Accounting for memes in sociotechnical systems: extending the abstraction hierarchy to consider cognitive objects

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ABSTRACT

Work domain analysis (WDA) is used to model the functional structure of sociotechnical systems (STS) through the abstraction hierarchy (AH). By identifying objects, processes, functions and measures that support system purposes, WDA reveals constraints within the system. Traditionally, the AH describes system elements at the lowest level of abstraction as physical objects. Multiple analyses of complex systems reveal that many include objects that exist only at a conceptual level. This paper argues that, by extending the AH to include cognitive objects, the analytical power of WDA is extended, and novel areas of application are enabled. Three case studies are used to demonstrate the role that cognitive objects play within STS. It is concluded that cognitive objects are a valid construct that offer a significant enhancement of WDA and enable its application to some of the world's most pressing problems. Implications for future applications of WDA and the AH are discussed.

Practitioner summary: Some sociotechnical systems include memes as part of their functional structure. Three case studies were used to evaluate the utility of introducing cognitive objects alongside physical ones in work domain analysis, the first phase of cognitive work analysis. Including cognitive objects increases the scope and accuracy of work domain analysis.

Abbreviations: WDA: work domain analysis; STS: sociotechnical systems; AH: abstraction hierarchy; CWA: cognitive work analysis; StrA: strategies analysis; WCA: worker competencies analysis; SAD: strategies analysis diagram; CAT: contextual activity template; SOP: standard operating procedure

KEYWORDS

Cognitive object; work domain analysis; abstraction hierarchy; meme; cognitive work analysis

Introduction

The accelerating pace of social and technological change is giving rise to increasingly complex sociotechnical systems (STS; Dekker, Hancock, and Wilkin 2013; Grote, Weyer, and Stanton 2014; Salmon et al. 2017). This includes the increasing mobility of people across international borders, advances in automation, communication, and data processing, and the increasing role of artificial intelligence in STS (Hancock 2014; Walker et al. 2017). With increasing complexity comes the need to adopt Ergonomics analysis methods to cope with the evolving problem space (Salmon et al. 2017). As complexity of STS increases, so does the need for appropriate methods to understand, control, and optimise them.

Cognitive work analysis (CWA; Vicente 1999) is a currently popular tool for understanding and attempting to optimise STS (Bisantz and Burns 2008; Stanton et al. 2017). The first phase, work domain analysis (WDA; Naikar 2013) involves using the abstraction hierarchy (AH) to develop a model of the STS in question. This resulting model describes system elements at the lowest level of abstraction as physical objects. Processes emerge from agent interactions with these objects that support system functions, values, and purposes. The development of CWA originated in the domains of industrial process control (Naikar 2013, 53; Rasmussen 1979). In those and many subsequent applications in manufacturing, healthcare, and aviation, objects at the lowest level of abstraction were deemed to be exclusively physical. In the words of Rasmussen (1986, 17), 'The lowest, most concrete level of abstraction is the representation of physical form, i.e. the physical appearance and configuration of the system and its parts'. For example, an agent interacting with a light switch in a house can give rise to the process of illuminating a room. This, in turn, supports the function of visibility, that in turn supports one purpose of the house, comfort.

However, it is apparent that the functional structure of some systems includes objects that are not physical, but ideational. For example, in a blues jam session, user interaction with the 12-bar blues pattern might support the process of remaining in tune and in time, which in turn supports the function of synchronised melody, which in turn supports the purpose of playing the blues. In this example, musicians did not need to interact with a physical object to interact with the 12-bar blues pattern. Rather, the 12-bar blues pattern is a cognitive object in the sense that the musicians each have their own internal representation of it. We argue that for accurate representation of this system in WDA, the 12-bar blues pattern can be accurately represented as a 'cognitive object'. The existence of written representations of the pattern in sheet music does not necessarily negate the need to independently represent it as a cognitive object, as agents may never actually interact with the physical sheet music.

As we will show, complex STS can include cognitive objects along with physical objects as components of their functional structure. These cognitive objects are no less real than any physical object. They are constructed by people and represent important design and analysis considerations for ergonomists. For analysts to ignore these artefacts as though they were beyond the control or influence of system designers could potentially represent a failure to recognise the full complexity of systems. We argue that it is important to recognise cognitive objects as system components that can, and must, like physical objects, be recognised, understood and modified to optimise system performance and human wellbeing.

An epistemological foundation for cognitive objects lies in the recognition of memes. Memes were first defined by the biologist Dawkins (2006, 217) as 'unit[s] of cultural transmission' in his attempt to note that genes were not the only kind of possible replicator that can give rise to evolution. Other definitions include 'unit[s] of imitation' (Dawkins 2006, 217), 'synaptic patterns that code cultural traits' (Delius 1991, 83), and 'a kind of way of behaving (roughly) that can be copied, transmitted, remembered, taught, shunned, denounced, brandished, ridiculed, parodied, censored, hallowed'. (Dennett 2017, 192). Just as only some explicit, enduring and transmissible ideas qualify as memes, only some memes qualify as cognitive objects. We argue that cognitive objects are memes that give rise to unique affordances and constraints in some STS, distinct from physical objects with which they may be associated. They exist at the lowest functional level of abstraction in those systems and their explicit identification in WDA gives rise to unique analytic outputs and design implications.

The continual evolution and enhancement of our analytical toolkit is required for Ergonomics to remain both useful and relevant (Salmon et al. 2017). The aim of this article is to show that a modification of WDA can improve that framework's utility for application to increasingly complex STS. This involves extending the abstraction hierarchy to support the identification of cognitive objects alongside physical objects. CWA has been used widely for the analysis and design of STS. Its latter phases are well suited to identify some cognitive constructs (e.g. skills, rules, knowledge; Vicente 1999) that reside in the minds of users of the system under analysis. However, we argue that CWA can currently overlook canonical or fixed ideas that exist independently of system agents and physical objects, and yet form part of the system's functional structure. We argue that such ideas play an increasingly prominent role in emerging, complex STS, and must be considered as objects and included in WDA, alongside physical objects.

Work analysis and sociotechnical systems

STS have been variously described as those systems which include social, technical, and psychological components or aspects (Klein 2014; Trist 1981; Vicente 1999). STS theory emerged in the mid-20th century (e.g. Trist 1981; Trist and Bamforth 1951) as a response to the increasing emergence of technology in work and a recognition of the need to understand the changing nature of work. STS is a work design approach concerned with both the performance of the work system and the experience and well-being of workers (Clegg 2000). A key tenet of STS theory is that systems require adaptive capacity; one of the primary means to achieve this is to analyse social, psychological and technical elements of the system and their interactions together. This holistic approach to analysis supports the joint optimisation of human and technical elements across the system of interest.

Although it originated in the domains of industrial work (Trist and Bamforth 1951), STS theory has become a popular means of both understanding and designing STS. In addition to typical systems of work, it has been applied beyond the workplace to social systems such as road and rail transport (Read, Salmon, and Lenne 2016; Salmon et al. 2018b), house design (Naikar 2013), home carpentry (Lintern 2009) and sport (Hulme et al. 2017; McLean et al. 2017).

Level of abstraction	Label	Description
High ↑	Functional Purposes	The objectives of a system
	Value and Priority Measures	Measurable criteria that can indicate the extent to which system purposes are achieved.
	Purpose-Related Functions	Functions that must be fulfilled to achieve system purposes.
	Object-Related Processes	The processes afforded by a system's objects that can serve system functions.
Low ↓	Physical Objects	The physical objects in a system that afford its functional processes.

Figure 1. Abstraction hierarchy standard labels (Naikar 2013).

Cognitive work analysis and work domain analysis

CWA (Vicente 1999) is a framework for analysing the physical and social environmental constraints and affordances in STS. CWA originated from the pioneering work of Jens Rasmussen at the Risø National Laboratory in Denmark (e.g. Rasmussen and Timmerman 1962). Beginning in the early 1960s, Rasmussen's aim was to provide a framework to help understand the human and technical factors that combined to determine the safety and performance of nuclear reactor systems (Vicente 1999). CWA provides a set of conceptual tools for modelling several nested dimensions of the physical and social environments within which STS occur (See Vicente 1999 for an overview of the framework).

The abstraction hierarchy (AH) is the foundational construct for WDA and therefore, for CWA. It consists of a five-tier model where the lowest level represents the least abstract view of the system and the highest level represents the most abstract view (Rasmussen, Pejtersen, and Goodstein 1994, 44). During the evolution of WDA, the labels for each level have been modified and adapted as scholars and analysts refined the method (Naikar 2013, 51–75; Rasmussen, Pejtersen, and Goodstein 1994, 45–48; Vicente 1999, 166). The highest level of abstraction in the hierarchy represents system elements that Rasmussen framed as 'reasons' for the system's existence, while the lowest level represents system elements that act as 'causes' to control the physical functions of the system (Rasmussen 1979, 3). Synthesising the work of foregoing scholars and noting the need for flexibility in both the number and labels of AH levels, Naikar (2013, 67–75) described a standard set of labels for an abstraction hierarchy, as represented in Figure 1.

At the lowest level, the AH identifies the physical objects that are or could be deployed to serve a system's purpose. The second level represents object-related processes that can arise from agent interactions with the objects. The third level shows general functions that serve the system's purposes. At the level above, there are values and measures that can guide and monitor system performance. Finally, the functional purposes of the system are represented at the top level.

This method produces a comprehensive, holistic picture of a system's structure, allowing analysts to discern what it is capable of achieving. Vicente (1999) describes how, while a task analysis describes a set of directions for a worker, WDA describes the functional environment within which the work takes place (157). The later phases of CWA introduce tasks and agents into the functional structure identified in WDA to offer a progressively rich analysis of the detail of actual or possible system performance.

The accuracy, and therefore the utility, of the latter phases of CWA is often influenced by the accuracy of WDA. Furthermore, the scope of application of CWA will be limited by the range of application of its foundational phase, WDA. If the description of the work domain provided by WDA is incomplete, so too will be the products of all other CWA phases. We argue that, in addition to physical objects, some STS also include cognitive objects. For the purposes of CWA, WDA, and the AH, these non-physical objects share many of the same attributes as physical objects. They are components of the system prior to their interaction with agents in the system. That is, the system does not rely on agents bringing these objects into the system. Agents may encounter them on every new interaction with the system. They are thus agent and event independent components of the system's functional structure. Most importantly, processes can uniquely emerge from agent interactions with cognitive objects that serve important system functions.

Two objections to the inclusion of cognitive objects alongside physical objects at the lowest level of the AH arise from traditional formulations of CWA (Naikar 2013; Rasmussen, Pejtersen, and Goodstein 1994; Vicente 1999). The first is that all cognition is abstract, and that the higher levels of the AH, along with latter phases and products of CWA (e.g. StrA, decision ladders, WCA; Jenkins et al. 2009) already account for memes. Cognitive objects as we will describe them are indeed in a global sense 'abstractions', as defined by Deutsch (Deutsch 2011, 114–119). That is, a cognitive object emerges originally from a physical substrate, such as a group of neurons in a brain. However, once the object exists, it can be transmitted to other brains. Its existence is not confined to the brain in which it emerged. Indeed, some cognitive objects will replicate and evolve independently of their origin in a process of cultural selection (Dawkins 2006, 214–218). Their subsequent instantiation consists of interaction between a cognising entity (i.e. a human or non-human agent) and the persistent cognitive object (i.e. the meme). We argue that in some specific STS, their functional role can best be located at the least abstract level of that system. We argue that where their omission from an abstraction hierarchy would diminish the utility of the analysis, cognitive objects should instead be identified and included. Therefore, we propose that the possibility of the existence of cognitive objects, along with a careful definition, should be added to the taxonomy of entities to be considered for inclusion in WDA.

A second related objection is that ideas are neither agent nor event independent. They can surely only exist in the flow of time within the mind of an agent. This should rule them out as candidates for inclusion in WDA's models of the agent and event independent functional structure of STS. We argue, however, that ideas are commonly transmitted from external sources into minds as described by Deutsch (2011, 93) and others (e.g. Dawkins 2006; Delius 1991). Theories of distributed and embodied cognition also offer an explanation of how ideas, along with other components of cognition, can be distributed among a set of agents, physical entities, and processes. These observations show that cognitive objects can be, and often are, independent of agents within an STS. We will draw on these theories in the sections below to support our proposal to include cognitive objects, where useful, at the lowest level of the AH. To qualify as event independent, physical or cognitive objects do not need to be timeless. After all, few physical objects described in WDA have existed since the beginning of time. Instead, to qualify as event independent for the purposes of WDA, an object merely needs to have existed as part of the system prior to the system's activation (triggered by agent interaction).

Following Rasmussen (1985, 4–5), Naikar (2013, 25–27) distinguishes between 'causal' and 'intentional' STS. The former are defined as those where actor behaviour in the system is primarily constrained by physical or natural laws while in the latter, behaviour is constrained more by social conventions, individual values, and internal goals. It is initially tempting to suspect that STS that include cognitive objects must be more intentional than causal. However, this may not be the case. The conventions, values, and goals noted by Rasmussen and Naikar are generally represented in AH at higher levels of abstraction, particularly at the values and priority measures level (e.g. health, pleasure, conservation; Naikar 2013, 26). There is a reliance in these systems upon the a-priori intentions of actors. In contrast, cognitive objects are truly actor independent and can have the selfish, self-replicating characteristics of memes, as described by Blackmore (2000, 27–32). Therefore, the presence or absence of cognitive objects in STS is not a predictor of the position of that STS along the spectrum from causal to intentional systems (Naikar 2013, 39).

The claim that cognitive objects can form part of the agent and event independent functional structure of an STS relies on the possibility that these non-physical entities can reside somewhere other than the minds of system agents.

Distributed cognition and schema theory

Recently, the theory of distributed cognition has become an important lens to analyse STS (Chatzimichailidou and Dokas 2016; Plant and Stanton 2016; Salmon, Read, and Stevens 2016; Salmon et al. 2008; 2014; Stanton 2016; Stanton et al. 2009). This fundamentally changes the understanding of cognition from that which underpinned the early development of CWA. As a result, the manner in which WDA incorporates objects that underpin cognition requires an update.

Both distributed cognition theory (Hutchins 1995) and the related exploration of distributed situation awareness (Stanton et al. 2006) describe how cognition can be distributed among agents and objects in STS. From the perspective of an agent, this means that some aspects of cognition can be externally represented (Zhang and Norman 1994). Schema theory (Bartlett 1932) provides a foundation to explain how stored frameworks of contextual concepts filter perception. A schema is a mental template that modifies information and influences behaviour (Stanton et al. 2009). While initially conceived as a phenomenon within individual minds, schemata may be distributed among groups. For example, Daft and Weick (1984) describe how assumptions about the environment among managers in organisations conglomerate into a shared model that informs collective decisions and action. Moreover, distributed cognition theory reveals the possibility that behaviour-shaping schemata may include or consist of external representations.

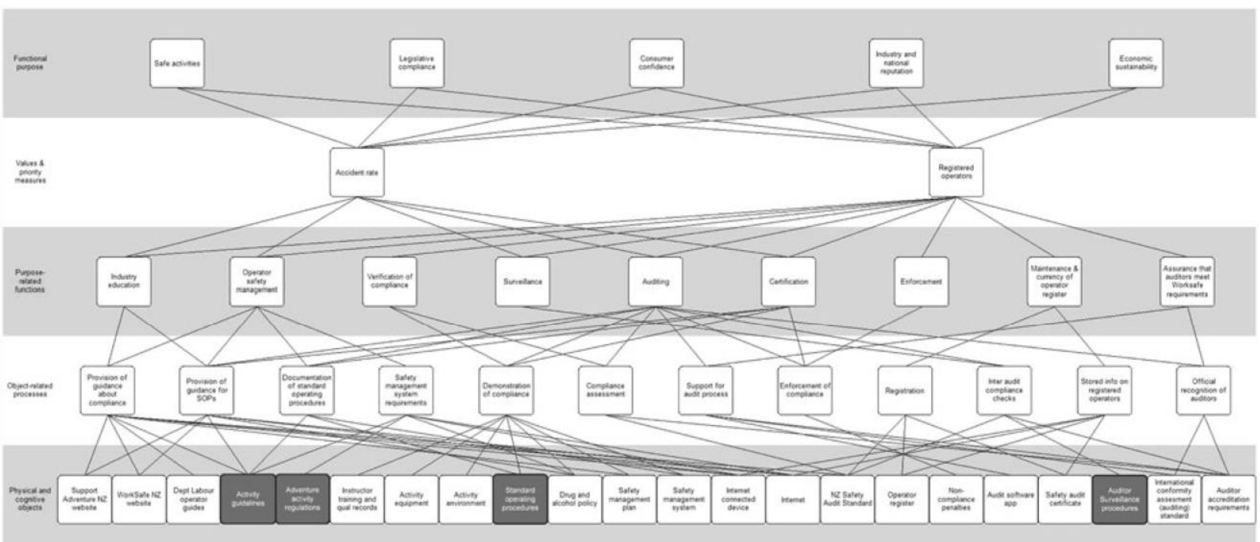

Figure 2. AH of the New Zealand Adventure Activities Certification Scheme. Shaded objects at the lowest level may best be modelled as cognitive rather than physical.

More recently ergonomics researchers have shown how schemata filter and shape individual agents' interpretation of perceived data in STS and thereby influence decision-making and action (Salmon et al. 2014). Stanton et al. (2009) discuss two levels of schemata held by individuals in STS: genotypic and phenotypic. A genotypic schema is a passive set of situational assumptions. When activated in a relevant situation, it is modified by perceived data and instantiates in a situational phenotypic schema which in turn influences decisions and actions in real time. This instantiation of the genotypic schema via a phenotypic 'child' schema can, in turn, modify the genotypic schema through internal feedback. CWA can currently support the modelling of these individual schemata in the upper levels of the AH, in decision ladders, and in WCA. However, some collective schemata and their affordances are so critical to STS performance, that system design either does not or should not rely on their importation to the system by agents. Furthermore, unlike schemata held within the minds of individuals, externally represented schemata are unable to be quickly modified through any automatic feedback mechanism. Instead, we argue that they are fundamental, incorrigible objects that form part of those systems' functional structure.

In summary, this paper examines the proposition that STS rely upon powerful ideas or concepts to the extent that these ideas constitute fundamental elements of the system's functional structure. In such cases, where these critical concepts are independent of their physical representations, of system users, or any particular instantiation of the system, we explore the validity of including them and explicitly identifying their cognitive nature at the objects level within an AH.

Method

Case studies

Case study 1

A regulatory system for adventure activity safety. The New Zealand Adventure Activity Regulations (NZAAR; Mateparae 2016) were implemented in 2011 after an extensive review and reform process, facilitated by the New Zealand Government. The scheme requires commercial providers of outdoor adventure activities to comply with regulatory requirements. (WorkSafe 2014).

While regulation has been more commonly viewed by ergonomists as a component of a work domain (e.g. Rasmussen 1997), Carden et al. (2017) analysed the New Zealand Adventure Activity Regulations (NZAAR; Mateparae 2016) as a STS in its own right. This analysis identified cognitive and physical objects at the lowest level of the AH (see Figure 2).

The AH for the NZAAR shows 22 objects at the lowest level, many of which are unambiguously physical objects and several of which could be considered as cognitive objects. For example, ‘activity guidelines’ is one object that may be considered as either a physical or a cognitive object. If the system reliably supports agents to interact with the physical object (e.g. a physical document, handbook, or webpage), it may be sufficient to identify the objects solely as physical. This would mean any desired changes to the object revealed by WDA

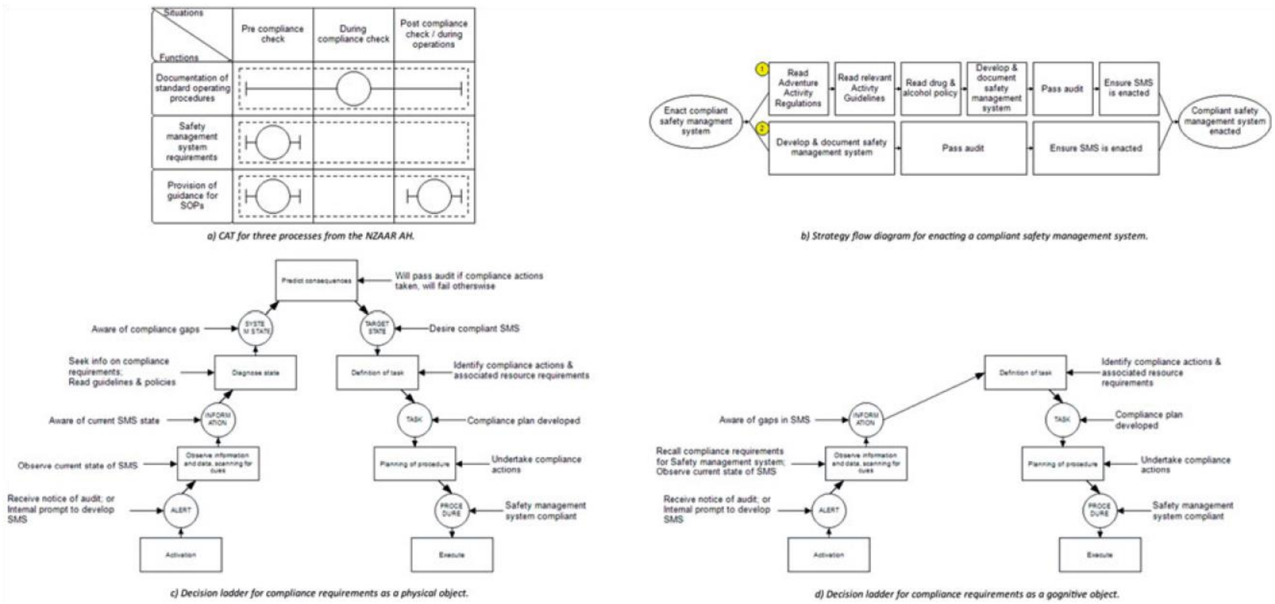

Figure 3. Contextual activity template, strategy flow diagram, and decision ladders for the NZAAR.

could be enacted upon those physical objects. However, if agents are likely to gain their understanding of the activity guidelines by other means, the object’s identification as physical may be insufficient.

An agent developing standard operating procedures (SOPs) for the first time is likely to read the authorised, current version of the activity guidelines. However, some agents may rely on their previous experience with writing SOPs for adventure activities, common industry knowledge, or memory of their previous reading of the official activity guidelines. These alternative means of accessing information show that the physical object may not actually be used in all cases and that the cognitive processes that support the development of SOPs are distributed across the system. In the former case, the agent relied on an external representation of relevant information while the agent in the latter case called upon an internal representation of the relevant information (Zhang and Norman 1994).

While a novice agent may be more likely to interact with a physical object (e.g. read the written guidelines to gain an understanding of their compliance obligations), they may for future compliance activity rely on their memory of the requirements. This memory will form the basis of that agent’s own iteration of the cognitive object, modifiable by their internal schemata and experience, with which they may subsequently interact to afford understanding of compliance requirements. This iteration of the cognitive object may also become a source for other agents who may gain their own understanding of the guidelines from the first agent, rather than by reading the written guidelines. The second agent will then have interacted only with a cognitive version of the object and not the physical version. The second agent then becomes another node for the distributed external representation of the cognitive object for future agents.

An important distinction comes into view here between the intent of system designers and how the system is actually used. A growing body of ergonomics literature refers to this distinction as 'work-as-imagined' versus 'work-as-done' (Hollnagel 2017; Hysong et al. 2005). This research reveals gaps between STS design and STS operation. Reasons for these gaps include time and resource pressures, leading agents to find and normalise shortcuts to achieve goals. In the case of activity guidelines, it seems reasonable to predict that agents would prefer to interact with a cognitive rather than a physical version if it saves time and money but still achieves the goal of affording sufficient understanding to meet compliance requirements. The explicit inclusion of cognitive objects in descriptive WDA improves the likelihood of detecting gaps between work-as-imagined and work-as-done. Their inclusion in formative applications of WDA supports designers' capacity to close such gaps.

Figure 3 shows 4 diagrams arising from the application of the second and third phases of CWA, Control Task Analysis and Strategies Analysis to a selection of processes afforded by the object, 'activity guidelines'. The four object related processes linked to activity guidelines in the AH (Figure 2) show that it is a means of affording compliance guidance, guidance for

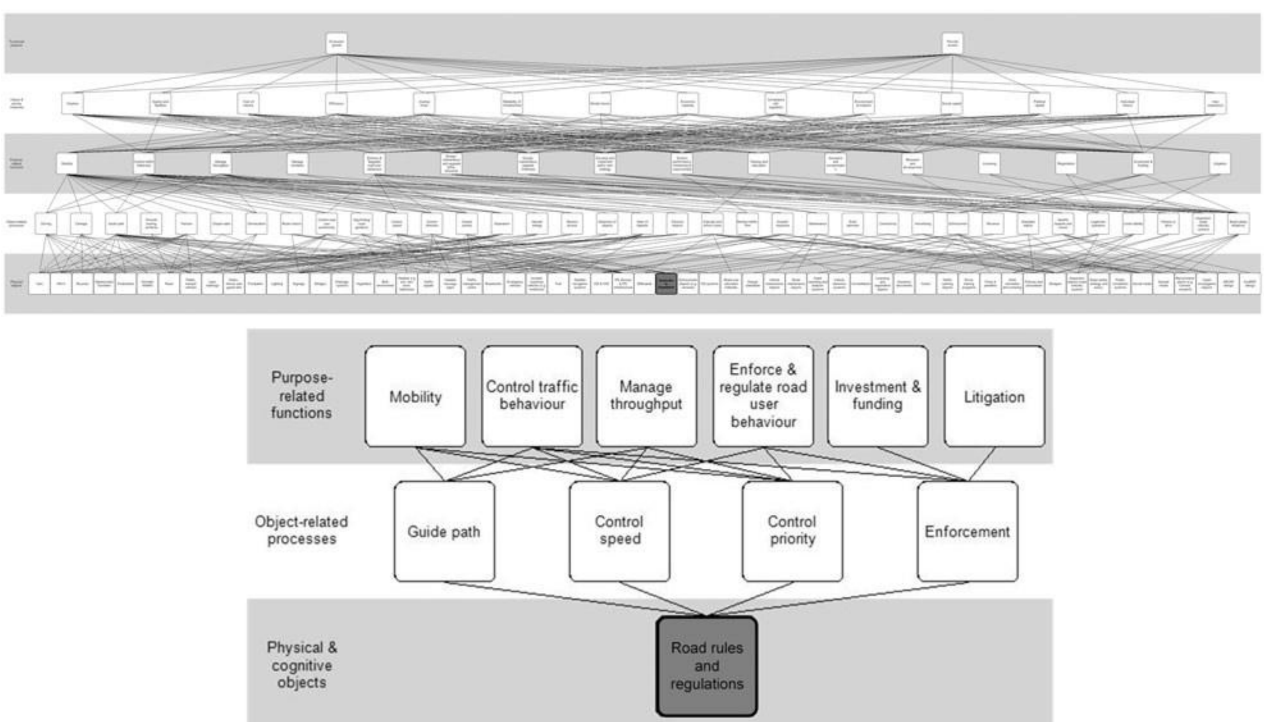

Figure 4. AH of the Queensland road transport system (Salmon et al. 2018a). As the node labels in the full AH are too small to be read at this scale, the nodes relevant to the present analysis are extracted below. These include the cognitive object, 'Road rules and regulations' along with its linked processes and functions.

developing standard operating procedures (SOP), the documentation of SOPs, and safety management system requirements. Three of these are shown in the Contextual Activity Template (CAT; Jenkins et al. 2009, 185–187) at the top-left of Figure 3.

Applying Cornelissen et al.'s (2013) strategies analysis diagram (SAD) formulation to the two strategies shown in the strategy flow diagram (top-right of Figure 3) and the two decision ladders (Jenkins et al. 2009, 187–189) below guides us to refer to object and function nodes linked to the object-related process, 'safety management system requirements', in the AH (Figure 2). We can then add a verb to describe how a user would interact with the relevant object under each of the two conditions shown in the strategy flow diagram and the two decision ladders. This results in two descriptive sentences. First 'Reading Activity Guidelines leads to an understanding of Safety Management System requirements which supports Operator Safety Management'. Secondly, 'Recollection of Activity Guidelines guides the application of Safety Management System Requirements to Operator Safety Management'. If the activity guidelines change, assuring that the change has the desired effect on the purpose-related function of operator safety management would require only a change to the content of the physical object if users could be relied upon to read it.

If it is likely that users will not refer to the official version of the activity guidelines on a regular basis to maintain a compliant safety management system, other strategies will be required to enact the desired system change. These strategies would need to affect the cognitive version of the activity guidelines object. They could include training, awareness campaigns, or the introduction of new technologies to update users.

Case study 2

Queensland road transport system. The AH shown in Figure 4 represents the functional structure of the road transport system in Queensland, Australia (Salmon et al. 2018a). This AH was developed initially using publicly available documentation about the Qld road transport system (e.g. National and state road safety strategies, road rules and regulations, standards) and existing systems analyses previously undertaken by the authors (e.g. Salmon, Read, and Stevens 2016). The draft AH was then reviewed and refined in a subject matter expert workshop involving researchers with extensive experience in road safety research as well as applied systems thinking research across a range of domains.

Naikar's (2013) nine-step WDA methodology was applied across the draft AH development phase and subsequent workshop. This involved initially establishing the aims and purpose of the analysis (as expressed

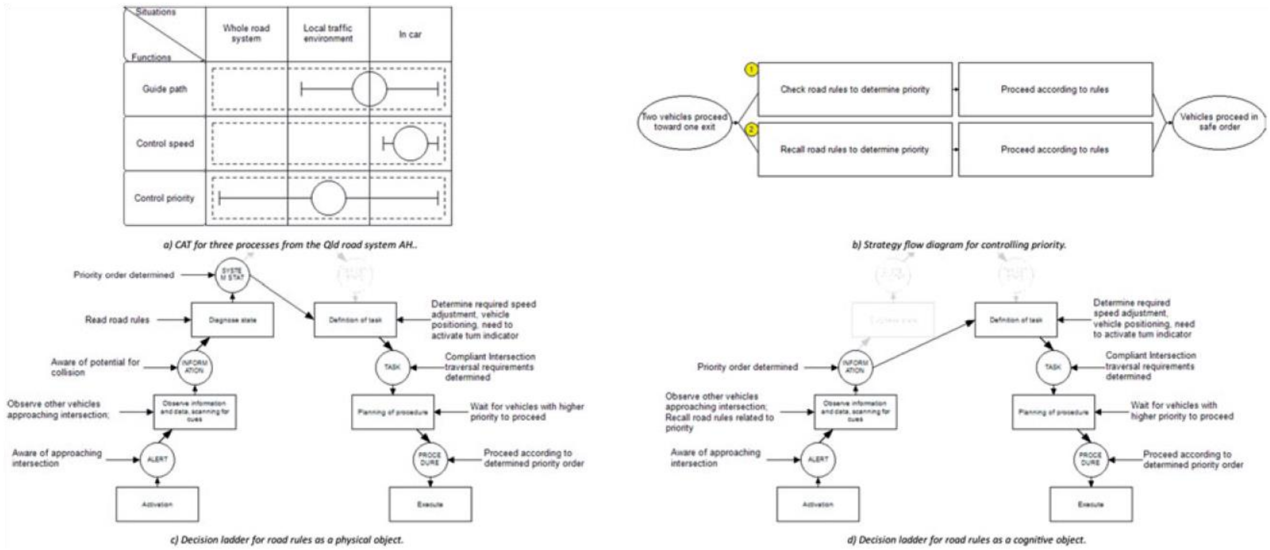

Figure 5. Contextual activity template, strategy flow diagram, and decision ladders for the QLD road transport system.

earlier) and discussing any relevant project constraints. Next, the analysis boundary was defined as the Qld road transport system incorporating the activities of the agents and organisations described by Salmon, Read, and Stevens (2016) in their Qld road transport system control structure model. Salmon et al's (2016) control structure model included all of the agents and organisations who play a role in the design and operation of the road transport system in Qld. This included agents across the following six levels: international context; parliament and legislatures, government agencies, industry associations, user groups, insurance companies, courts and universities; operational delivery and management; local management and supervision; and the operating process and environment.

While most of the objects shown in Figure 4 are unambiguously physical (e.g. cars, motorcycles, heavy goods vehicles, bicycles, buses), several are not. For example, the object 'Road rules and regulations', like the 'Activity Guidelines' in case 1, affords processes that directly rely on the content of the rules and regulations, rather than the properties of any physical document or display.

The CAT at the top-left of Figure 5 shows 3 object-related processes that rely upon the object, 'Road rules and regulations'. As with the object 'activity guidelines' considered in case 1, the strategy flow diagram and decision ladders in Figure 5 show that 'road rules and regulations' when considered as a physical object yields different analytic results than when it is considered as a cognitive object. Once again, the decision process is shown to be shorter when no reading of a document is included. As with the previous case, the analytic value in this case of separate consideration of the object as cognitive should be determined by an estimation of how likely it is that agents will access the object in its physical form. In the case of road rules and regulations, while some drivers may be relied upon to have read the road rules when studying for their driver's licence, it seems quite unlikely that most will read them again (Li and Tay 2014). As a result, external representations of the rules are distributed across the system in the form of additional physical objects (e.g. speed limit signs, warning signs) and cognitive objects (e.g. popular opinion). In practice, drivers use skill-based behaviour (Vicente 1999, 292–308) supported by their internal correlate (Zhang and Norman 1994, 90) of an external representation of the road rules. This suggests that, for a change of the road rules to be understood and internalised by drivers and thereby influence the linked system processes, functions, and purposes, modification of the physical object alone (e.g. the official road rules manual) is likely to be insufficient. Rather, road user education campaigns (World Health Organization 2004, 137) or other strategies (e.g. in-car warning systems) are required.

The strategy sentences generated by application of the SAD method support the suggestion that reading of any physical object representing road rules is quite unlikely when cognition occurs in real time: 'Reading the road rules clarifies which vehicle has priority, thereby controlling traffic behaviour'. This seems less likely to occur than the alternative strategy that arises from identification of road rules and regulations as a cognitive object: 'Recollection of the road rules

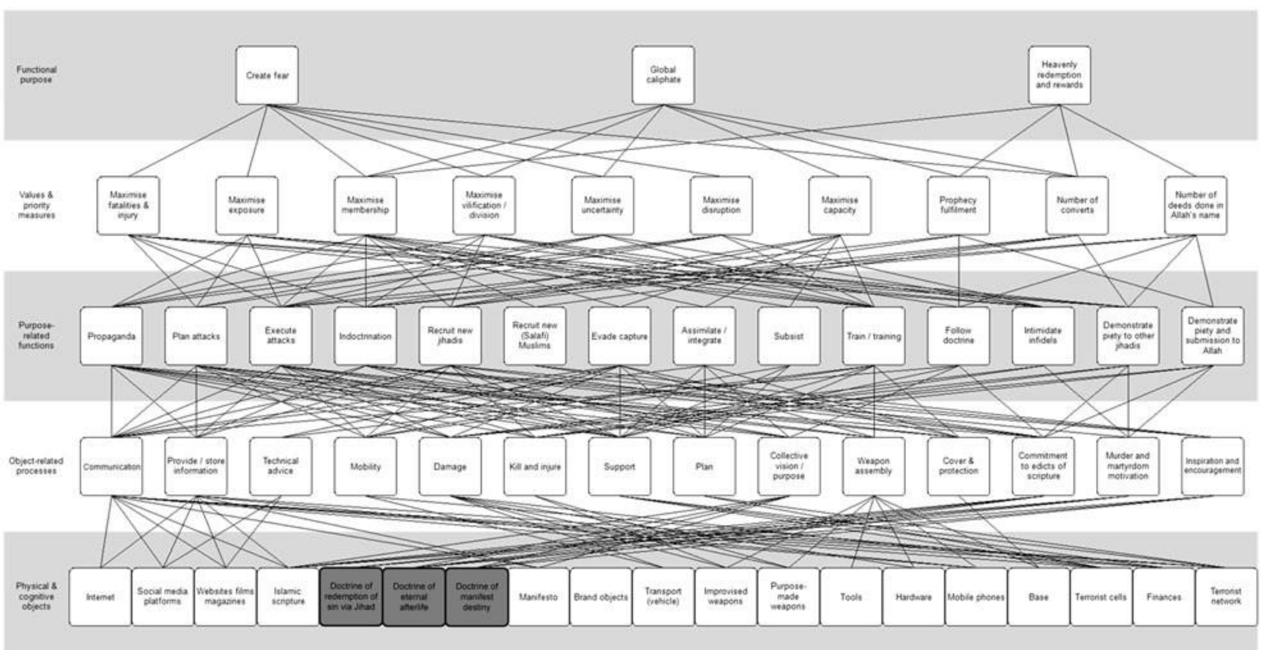

Figure 6. AH of a terrorist group (Salmon, Carden, and Stevens 2018). Shaded objects at the lowest level are cognitive rather than physical.

indicates which vehicle has priority, thereby controlling traffic behaviour'. However, the enactment and enforcement of any change in the road rules would require a physical reference point both for driver education and to support enforcement. To successfully change system outcomes by modifying road rules would, therefore, seem to require modification of both a cognitive and a physical iteration of the 'road rules and regulations' object. Both object types should, therefore, be included in the AH.

Jihadi Islamist terrorist group. The AH shown in Figure 6 represents the functional structure of the STS of a Jihadi Islamist terrorist group, such as Islamic State (Wood 2016). The analysis of this system (Salmon, Carden, and Stevens 2018) was based on data sourced from journalistic, academic and jihadi sources. Contrary to traditional applications of CWA and its components, this novel application of WDA seeks to produce analytic insights that support disruption of the system and its purposes.

The 19 objects shown at the lowest AH level include several that could be considered as cognitive objects. 'Islamic scripture', the 'doctrine of redemption of sin via jihad' (e.g. Quran 4:74), the 'doctrine of eternal afterlife' (e.g. Quran 30:40), the 'doctrine of manifest destiny' (e.g. Quran 8:39), and 'manifesto' are all objects that impose cognitive constraints upon system users. However, the objects 'Islamic scripture' and 'manifesto' may adequately be described as physical objects. 'Islamic scripture' is a broadly descriptive object which includes a wide array of material with varying degrees of authority and influence. It seems sufficient to consider this as a broadly described physical object which affords processes at higher levels of abstraction that impose more specific constraints on system users. 'Manifesto' can be considered as the set of operating rules or constitution of the terror group. Its content is, at least in principle, amenable to change by system users. In contrast, the three doctrines shown provide specific constraints and affordances for system users. As specific, canonical doctrines (Cook 2000, 28), these objects are not amenable to modification by system users. They can, therefore, be considered as components of the physical and social environment which forms the functional structure of this system (Vicente 1999, 50–51).

Like the physical objects identified, these three cognitive objects both constrain and afford a range of possibilities for action within this system (Vicente 1999, 119). No particular physical container or conduit for these doctrines is required. It is the meme itself – the cognitive object – which has the most concrete level of form that is relevant to these objects in this system. It may be noted that for the devout, these doctrines are held to be even less malleable than the laws of nature (Quran 35:43; Cook 2000, 60). Furthermore, none of them exists as a distinct, bounded component of a specific text. Instead, they

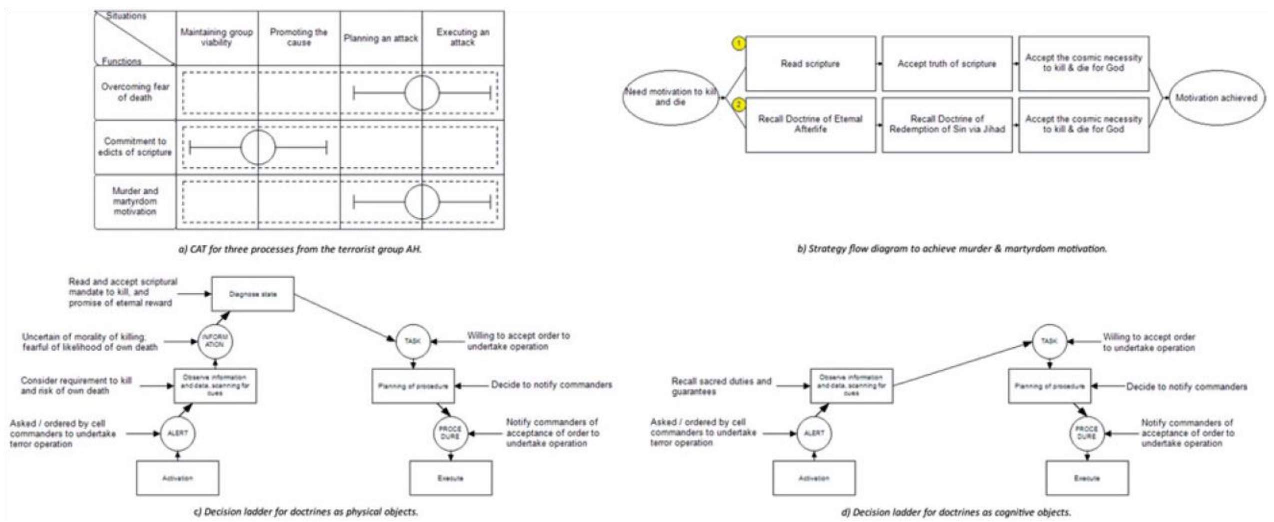

Figure 7. Contextual activity template, strategy flow diagram, and decision ladders for the terrorist group system.

are distributed widely across the canon of, not only Islamic scripture but many religious traditions.

The object-related process 'murder and martyrdom motivation' is supported by the three doctrines. The strategy flow diagram and decision ladders in Figure 7 show alternative strategies available to agents to allow them to find the motivation to overcome the fear of killing and dying. Both strategies rely on acceptance of one or more of the doctrines. However, the decision ladders illustrate a more deliberate and less certain decision pathway if the agent relies on the reading of scripture, compared with the pathway that relies instead on a pre-existing acceptance of these externally represented, shared memes.

As with cases 1 and 2, modifying the processes and functions that depend on the doctrine objects in this system look quite different if the objects are considered to be cognitive objects rather than physical objects. If the aim of the analysis is to disrupt this malevolent system, analysis showing the doctrines as physical objects suggest modifying the content of the canonical texts may achieve this aim. When analysis identifies these doctrines as cognitive objects, the necessity for a different range of disruption strategies appears. These might include, for example, existing and novel de-radicalisation strategies, along with other re-education and influence efforts (e.g. as cited in http://www.abdullahx.com/; Moonshot CVE 2018).

The divergent outputs of analysis are supported by the sentences that arise from application of the SAD method. For the strategy relying on the physical version of a doctrine object, the following sentence applies: 'Reading the doctrine of redemption of sin via jihad provides murder and martyrdom motivation allowing the jihadi to execute attacks'. The process and function being supported here appear to require a psychological force that seems unlikely to be attained by a simple reading of doctrine. A deeper, more enduring commitment appears more likely to achieve the necessary impetus: 'Recalling the doctrine of redemption of sin via jihad provides murder and martyrdom motivation allowing the jihadi to execute attacks'.

Discussion

This article aimed to justify an extension to WDA, a method that is currently popular in systems ergonomics applications, to include cognitive objects. Three case studies were used to show that, in some STS, some of the cognitive and behavioural affordances arise, not from the interaction of agents with any physical object, but from interaction with a cognitive object – an ideational representation or meme (Dawkins 2006) that exists independently of the agent. Accordingly, it is these authors' contention that the AH method should be extended to incorporate both physical and cognitive objects at its lowest level.

In case 1, the usefulness of identifying the object 'activity guidelines' as cognitive as well as or instead of physical was marginal and would depend on the purpose of analysis. Any such utility depended on the likelihood of relevant agents in the system rarely accessing the physical version of the object but instead relying on externally represented versions of the information it contained (e.g. word-of-mouth, observation of others).

In case 2, identifying 'road rules and regulations' as a cognitive as well as a physical object seemed more necessary, as most relevant system agents were unlikely to interact with the physical version of the object to give rise to the linked object-related processes identified in the AH. Explicit identification of road rules and regulations as a cognitive object as well as a physical one supports better-targeted interventions where analysis shows a need for change in that object.

In case 3, the identification of the three 'doctrine' objects as cognitive rather than physical was critical to the accuracy and utility of the analysis. These objects are widely distributed, are not confined to any specific physical objects, and to the extent that they are represented in physical objects, these objects (e.g. the Koran, the Hadith, the Bible) are beyond the scope of analysts or disrupters of the Jihadi STS to modify.

Our findings suggest that it is important to identify both physical and cognitive objects when developing AHs as part of a WDA. A cognitive object is an externally represented synaptic pattern that is a foundational component of the functional structure of an STS. To qualify as a cognitive object for inclusion in the AH, a cognitive object must meet the following criteria.

- It must afford processes that support functional purposes
- Its affordances must differ from any analogous physical object;
- The inclusion of the cognitive object must preserve the local agent and event independence of the AH;
- Memes must have sufficient endurance and stability to qualify as a cognitive object (i.e. the cognitive object must be capable of consistent recognition and use by novice agents);
- A cognitive object must uniquely support processes that support system functions in ways that cannot be fully ascribed to any particular container or conduit.

To offset the possibility that including cognitive objects may further complicate CWA, the current AH level labels could each be replaced with a single word: Purposes, Measures, Functions, Processes and Objects.

Whilst we have argued that the inclusion of cognitive objects is a novel extension to WDA and the abstraction hierarchy method, it is worth noting that previous analyses have included what appear to be cognitive objects. These analyses have either followed the orthodox level-labelling convention by conflating them with associated physical objects or locating them at a higher level of abstraction. For example, in his WDA of the management of microsystems design, Durugbo (2012) identifies 'virtual prototype' at the lowest level of abstraction, linked upward to the physical function (object-related process), 'model testing'. All other elements shown at the lowest level are unambiguously physical objects linked upward to affordances that would emerge from user interaction. However, the virtual prototype is not itself a physical object. Unlike the 'physical prototype' alongside it that affords the same physical function (object-related process), the virtual prototype is an ephemeral construct: a cognitive object. The author makes this explicit, noting 'Prototypes can be described as quickly created samples or replicas for analysis by physical means or abstract representation. Abstract representations or virtual prototypes for MST may be computer databases or CAD files generated by CAD software'. (Durugbo 2012, 613). Although an abstract representation, the virtual prototype is actor and event independent and unambiguously belongs at the objects level in the AH.

Lintern (2008) explicitly includes facts, ideas, and opinions as lower level entities in an abstraction hierarchy for a reasoning space. However, these entities are identified as physical functions (object-related processes) at the second lowest level of the AH rather than as objects. The objects level in Lintern's model is populated by physical sources of those ideational entities. Identifying facts, ideas, and opinions as processes emerging from user interaction with a selection of source objects such as sensors, maps, and spreadsheets may be appropriate for the military planning system Lintern describes. However, in some systems including those described in our three case studies, data is neither reliably available to users from such sources in real time nor do these systems rely upon such physical source objects. Sources of cognitive objects can include not only physical objects like rulebooks, web pages and scripture, but an imitation of the behaviour of others, and memory of culturally entrenched tropes. It may be the case that, if Lintern's Reasoning Space were to be generalised beyond the military context, the entities in the physical functions level of his AH might better be dropped down to the lowest level of abstraction replacing the now somewhat arbitrary list of physical source objects. The physical functions (object-related processes) level could then be populated with the cognitive filtering processes (e.g. comparing new data with existing data, interpretation of data) that provide the means to support the general functions of insight and understanding.

Cognitive objects need only be included in an AH where achievement of the purpose of analysis requires modification of processes and functions that depend uniquely on the cognitive object. Therefore, where a physical object supports the same affordance as a cognitive object and system users can be relied upon to interact with the physical object, identification of an analogous cognitive object that supports the same affordance may be unnecessary.

When cognitive objects and analogous physical objects provide different affordances that are found to require a change to achieve the aims of analysis, different strategies will be required to change each. In these cases, it is important to identify cognitive objects in the AH. In contrast, if the affordances linked to a cognitive object are not found by the analysis to require change, or if they are identical to the affordances of a physical analogue, it may be adequate to represent the object simply as physical, as no strategy development is required to achieve desired changes.

For each of the case studies, non-physical objects were identified which afforded object-related processes. While these objects could be found in various physical containers or conduits, their affordances differed from those of their containers and conduits. Although the container too should be included in the AH if its properties mean that it imposes constraints and affords actions that are relevant to purpose-specific functions, these should not be confused with the constraints and affordances provided by the cognitive object it contains. In each of the three cases, the analyses demonstrated how, were the cognitive objects to be conflated with their physical container, important system design requirements would be overlooked.

Indeed, if the relevant process is afforded by the content rather than the container, for some systems and some analyses it may be important to distinguish between the two. While the design and modification of books and webpages can be achieved with one set of actions, the design and modification of enduring concepts may require another. The examples provided by these case studies show three different outcomes of the separate identification of cognitive objects and their physical containers. They illustrate that in some systems where cognition is distributed, the explicit recognition of cognitive objects in WDA adds analytic value.

Future applications

Part of the impetus for the proposed modification to WDA and the AH comes from the fact that the ergonomics problem space is shifting. These changes are likely to bring about new and emergent problems that require the intervention of ergonomics. Examples include autonomous vehicles, advanced automation, and artificial intelligence. The identification and analysis of cognitive objects will be paramount when attempting to design or evaluate such systems. In the case of AI, for example, ideas will enter machine cognition post their engagement in the system. Like their human analogues, AI will bring some prior 'knowledge' to their role in the system. They will acquire more knowledge within the system from their interaction with other system entities. However, unlike their human counterparts, AI agents cannot be relied upon by system designers to bring a standard set of common-sense or cultural background knowledge to the system. Systems will need to include specific and reliable means to convey cognitive objects upon which they rely to AI agents. By supporting the understanding and modelling of units of knowledge as modifiable objects, the inclusion of cognitive objects in the AH will improve the utility of WDA and in turn CWA for evaluating and improving the design of STS in which AI agents play an increasingly prominent role. Furthermore, efforts by AI safety researchers to improve transparency of AI decision making (e.g. Wachter, Mittelstadt, and Floridi 2017) may be supported by this adaptation of WDA due to its enhanced capacity to make cognitive constraints and affordances more explicit.

In addition, it may be that adding this capacity opens up further areas of analysis for CWA and systems ergonomics. While it has traditionally been used to improve the performance of sociotechnical systems with desirable purposes, the application of CWA to the disruption of systems that are designed to achieve illicit ends may have potential beyond the terror cell (Salmon, Carden, and Stevens 2018). Other examples may include systems with damaging outcomes that emerge from the functional structure of the system, regardless of whether those outcomes reflect intended functional purposes. One example may be institutional child abuse where many entities at the bottom level of a WDA would seem likely to be cognitive objects. These could include international laws and cultural beliefs. Another example may be climate change. It may be that the inclusion of cognitive objects in an analysis of the functional structure of the global STS that causes environmental damage offers valuable insight for policy makers. For example, specific, canonical memes may underpin economic ideologies which are drivers of climate change. These memes might include widespread beliefs such as 'economic growth is necessary', 'local actions only have local effects', and 'the unregulated free market is the best means to meet all needs'.

Conclusion

This study has shown that some sociotechnical systems include cognitive objects as part of their functional structure. The constraints afforded by these objects independently precede the cognitive constraints brought to the system by agents acting within it. On the basis of three case studies, it is concluded that WDA, and specifically the AH, should be modified to include both physical and cognitive objects. The findings from the case studies indicate that a richer, more valid, and more useful analysis is constructed when identifying both physical and cognitive objects. Therefore, in systems such as these, specific recognition in WDA of cognitive objects as components of a system's functional structure improves the analytic accuracy and utility of CWA. It is proposed that extending WDA and the AH in this manner will improve its capacity to cope with emergent systems such as autonomous vehicles and AI. Further applications are encouraged.

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