the RLX, people who are more or less safety conscious, etc. These aspects may have been considered in the development of the standard, but no discussion is provided in the standard which is used as the basis for ongoing re-design and upgrades. Further, not all existing RLXs meet the current standards and thus may not meet the needs of pedestrians with physical disabilities and impairments.

Indicator 2: The design appropriately balances the needs of each user group ~ The focus on providing access for people who have disabilities in the standard is appropriate, as this is a vulnerable group. However, sometimes this constraint has led to unanticipated outcomes of the legislation such as where a decision was made to close a pedestrian underpass so that the RLX footpath above could be upgraded to be compliant with the requirements of the *Disability Discrimination Act* (VicTrack, 2014).

Indicator 3: The design is flexible so that each individual can tailor their interaction as they prefer ~ Apart from enabling pedestrians to access the road part of the RLX, the design does not support flexibility and tailoring by pedestrians nor by train drivers.

Conclusion: The value *respect for individual differences* does not appear to be embraced in the existing design.

3.1.5 Responsibility to all stakeholders

In line with open systems principles, the effects of the system on all stakeholders should be considered (Cherns 1987). Stakeholders could include users, manufacturers, unions, industry bodies, government bodies and the wider community. Potential negative effects on these groups is broad and could include physical damage or injury to individuals (e.g. through accidents), economic loss, social or environmental harms (Cherns 1987). Impacts on all stakeholders should be considered throughout all stages of the system lifecycle including design, construction and implementation processes, as well as system operation, maintenance and decommissioning.

Indicator 1: The design does not lead to unjustified negative consequences for safety, security, the environment, the economy, social inclusion and opportunity, etc ~ The current design intends to promote safety as well as social inclusion and opportunity by provided a access over the railway tracks. However, data indicates there has been little improvement in the frequency of train-pedestrian collisions across Australia (ATSB, 2012) suggesting that while the design may not have created negative consequences for safety, it is not achieving the vision enunciated in the National Railway Level Crossing Safety Strategy '*to reduce the likelihood of crashes and near misses at Australian railway level crossings*' (Rail Level Crossing Group, 2009). Further, there may be opportunities to improve the contribution of RLXs to wider goals of security, the environment, the economy and social inclusion and opportunity. While stakeholder and community consultation enabling community members to comment on designs currently occurs, this could be extended to co-design of RLXs with genuine and substantial participation of local residents and businesses in the design of RLXs that not only meet safety goals but also meet community needs and priorities for the area and surround land uses.

Indicator 2: The design appropriately balances potential harms ~ Overall, as with any high hazard system, RLX design appears to prioritise economic goals above safety goals. That is, trains are needed to move large numbers of people efficiently particularly into and out of city centres at morning and afternoon peak times. This meets economic purposes as large numbers of people need to access the city centre for work. RLX design is based on the notion that trains have priority through the RLX. Reversing this priority could improve safety, but could have serious effects for the city's economy, bringing it to a standstill. Alternatively, funding could be provided to install footbridges or underpasses at all existing RLXs which would virtually eliminate accidental train-pedestrian collisions. However, such an initiative would require large amounts of funding and is generally considered cost-prohibitive given that government funding is limited. Safety legislation requires risks to safety be reduced so far as is reasonably practicable, rather than requiring safety at any cost (Office of the National Rail Safety Regulator, 2014), and this is the paradigm within which level crossing decision making occurs.

Indicator 3: The design considers potential harm at all stages of the system lifecycle ~ Our data collection and analysis focused on the operation of the RLX system and to a lesser extent system design, rather than on other aspects of the system lifecycle such as construction, maintenance, decommissioning, etc. However, these are important processes and the safety, security, and wellbeing of workers who are involved in these processes should be considered when proposing changes. It is questionable to what extent considerations such as wider economic impacts are considered in RLX design. For example, if it would identified that RLX design could be improved by replacing warning devices with a cheaper alternative that is simple to install and requires no maintenance, this would be likely to be implemented because it would represent an economic benefit for government / RLX agencies. It would also provide a safety benefit as funds saved could be used to upgrade a larger number of RLXs. However, it would lead to job losses in the rail infrastructure construction and maintenance areas. Thus, there are economic consequences for them and their families to be balanced.

Conclusion: The value of *responsibility to all stakeholders* appears to be only somewhat embraced in the existing design.

4. Conclusions

It is concluded from the evaluation that existing RLX designs in Melbourne, Australia, are not aligned with the sociotechnical systems approach. This is not surprising, as, for historical reasons, the paradigm under which RLX design occurs is one of legal compliance (Aldrich, 2006), rather than industrial democracy and participation. A broader question then is whether the sociotechnical systems approach can provide benefit in a public safety design context? Historically, the approach arose around concerns of efficiency and wellbeing in the workplace and did not have a focus on accident prevention. Given this, is it more appropriate to continue on the safety management path where the focus is on elimination, engineering, rules and education as the core safety initiatives? The safety management approach taken in RLX design is considered good practice for public safety. However, crashes still occur. Given that elimination is generally considered to be out of scope because of the economic implications, that engineering is not reaching the required safety standard, and the known issues with rules and education, it may be beneficial to try a new paradigm and explore if that can achieve enhanced safety benefits. Whilst the current paper forms part of a broader research program implementing this new paradigm, a key research requirement across safety critical systems centres around the extent to which sociotechnical systems theory and methods are appropriate approaches for improving safety through the design of new systems and accident countermeasures. These changes would see a paradigm shift in how public transport systems are designed.

If this new paradigm of sociotechnical systems is to be explored, changes to the RLX design process as well as the design itself would be required. In terms of the design process, it would be beneficial to introduce stronger local community participation in the design of RLXs. Preferably this would involve the user community having decision making power over the final design, supported by appropriate professional guidance and advice. Further, feedback mechanisms between users of the RLX and authorities could be implemented to enable pedestrians to share their experiences and offer suggestions for improvement. This could engage users with the RLX and provide some sense of ownership over it.

In terms of the physical design of RLXs, making the environment around the RLX more attractive and conducive to waiting and to social interaction through the addition of seating, shelters, cafes, etc could influence to decision to stop or go when the warnings begin to activate, as well as providing an opportunity for social interaction and support between RLX users. A means to engage pedestrians with the train driver through some communication channel, be it real time or away from the RLX, could be beneficial to promote empathy for one another and a better understand of one another's' needs and motivations. Employing a person or a team to provide supervision at the RLX could not only increase adaptive capacity through their ability to intervene should an unsafe situation become apparent, but also increase social interaction and have economic benefits in terms of local employment rates. Finally, providing the train driver with higher levels of control over the situation could have positive implications for their wellbeing.

In relation to the sociotechnical values, we argue that they have provided a useful means to consider the existing system and have inspired some potentially useful design solutions that could be effective in improving safety. The indicators were developed from the literature by the authors and should be tested to ensure their usefulness in other domains and for other problems. Future research could focus on developing a valid set of indicators to enable formalised analyses and comparisons between systems. Even where the sociotechnical approach may seem to contradict existing paradigms (such as safety management) they can be useful to challenge assumptions and open up new perspectives in design.

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