

Internal representations, external representations and ergonomics: toward a theoretical integration

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Abstract

Ergonomics is concerned with how humans interact with systems to perform tasks that achieve goals. This interaction requires thought processes that construct and manipulate mental representations of situations to enable the selection of task-oriented actions having predicted outcomes. The argument for a link between concepts of mental representation and the concerns of ergonomists is a critical theme in the present review, which assesses the current state of knowledge regarding the nature of mental representations and the way in which they are deployed to enable effective system interaction. Other issues that we tackle head on include: (1) the vast range of existing terminology that underpins discussions about representational constructs; (2) the important role of memory in understanding mental representation; and (3) the tight coupling between external and internal representations during task performance. We conclude by proposing a novel, explanatory framework that aims to integrate disparate notions of mental and external representation.

Keywords: Mental representations; External representations; Mental models; Conceptual models; Mental imagery; Situation awareness; Ergonomics

1. Introduction

To perform a task or to interact with a system requires thought processes that create and transform mental representations of the existing situation (Bedny *et al.* 2004). Such representations enable the selection of task-based action sequences that have predicted outcomes relating to the attainment of current goals. Of course, the view that thinking involves the use of mental representations is not a recent one. Great thinkers such as Plato, Aristotle, Archimedes, Galileo and Einstein all explained how they used mental imagery in their creative work (Franklin 2000). In the first half of the last century, too, Craik (1943) referred to a different representational modality to imagery when he suggested that people mentally construct ‘small-scale models’ of reality that can be used to ‘try out various alternatives’. Indeed, the idea that thinking depends upon such *mental models* has driven a considerable amount of research over the past few decades (e.g. Johnson-Laird 1983, 2005, Gentner and Stevens 1983, Wilson and Rutherford 1989, Moray 1999). A related representational notion to mental models and images is that of ‘conceptual models’, proposed by Welford (1961) in an ergonomics context to describe system operators’ approximate, inexact, holistic mental images of systems that are acquired through experience.

The aim of our opening sentence was to claim a link between ergonomic issues concerning effective system interaction, and concepts of mental representation. We are certain that many ergonomists are familiar with this proposed link and accept its value (for examples of research examining ergonomics problems that pay close attention to issues of mental representation see Mogford 1997, Thatcher and Greyling, 1998, Niessen *et al.* 1999, and Sinreich *et al.* 2005). We also appreciate, however, that some

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more skeptical ergonomists may still question why they might benefit from any interest in mental representation. Perhaps a striking answer to such skeptical voices is to note that mental representations—and particularly deficiencies in them—seem typically to play out in the emergence of many accidents in high-reliability organisations. First, consider the Chernobyl nuclear accident that occurred in 1986 during a routine system test (see Medvedev 1991). Johnson-Laird (1999) proposes that an important contributor to the runaway nuclear reaction that arose was a failure on the part of the scientists who were conducting the test to draw a logically valid Modus Tollens inference from their model of the following rule: ‘If the test is to continue, then the turbine must be rotating fast enough’. Thus, with the knowledge that the turbine was *not rotating fast enough* the logical conclusion to deduce would have been that the test was *not to continue*. But the test did continue and a disaster ensued. Second, consider the role of mental representation in the Three-Mile Island nuclear core-meltdown incident in 1979. In the run-up to this incident the operators pushed a button to close a valve. The indicator light on the control panel signified that the valve was closed when, in fact, it was still open. The operators did not know that the indicator light did not monitor the valve itself, but the signal to the valve. This signal was telling the valve to shut, but it failed to do this because of a fault. In this incident the operators’ conceptual model of this part of the system was incorrect (arguably owing to poor design). Thus the mental representations used to deal with problems as they arose during the incident were incorrect, being based upon an erroneous conceptual model.

At a more routine level there is a clear use of mental representations in object-assembly tasks—an ergonomic domain that we have considerable interest in (e.g. Richardson *et al.* 2006) and that we will refer to repeatedly in this review as a way to

illustrate theoretical concepts with content-based examples. We simply note here that if people had no recourse to mental representations in object-assembly tasks then all assembly procedures would have to be tested by *physical* trial-and-error manipulations that operated directly on external objects. For example, in relation to the 2-D shapes in Figure 1, it can be seen—through mental representation—that B will join with C and not with A, and that A will not join with C. Physical manipulation is not required. We suggest that such simple examples provide compelling evidence for internal representations such as mental imagery underpinning mental-rotation processes. Imagery has also been claimed to underlie people’s understanding of mechanical systems (Shepard and Metzler 1971, Hegarty 2003), and imagery may well be a key medium for thought (Denis 1991). However, as will be discussed subsequently, mental representations of devices do not have to be image-based, and representational constructs such as mental models may offer a non-visual medium for thought that has different properties to that of imagery (cf. Johnson-Laird 1996).

[Insert figure 1 about here]

Suffice it to say for now, that we believe there are good arguments as well as impressive bodies of empirical evidence to attest to the importance of mental representations in task performance and system interaction. As such, we are keen to stress the value to ergonomists of a serious consideration of theoretical issues concerning the nature of functioning of mental representations. At the same time, we remain acutely aware that despite periodic attempts to clarify conceptual issues

concerning mental representation, the theorizing in this area continues to evolve rapidly and in an increasingly disconnected manner, hampered by a vast array of loose and overlapping terminology. For example, it is already apparent from the introduction that there are various different types of mental representation and a range of uses of the term mental model.

The present paper attempts to tackle such terminological and conceptual fragmentation head-on, so as to integrate the disparate notions of mental representation within a common theoretical framework. In progressing toward this framework we will begin with a detailed consideration of a variety of existing (and emerging) terminology that underpins discussions about representational constructs, including the important distinction between static and dynamic representations. We then discuss the important role of memory in understanding mental representation, as well as the tight coupling that exists between external and internal representations. Finally, we highlight apparent conceptual convergences in the literature and present a generic and unified representational framework that, we argue, has greater utility than the numerous task-specific proposals that have tended to dominate theorizing to date.

2. Mental models, conceptual models and mental imagery

2.1. What is a mental model?

There is much theoretical and applied research that refers to mental models, but the lack of unified terminology is confusing, especially when the same type of model is described with different vocabulary, by different authors, from different disciplines, and

from different perspectives (cf. Wilson and Rutherford 1989, Nielsen 1990, Payne *et al.* 1990, O'Malley and Draper 1992, Moray 1999). Indeed, we would argue that the advancement and integration of knowledge in relation to representational constructs is severely hindered by the lack of any serious attempt at developing unified terminology. Table 1, although not exhaustive, gives a good impression of the current confusion in terminology when researchers refer to mental representations in general, and mental models in particular. In this section we start to provide an overview of the concepts summarized in Table 1, and we additionally introduce the broader theoretical perspectives that subsume these representational notions.

[Insert table 1 about here]

To begin with, the most generic concepts are those of 'mental representation' and 'internal representation' (e.g. de Vega *et al.* 1996) which are equivalent, catchall concepts that serve to form a useful contrast class to notions of 'non-mental' representation or 'external' representation. Sometimes, however, the terms mental or internal representation are used synonymously with that of mental models (as noted by Wilson and Rutherford 1989), although mental models are just one form of mental representation. Indeed, Johnson-Laird (1983) proposed *three* distinct types of mental representation, which many other researchers would also recognise, even if disagreeing with details. First, there are propositional representations that encompass information in a way that resembles natural language, though in a tightly-constrained syntactic form. Second, there are 'mental images' that represent information in a visuo-spatial format.

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Third, there are mental models that are structural analogues of physical objects or states of affairs in the world.

The first two types of representation described by Johnson-Laird (1983) link closely with Paivio's (1971) 'dual-coding' view of cognition as involving two functionally separate yet interconnected representational systems specialized for processing either verbal and linguistic information (a propositional coding system) or non-verbal information (an image coding system). Johnson-Laird's third, models-based representational system involves abstract elements that cannot be visualized, but which reflect spatial information. Fleming *et al.* (in press) have shown that congenitally blind people with no visual experience are still able to construct such models—a finding that underlines their abstract, non-visual nature. Johnson-Laird further proposes that mental models and mental imagery are very closely related as 'images are views of models', with a model underlying the image (Johnson-Laird 1983, p. 157). The critical distinction between models and images remains, however, in that models are non-visual whereas images have a dominant visual component. More recently, Johnson-Laird (1996, 2004) has distanced himself from his earlier proposal that images are specific views of models, and he now sees images and models as being entirely separable representations. Given the impact of Johnson-Laird's mental models concept in domains as far ranging as reasoning, decision making, language processing, problem solving and creativity, the concept cannot be ignored, even if the precision of the notion is sometimes less than clear even in Johnson-Laird's own writings, where the representational construct is often finessed with the specific 'mental models theory' of reasoning (Johnson-Laird 2005).

The strength and general applicability of Johnson-Laird's mental models concept is supported by Manktelow and Jones (1987), who claim that users' models of interactive systems and devices (e.g. computer-based technologies) are an instantiation of mental models as described by Johnson-Laird (1983), and therefore work along the same essential principles. Similarly, Moray (1999) argues that people may use mental models in the way described by Johnson-Laird (1983) in a wide range of domains, including Human-Computer Interaction (HCI) and the navigation of supertankers. However, whilst these applications of the mental models concept further justify an acceptance of Johnson-Laird's terminology, we note that over the past few decades the term has been freely invoked in applied domains to refer to virtually *any* representation of the knowledge that a person may possess about physical devices (Tauber 1988).

Moray (1999) relates the differences in the use of mental models terminology to differences in the contexts in which people are forming and using mental models—with reference to the coupling between human, task and environment—and not to differences in the mental models concept per se. Nevertheless, the confusion of what constitutes a mental model can be seen from Table 1 and has existed (and been debated) for many years. In a particularly important review paper, Wilson and Rutherford (1989) examined mental models terminology and concluded that a 'mental model is a representation formed by the user of a system and/or task, based on previous experience as well as current observation, which provides most (if not all) of their subsequent system understanding and consequently dictates the level of task performance' (p. 619). This view is, again, closely allied to Johnson-Laird's theoretical position, as Wilson and Rutherford themselves acknowledge. In addition, Wilson and Rutherford give us an important reminder that in Johnson-Laird's theory (e.g. Johnson-Laird *et al.* 1992),

mental models are assumed to be constructed and manipulated within *working memory* (WM) rather than long-term memory (LTM). As we will discuss below, the role of WM as a mental substrate for model construction is critical in distinguishing between the notion of a mental model and that of a ‘conceptual model’.

Given the apparent generality of the mental models notion, a question that remains is: How are these models used in everyday tasks? The simple answer—as we noted in our introduction—is that they enable ‘thinking’, and in particular allow someone to predict the outcomes of their task-oriented or system-based actions. Indeed, the theoretical foundation of the mental models concept has been established through extensive laboratory research into specific types of thinking, such as deductive reasoning. However, as Johnson-Laird (2005) notes, in daily life no clear separation exists between different forms of thinking, such as deduction, induction or abduction. Earlier we considered how errors specifically associated with *deductive reasoning* were a likely contributing factor in the Chernobyl disaster, but apart from this one example, other salient illustrations of how mental models may underpin deductive competence or deductive failure in applied contexts are not that common. However, when the concept of mental models is considered more generally than in the limited sense of a representation underpinning deduction, then other applied examples are more readily forthcoming. For example, Shalin *et al.* (1996) consider mental models in their cognitive perspective on assembly tasks, and propose that people working from an inadequate mental model are disadvantaged owing to the model itself, which can have a persisting influence on performance (Gopher *et al.* 1985) as people protect their misconceptions (Feltovich *et al.* 1994), despite explicit instructions to strive to overcome them.

This difficulty in overcoming ‘incorrect’ models (even subsequent to explicit instruction) has also been noted by DiSessa (1982) and McCloskey *et al.* (1980), and it seems to arise because people avoid multiple perspectives when faced with a problem because such alternatives introduce too many action sequences to think about given the inherent limitations of WM capacity (cf. Feltovich *et al.* 1992). This account also relates to the phenomenon of ‘cognitive tunnel vision’, which is interpreted by Moray (1999) as the choice of an inappropriate mental model coupled with an unwillingness to change to a potentially more appropriate model. Interestingly, these tendencies toward a limited focus on initial mental models are also a cornerstone of Johnson-Laird’s mental models theory of reasoning (cf. Johnson-Laird and Byrne’s 2002 ‘principle of truth’ that drives model construction; see also Sloutsky & Golvarg, 2004, for discussion of the concept of ‘minimalist’ mental models). It is also recognised by Johnson-Laird (e.g. 2001) that knowledge and beliefs can have a profound affect on thinking and reasoning; sometimes beliefs can limit people’s construction of alternative models, whilst at other times they can encourage a more exhaustive construction of possible models (see Ball *et al.* 2006, for a recent discussion of belief-bias effects in model-based deduction).

2.2. Mental simulation and runnable mental models

Closely linked to the concept of mental models is the notion of ‘mental simulation’, a term originally introduced by Einhorn and Hogarth (1981) in decision-making research to refer to a process where a sequence of events is consciously enacted (e.g. to determine cause-effect relationships or to predict the likely outcomes of actions). The idea of mental simulation was quickly adopted by Kahneman and Tversky (e.g. 1982) in their pioneering research on heuristics and biases in reasoning and decision making,

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where they discussed the concept of a ‘simulation heuristic’ that could enable predictive reasoning and judgemental forecasting. Yet another concept that appears to be synonymous with the idea of mental simulation is that models can be ‘run’ in order to test out possible outcomes in advance of some action (Ehrlich 1996). Indeed, in the important edited collection of papers by Gentner and Stevens entitled ‘Mental Models’ published in 1983 (coincidentally the same year as Johnson-Laird’s identically-titled monograph) several authors expand on the issue of running mental models. For example, Norman (1983, p. 13) states that users’ models are constantly refined during user-system interaction, and refers to running a mental model in order to make predictions; Williams *et al.* (1983, p.1 33) refer to mental models that are ‘runnable’; and De Kleer and Brown (1983, p. 156) refer to ‘envisioning’ or constructing mental models and then the simulation or running of these models.

Klein and Crandall (1995) also discuss mental simulation and relate this more broadly to perspectives such as mental models, mental imagery and the simulation heuristic. They use the wider meaning of the term mental model as ‘representing knowledge’, although they also note the difficulty with this in that the term becomes over-general by referring to everything a person knows (cf. Rouse and Morris 1986). However, a particularly interesting contribution that Klein and Crandall make to theoretical clarification relates to their proposals that, first, mental simulation uses a *subset* of information from a mental model to run action sequences, and second, that running such action sequences can be perceptually driven and will be limited by capacity constraints of WM. In addition, Klein and Crandall report studies where people were required to use mental simulation to undertake tasks. By studying people’s verbal reports, Klein and Crandall (1995) identify four primary functions of the simulation

process: (1) to generate a course of action; (2) to evaluate a course of action; (3) to explain a phenomenon; and (4) to explore models of a phenomenon. Although Klein and Crandall list these functions and provide an account of mental simulation, it is not clear what exact form these simulations take—other than that they are linked closely to, and are a subset of, mental models in the broadest sense. As such, the relative roles of an imagery format versus an abstract model format remain unclear within this theory. Of course, whether there is a real need to know the format of the mental representations that underlie thinking is a moot point. The side of the debate that we take is to argue that such knowledge should allow us to understand more about the limitations and characteristics of human cognition, which should, in turn, enable us to optimize the fit between tasks and humans—a goal that is at the heart of ergonomics practice. We will return to this idea of running mental models in a later section where we discuss the crucial distinction between static and dynamic models.

2.3. What is a conceptual model?

Welford (1961) proposed the notion of a ‘conceptual model’ and saw it as an approximate, inexact, yet holistic mental image that is not task specific. This term has tended to be used primarily in theories of representation in applied domains such as HCI and ergonomics, but as with the mental model concept, there has been much debate as to what a conceptual model actually refers to. Young (1983) suggests that a conceptual model is a representation of a system that is adopted to guide actions and interpret system behaviour, whilst Wilson and Rutherford (1989) propose that it should be seen as ‘the user’s representation of the system, defined in terms as structured or loose as desired’ (p. 631). Card and Moran (1986) describe a user’s conceptual model of a computer system as an abstraction of the system and its components that allows the user

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to predict the system's state after commands have been executed, to facilitate methods for carrying out novel tasks, and to handle system errors. This latter definition highlights a key difference between tasks in different domains, such as HCI as opposed to object assembly. In HCI the user needs some kind of model of the computer system and how it functions in order to operate the system effectively to pursue task-related goals; in object assembly, in contrast, there are no inner workings of a system that need to be understood, and the task at hand is, therefore, more transparent, arguably requiring different levels of mental representation.

The various definitions of conceptual models can seem similar to most descriptions of mental models, leaving one with the view that a conceptual model is nothing more or less than a mental model. Norman (1983), however, takes an interesting stance on these definitional matters and warns that the conceptualization of a system should not be confused with a user's mental model of that system. Furthermore, he describes conceptual models as being invented by designers and teachers and being taught to users. But what Norman seems to be describing is more a distinction between the system models possessed by designers (or teachers) versus those possessed by users. In contrast, other authors (e.g. Wilson and Rutherford 1989) seem to be concerned more with a different distinction, that is, between users' conceptual models (i.e. models of systems) versus users' mental models (i.e. models of possible operations and actions that can be performed using systems).

To gain greater clarification on these definitional issues we next turn to a brief consideration of the 'activity theory' approach that emerged in the former Soviet Union (e.g. Zinchenko *et al.* 1978; we also discuss activity theory in greater detail below).

Activity theory embraces Welford's (1961) notion of a conceptual model, and further refines its definition in some highly informative ways. Bedny *et al.* (2004) give a clear account of the notion of a conceptual model as espoused by activity theory, which is a model that is based on experience and instruction and which is seen as existing in LTM—which renders it both static and resistant to change. So, a conceptual model can be seen as a person's holistic representation of a task or system and its parts, whereas mental models and imagery relate to the cognitive processes required to construct hypothetical actions and action sequence, which themselves draw upon information in the conceptual model. This process whereby the static conceptual model populates a working or dynamic mental representation or model can be identified as a mediator of task performance and a source of error. In the Three-Mile Island example given earlier, an incorrect conceptual model of the system led to incorrect dynamic mental representations and poor problem solving.

In terms of attaining effective task performance, the available instructions and the device itself need to match the conceptual model held by the user. For example, when implementing new devices people's existing conceptual models should be considered, especially as they are static and resistant to change. Consider a standard pay-and-display ticket machine in a car-park: You insert the requisite value of coins, push the salient button and take your ticket. Excerpts from two press reports below show how even simple devices can cause chaos if they ignore users' existing conceptual models:

CONTROVERSIAL new ticket machines have led to chaos in a town centre's biggest car park. A new council parking system – which requires drivers to type in the digits from their vehicle's registration number before they can get their tickets – caused jams in the town's Central Area car park over the weekend as bemused

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motorists attempted to figure it out. Many were angry that there had been no advance warning of the new system, which led to lengthy queues and heated scenes at the ticket machines. A man with an engineering degree was fined £40 for being unable to use a machine...he and other motorists were flummoxed by the new system when he visited the town on Saturday. The council employee who is overseeing the introduction of the new machines, said: "You can't legislate for thick. Some people are just so stupid. You type in the numbers of your registration, put your money in and press the green button. I can't see how simpler it could be, other than having somebody standing there to help.

Bradshaw, T. Burton Mail 12/05/2003 and 22/05/2003

A further example of the importance of effective conceptual models can be given in the domain of object assembly. Baggett and Ehrenfeucht (1988) studied people's 'conceptualizations' of objects so that assembly instructions could be designed to match them. They found major individual differences in conceptual models of objects, which presents a further factor for consideration by task designers and trainers, and which also raises the issue of how conceptual models are formed in the first place. In object assembly, conceptualizations are seen as how people think about an object, which is defined in terms of an object's perceptually salient and functionally significant parts (Tversky and Hemenway 1984). So, just by looking at an object it would seem that we form a conceptual model, and that one person's model may differ quite radically from another person's. Similarly, merely by interacting with a device we will form a conceptual model of how it operates, and often this model will be incomplete and inaccurate.

Norman (1988) emphasizes these latter points well when he proposes that our conceptual models are formed, in part, to allow us to explain what is observed. For

example thermostats have three possible conceptualizations, only one of which is correct. Consider a cold room that a user wishes to heat up. The three conceptualizations are:

- A valve theory—Turn the thermostat all the way up and heat of a greater temperature is produced such that the room will get warmer faster.

- A timer theory—Turn the thermostat up and the heating will stay on at the same temperature for a greater proportion of time.

- A switch theory—Turn the thermostat up and the heating stays on at full power until the temperature set is reached, at which point the heating then switches off.

Users of a thermostat may well possess one of the erroneous theories (conceptual models) of a thermostat, that may be formed from observation alone. Indeed, some systems such as thermostats give no hint as to their internal workings and the correct model that should be formed of their functioning. Without further information the conceptual model that a person develops is free to account for facts as perceived. As we have seen, too, in some situations erroneous conceptual models can have serious consequences.

A good conceptual model requires a transparent device; for example, the workings of a bicycle are visible and can facilitate a good conceptual model of how controls relate to functions (e.g. handlebars to steering). In contrast, a digital watch with four buttons gives no indication of the relationship between controls and functions (Norman 1988). Norman proposes that conceptual models are built from a range of factors such as affordances, mapping, population stereotypes, instructions, interactions and transfer

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from similar devices. Conceptual models may be incorrect if the above attributes are misleading. This can then lead to task difficulties, since conceptual models provide information to allow people to simulate mentally the operation of a device and to decide upon actions. If the conceptual model is wrong then the actions arising from the model may be wrong, and mistakes can happen.

Research has also demonstrated that people can overrate their level of understanding or knowledge of functional systems (Rozenblit and Keil 2002). Lawson (2006) examined people's conceptual knowledge of a simple and transparent everyday device, the bicycle. She found people, including cyclists, had a striking inability to produce accurate information about bicycle function and that conceptual understanding was 'sketchy and shallow'. The frequent and serious mistakes found cast some doubt on the role of conceptual models described above. However, we rarely work from conceptual knowledge alone; during a task when people are simulating the operation of a device they have the external representation of the task available. Hence, our inadequate conceptual knowledge of the bicycle is supplemented, allowing a fuller mental model of the device to be created for problem solving. The importance of external representations will be discussed later.

2.4. Visuospatial cognition and mental imagery

Many tasks involve visual and spatial information and operations, and visuospatial representations allow people to process visuospatial information and perform mental transformations associated with problem solving and the attainment of task-related goals (de Vega and Marschark 1996). Mental imagery can be thought of as the key example of visuospatial cognition, and Shepard and Metzler (1971) have provided some

compelling (though not uncontested) evidence for the role of image-based representations in tasks such as mental-rotation. The term imagery refers to the processes that underpin the representation of structural, modality-specific properties of objects. Rather judiciously, Denis (1991) does not accept the rather extreme views that ‘imagery is thinking’ or that ‘thinking involves only abstract representations’. Instead, imagery is seen as being one potential medium for thought, but not at its core. The properties of imagery can vary, with Denis describing instances of single or multiple images that may simply be read or that may be manipulated to perform realistic simulations of physical objects. Mental images, then, are a seemingly important part of human cognition and can be further divided into visuospatial representations in 2-D or 3-D (Knauff and Johnson-Laird 2002).

It appears that incoming visual and spatial information is processed through the visual system and that mental representations can have visuospatial properties similar to the object being represented. Indeed, the concept of ‘analogue imagery’ denotes the high level of structural isomorphism that can exist between an external object and the object as represented mentally (Denis 1991). Many researchers have also argued that visuospatial representations cannot be reduced to propositional code (de Vega *et al.* 1996), though see Anderson (1978) and Pylyshyn (2003) for alternative views. Although visual perception and mental imagery are different, it is likely that they share neurological and psychological mechanisms (Kosslyn 1994). This view is supported by studies of unilateral spatial neglect patients whose representational deficits on remembered images mirror their perceptual neglect (Bisiach and Luzzati 1978). Kosslyn *et al.* (1995) also found evidence of visual area activation with mental imagery. However, double dissociations found since make it untenable to claim identical imagery

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and perceptual systems, although a fair degree of overlap seems likely (see Bartolomeo 2002 for a review). Farah (1988) also concludes that imagery is not visual in the sense of a ‘mind’s eye’, but rather imagery shares some of the same processes as vision. Furthermore, Farah suggests that people have a choice of using either visual or non-visual spatial representations, depending upon the problem at hand and their experience.

The similarity and differences between perceptually-based images and mental images can be defined further. There is strong evidence that mental images retain properties of their referents and that the spatial manipulation of representations—such as arises in mental rotation or in tasks such as object assembly—involves continuous mental transformation or analogue imagery (e.g. Paivio 1975, Kosslyn 1978). Furthermore, it has been suggested that visuospatial images are conceptually based and are derived from top-down memory retrieval, that is, they are not like perceptual images that are built up from edges and shadows (de Vega and Marschark 1996). These points are of considerable interest and relate to our previous discussion regarding mental models and conceptual models, as it would seem that a person’s conceptual model could also inform their mental imagery.

So, how might mental imagery be used during a task? In Figure 1 an example was presented whereby mental imagery would allow the manipulation of elements of a task to enable predictions. As such, mental imagery would be a core aspect of a task such as object assembly. Likewise, Schwartz and Black (1996) refer to everyday situations where people infer physical events or solve mechanical problems—such as the meshing of two gears—using analogue spatial imagery. Mental imagery can also be used to understand mechanical devices such as toilet cisterns, where it seems that people follow

a chain of events and infer the motion of components one at a time, rather than pursuing a more realistic mental animation with components in simultaneous motion (Hegarty *et al.* 2003).

2.5. Interim summary

So far we have discussed in detail three main forms of mental representation: mental models, conceptual models and mental imagery. Mental models and mental imagery relate to cognitive processes that are required to pursue ‘hypothetical thinking’ about possible actions (cf. Evans and Over 2004). Both types of representation appear to be constructed and manipulated within WM. Conceptual models, in contrast, reflect a more holistic understanding of systems, and are primarily held within LTM. The present theoretical clarification concerning the nature and cognitive locus of mental models and conceptual models seems useful as a counterpoint to the often loose and ambiguous terminology that pervades applied research. Indeed, we would urge all researchers who are referring to mental representations to make some attempt to clarify how they are using terminology in terms of both the nature of the representations that they are discussing as well as the assumed location of these representations within the cognitive system. We will now move on to consider in detail two research traditions that have been especially helpful in informing the debate over the nature of mental representations, that is, situation awareness and activity theory (the latter was briefly discussed above in relation to the concept of conceptual models).

3. Situation awareness and activity theory in understanding representational issues

3.1. The impact of situation awareness

The increasing size and complexity of modern technological systems, together with the sheer volume of data available to the human operator, have led to a dramatic burgeoning of interest in the concept of ‘situation awareness’ (SA), which refers to ‘a person’s mental model of the world around them’ (Endsley 2000b, p. 2). SA, therefore, is fundamentally concerned with an individual’s knowledge of the prevailing context in which they are operating, as well as the information that is important for achieving task-oriented goals. SA is derived via the cues received through our senses and provided by systems or the surrounding environment, for example, warning lights or the tone of an engine. Endsley (2000) presents a visual depiction of her model of SA which shows it as an operator’s ‘internal model’ of the state of the environment—a representation that requires perception, comprehension and projection or prediction of future events, and which forms a basis for decision making. Furthermore, Endsley (2000) emphasizes how a full SA can help decision making but cannot guarantee a correct decision. This is because knowledge, experience, technical limitations and individual differences (e.g. in personality or motivational dispositions) may well all hinder optimal decision making.

In discussing SA, Endsley (2000) places mental models within LTM, and associates them with the concept of schemata, a form of knowledge representation in LTM that will be discussed below. The use of mental models in SA depends crucially on the operator being able to match environmental cues to their mental model. This choice of terminology is repeated throughout the SA literature, but interestingly

overlooks the mental models notion as espoused by Johnson-Laird and colleagues. Instead, Endsley's concept of a mental model really describes a 'conceptual model' as discussed in the previous section (see Welford 1961). However, Endsley also introduces new terminology with the concept of a 'situation model', which describes the *current state* of a mental model, presumably as represented in WM. This situation model guides attention, integrates information perceived and provides a mechanism for predicting future states of the system. Whatever the chosen terminology, Endsley presents studies demonstrating that problems with mental models accounted for 18% of the SA errors observed. These problems included the existence of poor models, the use of incorrect models, and over-reliance on default values within models.

SA requires perceived information to be compared with goal states and projected into the future, a process that places heavy demands on WM. Endsley (2000) argues that SA is not itself solely located in either WM or LTM. Rather, information from the senses activates LTM representations such as schemata and other static mental representations; these then enable recognition processes and the generation of salient recognition products that are maintained in WM. The relationship between models in LTM and WM in SA theory is clearly congruent with the conclusions in Section 2 concerning the nature of conceptual models and mental models. As will be discussed later, Bedny *et al.* (2004) also observe that the mental and situational models in SA are similar to the conceptual and dynamic models of activity theory. Such overlapping notions across different theoretical perspectives is very encouraging for the development of an integrated perspective on representational issues. Such conceptual consistency clearly allows for greater unity and crossover between different theories and approaches.

One especially appealing aspect of SA is that it goes beyond mere concerns with situations and additionally provides an encompassing theoretical framework to facilitate the systematic analysis and design of complex systems from a cognitive perspective. For example, SA would deal with a task such as object assembly in terms of: (1) the inputs arising from the external world, such as the perceived current state of the object assembly and incoming information from the task instructions; (2) the goals, mental models and schemata that are held in memory and the way that they are activated by, and combined with, external inputs to create an internal representation of the current state of the object assembly; and (3) the comparison between perceived information and current goal states, and the projection of perceived information into the future so that a decision can be made on the next action to take.

It will be seen in subsequent sections that the framework proposed by Endsley (2000) contains many of the components depicted in the ‘relations of mappings’ in mental models as described by Moray (1999), as well as key aspects of Zhang’s (1997) theoretical proposals for discussing the role of external representations in problem solving. A framework such as SA seems very powerful, and its application is potentially wide ranging. It would clearly be beneficial to see how far SA theory can be integrated with other dominant theoretical frameworks—a theme that we will return to later on in this review. One final aspect of cognition that is not commonly covered in discussions of mental representations but which is highlighted very well in SA theory is the dimension of ‘time’, that is, the temporal aspects of a current task (e.g. rate of change, perception of time, and time available to complete the task). Temporal factors are critical when considering human awareness in a developing situation. Although not

explicitly mentioned by mental models theory or imagery-based theories of representation, it is likely that such accounts are capable of dealing with temporal issues.

3.2. Activity theory: An alternative perspective

In terminology which is relatively new to the Western World we can see how a similar framework of cognition to SA theory developed in the former Soviet Union in the form of ‘activity theory’ (AT). AT is a psychological approach for the study of work-based behaviours that is goal-directed in its emphasis (see Bedny *et al.* 2000, for a review). Moreover, within AT cognitive, motivational and behavioural constructs are unified and the concept of ‘action’ gains centre stage in connecting theory to practice (e.g. in domains such as ergonomics). As such, AT is an extremely broad and all-encompassing framework that extends well beyond the present paper’s more modest ambition for a unified framework for considering issues concerning internal and external ‘representation’.

Despite its breadth, there is no doubt that the AT approach provides a valuable supplement to the human information processing approach used in ergonomics, and also has relevance to the present discussion of mental representations. AT classifies ‘mental actions’ as being the building blocks of activity, and includes representations as a core element of these mental actions. Some mental actions are direct perceptual events, such as recognition of a familiar object, whilst others include imaginative actions or mental imagery. In addition, AT includes functional blocks, which include a mechanism termed the ‘operative image’ - a ‘dynamic reflection of a situation in imaginative form that is not always accessible to verbalization’ (Bedny *et al.* 2000, p. 198). The operative image

of the task conditions will be especially critical during the performance of a dynamic task.

Nusulenko *et al.* (2005) provide a further discussion of engineering psychology in Russia centred on AT and human-machine interaction, and reveal further terminology. They introduce the concept of an 'image-goal', which is the reflection of a device in a mental image that must be related to the current task-goal. This image-goal absorbs the operator's experience and also requires information about the system's current condition. This information is perceived by the operator and consists of information from the device as well as non-device information that can be the prime determinant of behaviour. Furthermore, the perception of the device will be mediated by technology. Nusulenko *et al.* relate the concept of an image-goal to the notions of a 'conceptual model' and an 'operative image' mentioned above (Oshanin 1966). First, the conceptual model is seen as essential in activity as it integrates an individual's experience and knowledge of the system. By Nusulenko *et al.*'s definition the conceptual model includes device/system characteristics, dynamics and structure, including possible actions and mental images of real and predicted events. It is a set of relevant background knowledge that forms a basis for decisions (i.e. an operator's 'inner world'). During a task the operator brings into consciousness the content required for tackling the task. The 'operative image or model' differs from the conceptual model in that it is a mental image of the device generated *during* the task interaction. It is dynamic and regulates activity. In summary the conceptual model is relatively constant and the operative image is dynamic. In practice, a task will require a device or system to be controlled from a current state to a goal state, with the latter represented by the image-goal. The difficulty of the task will then be defined by the difference between the

conceptual model and the image-goal, and how well the image-goal and conceptual model are developed.

In a similar vein, Bedny *et al.* (2004) state that operative thinking is important in the study of human-machine interaction, and that this involves the creation of ‘dynamic models’ of the situation used to develop and plan actions. The dynamic model has different aspects, such as imagery, and exists in WM. The conceptual model is the ‘inner idiosyncratic world of the operator’ that is held in LTM, and is generally resistant to change; it is based on experience and instruction and is available to the operator before initial actions. In addition, the conceptual model is viewed as being task-independent, and, therefore, can contain substantial redundancy in relation to a particular task, with only components relevant to current operator actions being extracted into a dynamic model. This essential distinction between dynamic and conceptual models has received rapid and widespread recognition in AT.

We conclude this section by noting that AT remains an interesting approach to the analysis of work-based activity that has developed in parallel to Western theories. In addition, when considering the concept of mental representation, the published summaries of the AT approach present a clear framework based upon the proposed existence of static models in LTM and dynamic models in WM. However, although AT certainly provides a far-reaching and important conceptual framework, it is unlikely to become pervasive in Western theorizing for some time given its relatively recent emergence in Western research. Intriguingly, too, we note that SA theory—which has already gained dominance in Western theorizing—provides an impressive level of overlap with many core AT concepts (cf. Bedny *et al.* 2000). In particular, the mental

models and situational models in SA are similar to the dynamic models and conceptual models introduced in AT. It is proposed that the closer integration of AT and SA in future research on work-oriented behaviour would be a useful next step toward the enhancement of functional analyses of activity (cf. Bedny *et al.* 2004).

4. Mental representations and memory

4.1. The interplay between LTM and WM

It has been proposed in previous sections that mental models (e.g., Johnson-Laird *et al.* 1992, Johnson-Laird 1996) and mental imagery (e.g. Narayanan and Hegarty 1998) are specific forms of internal representation that are held in WM, whilst conceptual models are primarily artifacts of long-term memory (LTM). These distinctions create a framework where mental representations are constructed and manipulated in WM and draw upon conceptual models stored in LTM. Intuitively, it certainly seems to the case that at any one time a person can recall a conceptual model of a device from which a mental model can be derived, held in WM, and used for reasoning. Moray (1999) similarly argues that models in LTM can be used to construct models in short-term memory to allow one to think about specific problems, and de Vega *et al.* (1996, p. 214) conclude that there is ‘no doubt that subjects can use existing knowledge to modulate visuospatial images and evaluate the plausibility of models’, although it is not clear whether this is automatic or subject to control and awareness. Denis (1991) considers the role of WM and LTM in the terms of transient versus long-term representations, and describes thinking as the mental activities involved in the manipulation of transient representations in order to construct new pieces of information. This is distinguished from the long-term representations which form a person’s knowledge. Likewise, in the

‘perceptual symbol theory’ presented by Barsalou (1999) and discussed later, it is argued that LTM contains representations while WM implements specific representations. That is, WM is the system that runs perceptual simulations during action or during preparation for action.

These latter proposals also relate to the work of Cañas *et al.* (2003), where mental models are considered to be dynamic representations created in WM from information stored in LTM, and information extracted from the environment. The balance between the latter two determinants of mental model construction will be dependent on the user. Where the user lacks knowledge, Waern (1990) suggests a bottom-up approach where the user gradually builds a model that is based on incoming information as they interact with the system. In the top-down approach, users rely on existing knowledge for the basis of a new mental model according to information extracted from the environment. This use of current information and experience is consistent with the conclusion of Wilson and Rutherford (1989) quoted previously, and it is worth reiterating that the resulting mental model will dictate the level of task performance as it provides most (if not all) of the user’s system understanding.

As we have seen, too, Bedny *et al.* (2004) echo these arguments and present a clear vision from AT, whereby the conceptual model resides in LTM and the dynamic model—which includes mental representations such as imagery—exists in WM. As it is based in LTM the conceptual model has a number of important characteristics: It is resistant to change, it is task independent and it is based on experience and instruction. These LTM/WM distinctions, however, may not be entirely rigid, and Endsley (2000) has argued that situation awareness is neither solely located in LTM nor WM. What is

clear, however, is that information from the senses activates LTM representations (i.e. schemata and other static mental representations) in order to be recognised, and then the salient products of such recognition processes are maintained within a WM system. In other words, there are vital *mappings* between conceptual models in LTM and dynamic models in WM. It is also possible that LTM and WM may not be physically separate entities as some widely accepted models of memory have suggested (e.g. Baddeley 1986). Endsley (2000) points to the finding that pilots could refer to SA information for six minutes following simulation freezes and that this is not compatible with theories that posit a rapidly decaying WM system. Such arguments have led to calls by theorists for a model of WM as a subset of LTM (e.g. Cowan 1988) or a form of 'long-term working memory' (e.g. Ericsson and Kintsch 1994).

Further important ideas regarding the interplay between LTM and WM representations are discussed by Baguley and Payne (2000). They note that research into mental models in reasoning supports the view that whilst construction and manipulation of models occurs in WM, mental models can also be encoded in LTM to enable more persistent retention and retrieval. Baguley and Payne (2000) additionally discuss the concept of an 'episodic construction trace' (see also Payne 1993), which is a propositionally-based representation of the processes that a person went through during the construction of a WM-based mental model. The idea of a construction trace is intriguing as it provides yet another form of LTM representation that could be used as an aspect of subsequent behaviour (e.g. that could be utilized when having to reconstruct a mental model on a future occasion).

4.2. Schemata and LTM

The term 'schema' is used to denote the representation of conceptual or categorical knowledge in LTM (e.g. Rumelhart 1980). Schemata are described as having 'slots', which are used to structure and categorize the information linked to a schema. For example, a schema for a house would have a 'materials' slot that could have values such as brick or stone. Schemata, therefore, are abstract representations of 'concepts' and are built from specific instances (Anderson 2000). Furthermore, schemata are viewed as being hierarchically embedded one within another through levels of abstraction. Such hierarchical structuring allows inferences to be made, for example, from the knowledge that walls are parts of houses and that walls have windows, we can infer that houses have windows. This general description of schemata as representing concepts is strikingly similar to the notion of 'conceptual models' introduced earlier. Such conceptual structures are not only able to represent conceptual knowledge of objects, but also conceptual knowledge of events and typical action sequences, as in Schank and Abelson's (1977) discussion of 'scripts'. Scripts are a particular implementation of schema theory that relate specifically to everyday events and typical goal-directed activities (Zacks *et al.* 2001).

Wilson and Rutherford (1989) discuss the relationships and distinctions between LTM constructs such as schemata and scripts (which are sometimes also seen as being an implementation of Minsky's 1975 notion of 'frames'). They suggest that these various theoretical constructs can be used to organize the knowledge that is required for any cognitive task. Whereas scripts have been employed primarily in relation to social activities, schemata have been applied more widely to areas such as motor actions, perception and decision errors. Interestingly, too, Johnson-Laird (1983, pp. 446-447)

has referred to schemata as ‘procedures that specify by default the values of certain variables in mental models’. Further, Moray (1999) sees frames and scripts as aspects of LTM, with the former informing the mental representations held in WM, which in turn inform scripts in a reciprocal manner. Wilson and Rutherford (1989) conclude that structures of ‘background knowledge’, such as schemata, are artifacts of LTM which, when activated, are utilized by mental models in a dynamic manner. This is supported by Johnson-Laird (1983) and Manktelow and Jones (1987), who see schemata as providing the means for the construction of mental models. Once again, we see that these ideas concerning schemata match the more general account of the role of LTM in task-oriented behaviour given above, where mental models were described as being constructed and manipulated in WM and being informed by LTM and environmental cues.

5. Further issues concerning the nature and functioning of mental representations

5.1. Mental representations and task specificity

The difference between the use of the mental models concept in theoretical and applied research has been noted above, and derives from the distinctive emphasis of two, key published volumes: the monograph of Johnson-Laird (1983) and the collection of papers edited by Gentner and Stevens (1983). Whereas Johnson-Laird proposes a general cognitive theory to explain human thought, Gentner and Stevens’ volume considers models in relation to specific domains of expertise. For example, it contains chapters by Norman (1983) and Young (1983) that discuss mental models in relation to a range of physical or mathematical systems and devices (e.g. the instruction-based learning of computer systems and scientific concepts such as electricity). One clear theme in the

more applied emphasis of the Gentner and Stevens volume is that people's existing knowledge has a considerable influence on their reasoning about a new device or problem. However, Payne (1992) notes that this theme is also resonant in Johnson-Laird's theory, which is the more well developed as it specifies the format of representations. Payne's position is also supported by Manktelow and Jones (1987). These points, however, usefully serve to highlight a key difference in mental-models theorizing, which is the distinction between task-specific (or domain-specific) theories on the one hand and domain-general theories on the other.

One area of applied research where task-specific notions of mental representation have tended to be the mainstay of theorizing is in the area of HCI, which is fundamentally interested in how users acquire knowledge of a computer system that can facilitate (or potentially hinder) their interaction with the system (Bibby 1992). Mental models in the domain of HCI, therefore, relate to how people understand and learn the internal functioning of devices. In other domains, however, such as object assembly, the tasks are more transparent and do not involve a functioning device with particular internal features that need to be understood. Therefore, many task-specific mental representation theories, such as those from HCI, appear not to be readily generalisable to other domains—which seems to be an inherent weakness of such accounts.

As an example of this latter difficulty, consider Payne *et al.*'s (1990) Yoked State Space (YSS) hypothesis, which he proposed as a way to understand people's interaction with computational systems. The YSS refers to two mental constructs that are maintained by the system user—the 'goal space' and the 'device space'—with mappings taking place between the two. The goal space represents the possible external

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states that can be manipulated using the device. The device space represents the possible states of the device, in this case a computer system, with ‘device operators’ allowing the user to transform states in the device space. A semantic mapping relates the constructs in the device space to those in the goal space. A transformation in the goal space is achieved through applying operators in the device space. As with SA, we can attempt to consider object assembly tasks in terms of the YSS hypothesis. Straightaway, however, the goal space and device space in object assembly are far less distinct than in HCI, and, indeed, appear to merge. The goal space can be related to the possible states of the external assembly object. However the device space either refers once again to the actual assembly object, or else is non-existent, as there is no device that is acting on the assembly. The YSS hypothesis arguably fits the object-assembly domain far better if the goal space is related to the required ‘next state’ of the assembly, as depicted in the instructions. The device space then represents the possible states of the assembly object, with device operators allowing the user to transform states in the device space, which are mapped onto the goal space. This account helps to save the generality of the YSS hypothesis—though admittedly at the cost of some stretching of core concepts. It also returns us to a consideration of how mental models and mental imagery might allow users to reach task-related goals when engaging in mechanical reasoning.

5.2. A task-specific framework from mechanical reasoning

Research into the task-specific mental representations associated with the comprehension of mechanical systems is particularly relevant to object assembly since both domains involve people seeing or inferring state changes over time (Novick and Morse 2000). To understand a mechanical system, including its assembly, people need to construct an internal representation of the machine (Hegarty and Just 1993). Hegarty

and Sims (1994) describe a three-stage process that requires spatial visualization and the transformation of mental images when running a mental model to solve diagram-based mechanical reasoning problems. Stage one involves the comprehension of the diagram to construct a spatial representation. In stage two this representation is animated, and in stage three inferred motion is compared to the problem in question.

The stages proposed by Hegarty and Sims (1994) are elaborated upon by Narayanan and Hegarty (1998), who present a more detailed cognitive model of people's comprehension of machines from diagrams. This revised model is highly process-oriented and is based upon their own previous research as well as the production-system account of diagram processing forwarded by Larkin and Simon (1987). Narayanan and Hegarty argue that the comprehension of mechanical systems involves the construction of a mental model (their terminology), based on prior knowledge, presented information and reasoning skills. Furthermore, working from external, static displays involves visualization to infer motion which loads WM, especially as the mismatch between the internal and external representation grows as motion is inferred. This latter process of mental animation or rehearsal as preparation for subsequent action has also been described by Logie (1991). The stages of Narayanan and Hegarty's (1998) cognitive model of machine comprehension can be summarized as follows:

Stage 1—Decomposition of the diagram into basic elements. Errors are likely to occur owing to poor diagrams and lack of prior knowledge.

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Stage 2—Construction of a ‘static mental model’, making connections to prior knowledge and between components. Poor spatial information and highly schematised, unrealistic diagrams can interfere with this process.

Stage 3—Mental animation using rule-based or imagery-based inference, which is dependent on WM capacity.

The third stage of this account is expanded into a full process model of mental animation by Narayanan and Hegarty (1998), and this final stage is easily adapted to be relevant to domains such as object assembly (see Figure 2). The proposals of Narayanan and Hegarty (1998) present a task-specific, process-oriented approach to the comprehension of mechanical systems. Although the approach can be applied more broadly to related tasks such as object assembly, the model remains limited in terms of its reflection of underlying cognition. We propose that more generic frameworks are able to present a fuller picture of the cognitive functions involved in a far wider range of tasks. We also suggest that task-specific frameworks run the risk of creating further divergence in the literature, and that testing a generic framework from alternative perspectives is far more likely in the long term to produce a unified approach to mental representations. We will return to these points later.

[Insert figure 2 about here]

5.3. The interconnections between mental representations

The previous discussion has introduced various different types of mental representation, but the interconnection between such representations has only been given limited consideration. As noted earlier, researchers, including Johnson-Laird (1996), distinguish between mental models and mental images as being different forms of representation. Johnson-Laird's (1996) theoretical shift toward viewing these representations as distinct was based on two sources of evidence: (1) the mental rotation studies of Shepard and Metzler (e.g. 1971) that pinpointed how an image is a unique representational format that preserves perceptual properties of the rotated object; and (2) research showing that during reasoning, representations depend on information such as negation that cannot be visualized in mental imagery and which must, therefore, be reflected in some abstract, token-based system such as mental models (de Vega *et al.* 1996). This emphasis on the differences between images and models, however, begs the question that if they are separate, do they co-exist? Furthermore, do images and models interact—perhaps with models informing imagery or imagery informing models?

Johnson-Laird (1983) proposes that a mental model, with accompanying imagery, can be used in making a decision, which suggests that the two types of representation can function in concert to determine action. It can also be posited that mental models can place constraints on imagery. For example, during object assembly the situation may arise where an abstract (and non-visualizable) element of a mental model exists that negates a particular component position. In this way, the mental model could constrain the mental imagery used during a task such as object assembly. This ability of mental models to limit mental imagery is supported by de Vega *et al.* (1996), who

suggest that evidence of diagrams facilitating comprehension of text-based procedural information shows that abstract mental models can control imagery.

Of course, the idea that mental models can constrain imagery would be problematic if this was the only form of interaction that could take place between the two types of representation. This is because there is much research that suggests that diagrams and visual aids are a major benefit to performance, through facilitating cognition (e.g. Larkin and Simon 1987) and through reducing WM load (Johnson-Laird 1996). In particular, visual aids are directly able to facilitate internal mental imagery that can enable the attainment of task-related goals (e.g. Kieras and Bovair 1984). Although, it could be the case that it is mental imagery alone that provides the performance benefit, it seems more likely that mental imagery also informs the development of mental models such that there is a bi-directional relationship between mental models and imagery. This view is supported by de Vega *et al.* (1996), who suggest that all internal coding systems are uniquely suited to certain forms of information, and that real-world tasks are, therefore, unlikely to rely exclusively on one single system.

We note that the emphasis on representational separateness that is evident in the research literature seems to arise, in part, from a natural human trait to divide and classify phenomena in order to understand them. This generates an appearance of disconnected representational systems that are, in reality, highly interrelated. This conclusion, in turn, demonstrates once again the need for a unified theoretical approach to the issue of mental representation. The limitations of the divide-and-conquer approach of many cognitive researchers interested in representational issues is echoed in

comments by Schwartz and Black (1996), who investigated the use of imagery in the simple physical behaviour of the meshing of two gears. Schwartz and Black consider whether physical inferences are based on spatial imagery (as suggested by Hegarty and Just 1993) or on a representational qualitative calculus (see de Kleer and Brown 1984). They suggest that the debate is largely due to different research traditions between those supporting spatial reasoning (such as Kosslyn), and the mental models fraternity (e.g. Johnson-Laird). The results of their own research support the argument that mechanical problems can be solved through analogue imagery, but they also conclude that neither qualitative mental models nor purely spatial descriptions can provide a full account of their spatial processing tasks. They propose that many imagery and mental model theories are united in assuming that people construct representations that ‘reveal’ the external environment rather than merely describe it. Schwartz and Black (1996) further propose that the primary conceptual entity is the object of reference, and that this can bridge the gap between mental imagery and mental models as both are dependent on the type of object being considered.

The interrelation between mental representations has also been considered by Moray (1999), who describes an individual’s multiple mental representations of a system in terms of lattice theory. Each mental representation relates, or maps onto, a specific form or function of the system. Therefore, the mental representations are ‘homomorphisms’ (where system details are not present in their entirety), rather than being ‘isomorphisms’ that map precisely onto the physical system. Such homomorphic mental representations can involve models or imagery that map onto physical forms, physical functions, general functions, goals, means and ends. Moreover, homomorphic mental representations create a hierarchy of ‘models from models’ such that mental

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representations can inform one another: the physical form informs the physical function, which, in turn, informs the model of general functionality, which informs the model of goals, means and ends. There is, therefore, a progressive development of the user's mental representations as they think about their work (Moray 1999). Moray also uses lattice theory to explain causal relations between system components. If two elements in a system are related they can be linked in a hierarchy of causal and relational connections between system components. In effect, an external representation of a lattice reflects the user's knowledge of a system. Therefore, rather than a single complex mental model, each component becomes a mental model which exist at different levels within the lattice. In addition, this use of multiple models will reduce the processing load associated with a single, complex model. However, it can also lead to difficulties; an operator may be at a level in the lattice that does not provide some of the key information required to achieve a task-related goal.

This hierarchy of 'models from models' resembles the abstraction hierarchy of Rasmussen (1986), which implies that users have many mental models of a system that can be invoked when appropriate. In contrast, the research presented in Gentner and Stevens (1983) aims to discover *the* mental model relevant to a task, and may, therefore, conceal the real nature of task-based models (Moray 1999). The concept of multiple models is particularly useful in explaining task failure and not just task success. For example, the wrong model could be instantiated and adhered to by an individual. This could lead to misinterpretations that might be resistant to change since resulting top-down influences will impact the operator's perception of events. In this way Moray (1999) interprets the phenomenon of 'cognitive tunnel vision' as the inappropriate choice of a model and a subsequent unwillingness to change the selected model.

Whatever the exact form of mental representations, it seems likely that single pieces of information can be encoded in multiple forms which are then used productively in problem solving (Petre 1999). However, although multiple models have benefits it is also possible that spatial problems which require multiple models are more difficult than those based on a single model, with errors being more likely (Byrne and Johnson-Laird 1989). It is also the case that certain tasks will require multiple models in order for all possible interactions to be considered, and a situation that requires fewer models is likely to be easier (Johnson-Laird 2001).

Returning to the fundamental relationships between mental models and mental images, the literature that we have considered is generally consistent in distinguishing between non-visual mental models and visual mental imagery. This distinction implies that mental representations of a device do not necessarily have to be visual. Furthermore, Tye (1991) proposes a view of hybrid representations, consisting of both pictorial and discursive elements, or what one might refer to more simply as 'labeled images'. If we again use object assembly as an example, it is possible that as part of the mapping between internal and external representations, propositional labels will be attached to components (in either their external or internal form). Let us consider a simple assembly where Component A, B or C ('CA', 'CB' or 'CC' respectively) could be inserted into a square opening in the existing assembly ('EA'). It can be proposed that if CA was round, then existing knowledge may code CA as 'NO GO' without further effort, as round pegs do not go into square holes. Mental or physical simulation of CB may reveal that it will not insert into EA. CB can then be coded as 'NO GO' for the current assembly procedure. Mental or physical simulation of CC may reveal it will insert into EA and CC is coded 'GO'. These states can be held as a propositional code

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in WM with the external components as referents while the assembly procedure is further facilitated, such as through the choice of a suitable fastening. This example can also be related to how existing knowledge or conceptual models can bias or interfere with correct object assembly. Although a round component does not generally fit into a square hole, it can, depending upon its size.

The previous proposals suggest that some form of propositional notation would be likely to accompany images and their external referents, otherwise imagery alone would have to store such propositional information. Likewise, the idea that mental models allow for the representation of negation in a way that is difficult to achieve through imagery suggests an important role for such models in task performance. Similar concepts to Tye's (1991) notion of labelled images have also emerged in the recent literature on mental models in reasoning. For example, Schaeken *et al.* (in press) propose that reasoners construct 'isomeric' mental models to represent indeterminacies and uncertainties. An isomeric model captures all possibilities (whether determinate or indeterminate) within a single mental model via an additional *non-analogue* element (i.e. a propositional or verbal 'tag'). Another, similar notion is that of 'annotated' mental models espoused by Vandierendonck *et al.* (2004).

An alternative perspective to these hybrid views of interrelated representations is provided by Barsalou (1999), who proposes that cognition is inherently perceptual in nature (i.e. cognition and perceptual systems are not seen as being in any way independent). Barsalou claims that the representations that underlie cognition are imagistic, and not amodal symbol systems that enter into structures such as schemata. A number of arguments against amodal theories are presented, and it is concluded that

other alternatives should be considered. Barsalou notes that when Shepard and Metzler (1971) offered image-like representations in WM there was considerable resistance, possibly related to the criticisms of imagery within philosophy. Indeed, the task of understanding human cognition has required cognitive psychologists to divide and conquer restricted areas of cognition and develop theories using amodal computation. However, more recently there has been greater acceptance of perceptual theories of cognition, and as is often the case in polarised debates it is likely that both imagery and amodal systems are used during cognition. Indeed, Barsalou (1999) presents a perceptual symbol approach which combines structured amodal representations with a dynamic view of imagery to produce a powerful form of multimodal representation. Within this theory object-based percepts assume the role often allotted to abstract symbols, and perceptual simulation is proposed instead of the symbol manipulation that is typically claimed to be used in domains such as deductive reasoning. The theory of perceptual symbols and the role of simulation in conceptualization is claimed to liberate cognitive science from a basis in amodal computation (Fauconnier 1999).

5.4. Static versus dynamic representations

Barsalou's (1999) reference to simulation in WM brings us back to the issue of dynamic representations that we touched upon earlier. It is generally proposed that mental representations, both mental models and imagery, can be dynamic rather than purely static, and there is considerable support for this notion. If we start with the case of mental models, a number of studies maintain the existence of such dynamism and refer to concepts such as 'running a mental model' (Ehrlich 1996), 'envisioning' (de Kleer and Brown 1983) and 'simulating in the mind's eye' (Sims and Hegarty 1997). As

Carroll and Olson (1988, p. 51) put it: 'A key feature of a mental model is that it can be "run" with trial, exploratory inputs and observed for its resultant behaviour'.

This latter notion of running a model is especially commonplace in the literature (see, for example, the volume by Gentner and Stevens 1983), and captures very effectively the idea that a model can be deployed to test out the possible outcomes of an action in advance of taking that action. Indeed, it is the running of the model which allows it to be used predictively in advance of performing some action. If the model was static, prediction would not be possible. A somewhat different perspective on representational dynamism and mental models is provided by Bibby (1992), who sees mental models as being produced in an active process through the dynamic use of several interacting representations. This brings forward the notion that not only can a mental representation depict a dynamic situation in the external environment, but that the interaction between these mental representations can itself be dynamic.

In relation to image-based representations, Paivio and Clark (1991) consider the contrast between static and dynamic mental imagery, but do not attempt to justify the existence of dynamic imagery, instead speculating on its possible underlying mechanisms. There is, however, considerable support in the literature for the existence of dynamic mental imagery. For example, Pani (1996) rejects static 'picture in the head' approaches to imagery and proposes that symbolic, abstract, schematic images are active in nature. The concept of dynamic imagery is also noted by Brewer (1999), and Denis (1991) refers to models relying on imagery as being more than static cognitive entities, instead involving dynamic simulation and manipulation. With diagrams, too, people form visual representations of the diagram and can imagine moving about pieces

to solve a task. These movements are taken by Johnson-Laird (1996) to be visual transformations of images. Likewise, too, Narayanan and Hegarty (1998), in their cognitive model of mechanical comprehension, refer to 'mental animation' using rule or imagery-based inference. They suggest several lines of evidence for this, including the work of Sims and Hegarty (1997), Schwartz and Black (1996) and studies indicating the importance of physical gestures when people reason about dynamic physical systems (e.g. Clement 1994).

With regards to the location of dynamic models and images, it has been noted previously that non-conceptual mental representations reside in WM, and, therefore, this must be where they are run. For example, Cañas and Antolí (1998) propose that mental models are dynamic representations created in WM that are constructed by combining information stored in LTM and information extracted from the environment. Likewise, Barsalou (1999) specifies WM when referring to running perceptual simulations. The dynamic nature of WM is in contrast to the more static characterization of LTM. For example, Wilson and Rutherford (1989, p. 625) refer to mental models as being 'computationally dynamic' in comparison to structures such as schemata that represent background knowledge. Likewise, Ehrlich (1996) describes mental simulation as a dynamic process of building, running and perhaps changing internal mental representations, and contrasts mental models with schemata, which are argued to be static LTM representations.

6. Representations, Problem Solving and Cognitive Task Performance

6.1. Representations and problem solving

The sections above have presented a detailed discussion of issues concerning the nature and functioning of the mental representations that underpin cognitive task performance. Since it can be argued that all higher-level cognitive tasks are fundamentally problem solving tasks because of their goal-directed nature (Anderson 2000), then a brief consideration of the topic of problem solving could potentially add useful insights to the current review.

Three essential features can be identified in problem solving (Newell and Simon 1972). First, cognition is directed towards some end goal (e.g. the achievement of a task). Second, this goal can be broken down into subgoals or subtasks. Third, the subgoals are achieved through applying actions or operators that transform states of the problem. Once a problem has been repeatedly solved it becomes a learned procedure. Problem solving is frequently described in terms of a 'problem space', which consists of the many, various possible states of the problem, with the term 'state' referring to the representation of the problem at some degree of solution (Newell and Simon 1972). The problem solver, then moves from an initial state, through intermediate states, to a goal state. These states define the problem space. In this way, problem solving is about searching through the problem space for a path to the goal state by applying 'operators' that can move the problem solver from one state to another.

A significant question at this point is how does the problem solver select an operator when there are a number that may be available? Problem solving operators can

be found through discovery, or through learning via instruction, or by observation. A further proposed method of operator selection is 'difference reduction', whereby operators are chosen that reduce the difference between the current state and the goal state. The so called 'means-ends analysis' heuristic proposed by Newell and Simon (1972) is one highly effective strategy for operator selection that is based on identifying the biggest difference between one's current state and a goal state. Much of the strength of means-ends analysis resides in the fact that the strategy can: (1) add a new sub-goal to reduce an area of difference between the current state and the goal; and (2) invoke itself recursively to achieve the subgoal, at which point the strategy can recommence to progress toward the main goal. A further theoretical proposal relating to effective problem solving is that of 'backup avoidance', which relates to the idea that people are biased against any action that returns them to the previous state. With regard to mental representations, backup avoidance also relates to the view that a mental representation can have a persisting influence on performance as people protect their misconceptions (Gopher *et al.* 1985).

When considering the activity of problem solving from a more unified perspective, it seems clear that it is essentially a process of constructing representations in working memory that lead from an initial state to a goal state (Barsalou 1999; see also Visser 2006 for a related proposal in the context of problem solving in the domain of design). The process of working forward or backward between the initial and goal states involves simulating a plan that may achieve the goal. Furthermore, a component may be added to the simulation either due to prior knowledge of what has been successful in the past (what are termed 'set effects' in problem solving theory), or because simulations suggest that the component may work. In a similar way, the related

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domain of decision making can be viewed as involving the application of various adaptations to a simulated plan to see which version offers the best outcome. As possible plans are formed, each is simulated to assess which works best (Barsalou, 1999). The proposal that mental representations underlie cognition in areas such as problem solving and decision making is further supported by Johnson-Laird (1983), who also explains reasoning behaviour using mental models theory. Furthermore, Payne (1992) includes the notion of the problem space as an example of the mental models concept and states that there is a clear overlap in ideas. Indeed, Simon (1989) himself refers to the problem space as being a mental model of the task domain. In these ways, then it can be clearly seen that mental representations are claimed to underlie all aspects of higher-level thinking, including problem solving, decision making and reasoning.

6.2. Representations and display-based problem solving

Although we have discussed above how mental representations underlie thinking, the focus has been entirely on internal representations, yet it is clear that most tasks exist in an environment that is external to the mind and that can, therefore, interact with it. Indeed, this essential notion of 'human-machine interaction' is at the core of most ergonomics research. When considering theoretical issues such as mental representation it is easy to forget the role of the external world that must, at the very least, inform ongoing cognition. For example, 'affordances' are the information in the environment that can guide behaviour and provide action opportunities directly through perceptual processes (Gibson, 1979). Zhang (1997) describes how the actions supported by affordances do not depend solely upon their physical properties, but also upon the properties of the perceiver. Whilst affordances can make a task easier, they can equally make it more difficult.

In terms of visuospatial cognition, Johnson-Laird (1996) argues that reasoning becomes difficult when the possibilities increase (as this taxes WM), and it is suggested that the construction of internal mental representations will be easier if an external model or diagram is available. Bauer and Johnson-Laird (1993) found that diagrams can help individuals reason, improving both the speed and accuracy of deduction. With a diagram people appear to form a visual representation of the depicted information and then imagine moving elements around this image to solve the task (Johnson-Laird 1996). Zhang (1997) considers external representations in problem solving in great detail, and proposes that much about the internal mind can be learned through studying external representations, since the mind reflects the structure of the external world. External representations are intrinsic to many tasks and will therefore guide or even determine cognition. Clearly the implications of this view for ergonomics science are critical, since it suggests that any tasks involving a predominance of external information (e.g. object assembly or interface-driven system interaction) need to be researched with very careful consideration to the role of external displays on cognitive functioning.

Like Johnson-Laird (1996), Zhang (1997) is especially keen to emphasize the striking benefit of diagrams for task performance, and notes how information can be processed by perceptual systems alone, such that internal representations may not even be required for performance if external representations are available. This view clearly contrasts with the common assumption inherent in traditional research in Artificial Intelligence and Cognitive Science, which views external information as being internalized before internal processing is then externalized (e.g. Newell 1990). Under

Zhang's view it is possible that problem solving is no longer the higher-level cognitive task that it is typically assumed to be.

In related work, Larkin (1989) emphasizes that problem solving is often performed with external displays or physical objects that may form an extremely important resource. She notes that most models of problem solving only really consider internal reasoning during problem solving as opposed to the role of external displays. Larkin (1989), therefore, proposes a model of 'display based problem solving', which assumes that often very little information needs to be held in WM, since many attributes can be observed in the external environment. The central premise of the display-based problem-solving model is that the external display is the main representation of the current problem state. If internal goals or information are lost then they can always be reconstructed from the display. Larkin (1989) notes that there is a crucial interaction between the external display and internal problem solving processes, with problem solving being facilitated by a good display. An effective display is one that shows all of the essential features of the current problem state and does not hide crucial information. Failure to encode essential features of the display will typically lead to problem-solving errors. The importance of the external environment is also noted in SA theories, but often not considered in the mental models literature.

6.3. The nature and functioning of external representations

It has been proposed above that external representations impact on problem solving to create the concept of display-based problem solving. In this respect, it is clear why O'Malley and Draper (1992) argue that understanding the nature of the *interaction* between users and tasks is the best way to obtain a good understanding of users' mental

representations, especially for tasks where much of the information needed for effective performance is presented externally. Essentially, then, it cannot simply be assumed that all of the information required for a task must be internalized. This criticism of the narrow view that can stem from mental representations research can also be related to problem solving research, where users' behaviour is not solely the result of internal goal-directed activity; it also relates to the impact of physical and functional aspects of external devices (Young and Simon 1987).

O'Malley and Draper (1992) argue that at times people may not even have a model from which knowledge about the task can be derived, as sometimes information can be extracted or provided by the task and its environment (a point also noted by Moray 1999; see, too, the view of Zhang 1997 presented above). At some level, however, it must be the case that a system user will at least have to possess the knowledge required to interrogate the environment for the information required. Nevertheless, it is certain that the internal and external distribution of knowledge makes the capturing of mental representations inherently difficult for researchers. Indeed, studies suggests that when using display-based systems, users do not internalize a great deal of information (Payne 1991a), and only use internal representations when necessary (i.e. when information is not available externally), which can lead to highly fragmentary internal representations (O'Malley and Draper 1992). These observations have led to the concept of 'distributed models', where internal representations are complemented by external representations.

At this point it seems useful to return in more detail to the question of what information external representations provide? Larkin and Simon (1987) specify the

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advantages of external representations or diagrams, in particular identifying how diagrammatic external representations can assist in search, recognition, and inference—three key components of information processing. Larkin and Simon describe the most important advantage of external representations in the form of diagrams as being the efficiency of search that they afford and the explicitness of information that they provide; essentially, the perceptual work is automatic and easy. Diagrams also facilitate inference, since basic (perceptual) information can be perceived initially with little effort. For example, spatial relationships do not have to be described; they are immediately apparent. People can also use perceived information as cues to retrieve problem-relevant inference-operators from memory. However, this means that external representations are only useful to those who know the appropriate computational processes for taking advantage of them.

Research subsequent to that of Larkin and Simon (1987) has generally supported the benefits for task performance that are engendered by external representations. For example, Cox (1999) notes how external representations reduce search and WM load and promote distributed cognition that involves neither wholly internal nor entirely external representations, instead involving a seamless interaction between both representational domains. Cox also claims that illustrations encourage the formation of ‘spatial mental models’, and that the comprehension of external representations makes use of the visuospatial sketchpad component of WM. With regard to imagery and reasoning with an external representation, Stenning and Oberlander (1991, 1995) suggest that the non-abstract nature of mental images provides an advantage by reducing the number of possible interpretations of a situation that are possible, thereby making reasoning from diagrams more efficient. The interaction between internal and

external representations noted by Cox (1999) and O'Malley and Draper (1992) is further supported by Bryant and Tversky (1999). They emphasize that external representations in the form of 'schematics' (i.e. simplifications of the represented world) can affect how a depiction is mentally interpreted and used. Such schematics and display designs can simplify the world by omitting, adding, or distorting information, thus affecting people's mental representations, which further schematizes the information. Bryant and Tversky (1999) also note that diagrams may depict 3-D relations, but are themselves 2-D, whereas external models are 3-D. Interestingly, Bryant and Tversky found that external models promoted 3-D mental representations whilst diagrams required some instruction to be fully exploited. Essentially, then, the external models and diagrams created different kinds of mental representations.

Having discussed evidence for the view that external representations can have a marked impact on cognitive actions when problem solving, we now consider Zhang's (1997) theoretical framework that attempts to encapsulate the links between the structure of tasks and external and internal representations. Within Zhang's framework, 'operations' are representation-specific, for example, external representations activate 'perceptual operations' such as component selection during object assembly, whereas internal representations activate 'cognitive operations'. Lookahead—the process of mentally imagining and evaluating actions—is used to choose which action to take. This lookahead process would appear to resemble the use of mental imagery introduced previously. The central control component of the framework is the most complicated aspect of the theory—but arguably the least specified—and includes WM, learning, and decision making. Its importance in Zhang's framework relates to the coordination of the level of attention given to external and internal representations, and hence perceptual

and cognitive operations. Although the framework does not require internalization of external representations, this does not mean that internal and external representations function entirely independently, as external representations still have to be processed by internal perceptual mechanisms.

In reviewing what they refer to as ‘external cognition’, Scaife and Rogers (1996) propose the need for considerably more research into graphical representations based on an analysis of the interactivity between external and internal representations. Although related specifically to ‘graphical’ representations, their conclusions seem generalizable to any tasks involving an external component. Scaife and Rogers (1996) remark on the three central characteristics of the emerging literature on internal and external representations as being an emphasis on: (1) ‘computational offloading’, whereby external representations reduce the amount of cognitive effort required; (2) ‘re-representation’, whereby external representations have the same abstract structure as internal representations; and (3) ‘constraining’, which refers to the way external representations can influence the inferences made about the represented world.

We note here that Scaife and Rogers’ (1996) views closely parallel the proposals summarized above by Larkin (1989), O’Malley and Draper (1992), Zhang (1997), Bryant and Tversky (1999) and Cox (1999), who all presents a fundamentally similar picture that emphasizes the benefits of external representations in cognition. Moreover, when considering external representations (including related notions of ‘distributed models’ and ‘distributed cognition’) the researchers above frequently remind us that the interaction between internal cognition and the external components of a task must be considered in combination, since external representations certainly will impact on the

nature and scope of internal representations (cf. Zhang 1997). It seems sensible to conclude, therefore, that task-based interactions fundamentally involve multiple mental representations manipulated in WM, that are informed by knowledge and constrained by the external environment.

6.4. Cognitive constraints on mental representation

The focus of much of the literature presented above has been on the mental representations that underlie task performance. However, it is important also to consider aspects of the overarching cognitive system that may constrain the nature and functioning of mental representations. Indeed, one fundamental conclusion that has been drawn from the previous discussions is that the construction and manipulation of mental representations can place a considerable demand on cognitive resources, although the specific nature of the task, instructions, and associated mental representations will all influence the specific level of demand. Sweller's (e.g. 1988) 'Cognitive Load Theory' deals head on with this interaction between cognitive structures and task-based information, as well as with the resulting implications for task performance and learning.

These issues of task demand and mental representation can also be considered more generally from the perspective of theories that discuss the limitations of the human information-processing system, such as the capacity constraints of WM (Miller 1956). For example, it has been noted above that mental representations exist in WM, and it is likely that more specialized sub-systems of WM exist for dealing with mental imagery and mental models. In particular, the visuospatial sketchpad component of WM (Logie 1991, Baddeley 2002) is claimed to be dedicated to the processing of visuospatial

information, although Miyake *et al.* (2001) have also found evidence to support the proposal that the visuospatial sketchpad is closely tied to the central executive component, thus potentially implicating a number of aspects of WM in visuospatial task performance.

A further, key issue in cognition concerns individual differences that are known to exist in WM and which can vary dependent upon the task (e.g. whether it calls upon verbal or visuo-spatial resources). There are, for example, observable differences across individuals in spatial abilities such as mental rotation performance (Karadi *et al.* 2001), and it can be expected, too, that there will be discernable differences in people's underlying mental representations. Indeed, de Vega *et al.* (1996) support the notion of individual differences in visuospatial ability, and take the view that it can be measured through tests that require mental re-assembly or rotation. The precise location of such individual differences in ability remains unclear, but is postulated to be related to effortful processes that underpin the construction of mental representations. Baggett and Ehrenfeucht (1988) also found difference between individuals' conceptual models, and observed both typical and atypical conceptualizations of objects during assembly tasks.

7. Toward an Integrated Representations Framework

The journey that has been mapped out thus far in the paper has passed from mental models and visuospatial cognition, through discussions of the nature of external representations, and has ended up considering critical interactions that take place between internal cognition and external task components. This latter human-machine interaction or ergonomics approach, in fact, brings us full circle to the fundamental aim of the present paper, which was to gain an understanding of the representations

associated with performance when people work with technological systems to achieve task-related goals. The recognition of the inherent interactivity between external and internal representational domains underlines the importance of applying research methodologies that are capable of examining tasks and cognition in an integrated manner rather than in isolation. For example, Richardson *et al.* (2006) present a methodology for studying such interactions in the domain of object assembly. In their research they proposed a whole range of external characteristics possessed by assembly objects that should, on a priori grounds, have predictable effects on internal cognition, and they then went on to examine such influences empirically.

Returning to the core issue of the nature of internal representations, we are left in no doubt that such representations can be described in a large number of different ways and from a vast array of different perspectives. As such, any attempt at formulating a unified, descriptive framework for encompassing mental representational concepts is very likely to falter (cf. Payne 1991b), at least in the short term. As such, any proposals in the current section are perhaps best viewed as an attempt to bring together some useful, high-level insights from the literature that we have reviewed in a way that can provoke further debate and discussion, and that may help, in time, to advance theoretical understanding and conceptual rapprochement. With these caveats in mind, what we sketch out below are the core elements of a generic cognitive framework that aims to capture the representations and processes that underlie task-based, goal-directed performance (see Figure 3). As is readily apparent from the visual depiction of this framework in Figure 3, we draw heavily on conclusions about mental representations introduced earlier by Endsley (2000), Moray (1999) and Zhang (1997).

[Insert figure 3 about here]

The work of Moray (1999) is considered as particularly important to our proposed ‘Integrated Representations Framework’ because of its completeness and its sheer breadth of scope. First, Moray’s refers very effectively to the classic mental models literature, and his proposals that are based around the mental models concept are neither domain-specific nor task-specific in emphasis. Second, Moray’s theoretical viewpoint encapsulates the importance of multiple mental representations and the role of the environment in task performance. Third, Moray himself builds upon an observed degree of convergence in the literature that leads to the possibility that a unified approach to mental models can be developed. The theoretical position of Zhang (1997) is likewise considered important to our Integrated Representations Framework because it complements Moray’s (1999) proposals whilst also paying particularly careful attention to the role of external representations in problem solving—which relates to Moray’s notion of the ‘environment’ whilst also being distinct in important ways. In particular, Zhang’s recognition of the importance of ‘perceptual operations’ in task performance is seen as a real strength over other perspectives that tend to overemphasize the dominance of cognitive operations. Finally, the theory of SA and the work of Endsley (e.g. 2000) is of key relevance, both because it has become so well established and because its conceptual underpinnings and terminology (e.g. emphasising the role of mental models and goals in task performance) allow for an excellent degree of integration with the perspectives of Moray (1999) and Zhang (1997). We are especially impressed by the fact that much of Endsley’s SA theorizing has a strong basis in previous ergonomics-

related literatures, such as Wickens' (1992) pioneering model of information processing and task-based activity. Proposals deriving from the SA perspective also add new elements to our Integrated Representations Framework, such as the idea that external features of the environment can include workload and stress, and the notion that the 'interface' between the internal and the external is a core theoretical construct, which itself embodies information-processing mechanisms such as attention, perception and feedback.

Although aspects of terminology and structure certainly do differ—sometimes quite markedly—across the proposals of Endsley (2000), Moray (1999) and Zhang (1997), all three theories have a number of similarities. Some degree of commonality is, perhaps, only to be expected, such as the inclusion of mappings between components such as mental imagery, LTM and WM. More notably, Zhang proposes that external and internal relationships relate directly to task structure, a claim that relates to Moray's notion of certain mental representations being linked to either system form or system function. The key differences between these two proposals, however, appear to reside in Zhang's inclusion of perceptual operations and Moray's conceptualization of multiple mental representations. Certain, more specific differences between Zhang and Moray's theories, are not considered in our Integrated Representations Framework. For example, Zhang chooses to group the components of his theory differently, such as learned knowledge being combined with lookahead, whilst Zhang does not specify or separate scripts and plans from actions. Although much of the content from Endsley (2000) is mirrored in the frameworks of Zhang (1997) and Moray (1999) it adds to the processes and mechanisms involved. The models of Endsley highlight the impact of stress and workload and individual qualities such as experience and training. Endsley also brings

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the interface between the task and cognition to the fore, such as aspects of information processing and, for example, the need for perception before comprehension and lookahead (or projection) can occur.

It is with an emphasis on the similarities between extant theories, rather than their subtle differences, that we propose the Integrated Representations Framework depicted in Figure 3, which summarizes in a diagrammatic form many of the core concepts from the literature on mental and external representations and their interaction. Its greatest strength is arguably that it brings together the proposals of Endsley (2000), Moray (1999) and Zhang (1997), which are theories that themselves embody many of the central notions concerning representational issues that have been presented in this review. In terms of the actual notation associated with our proposed framework, we follow Zhang (1997) very closely in highlighting ‘external representations’, and we include ‘the task’ and ‘the environment’ as fundamental constructs that are part of this external representation. The task is the problem to be solved, and the environment is the medium in which the task is embodied (Moray 1999). These external representations are perceived by a problem solver or system operative and can lead directly to perceptual operations, such as component search, or to the construction of mental representations in WM. These mental representations can involve mental models or mental imagery, and map onto physical form, physical function, general function, goals, means and ends (Moray 1999). Mental representations can also sustain ‘lookahead’, the process of mentally imagining and evaluating actions in order to choose which action to take (Zhang 1997). The mental representations are informed by—and themselves inform—LTM representations such as conceptual models and schemata. Conceptual models and schemata in LTM, together with the outputs of mental representations in WM, inform

the scripts and plans that form the actions taken on the task. The ‘central control’ component relates to the ongoing coordination of perceptual and cognitive operations within the framework. The importance of central control within Zhang’s theory relates particularly to the level of attention given to external and internal representations and to the integration of information from these external and internal representations (Zhang 1997).

As a final few comments on our proposals, we again reiterate that there is likely to be no single, optimal theoretical framework for considering external and mental representations for some time to come, but we believe that it is still of considerable value to draw out aspects of commonality across theories whilst recognising elements of uncertainty. In a similar, cautionary remark, Moray (1999) refers to his proposal of mappings in mental models as a ‘rough indication’ rather than a definitive account. We also acknowledge that we have not attempted to cover concepts relating to shared mental models (e.g. Levesque *et al.* 2001) or team mental models (e.g. Langan-Fox *et al.* 2004) as part of theoretical framework. This omission, however, simply reflects an effort to maintain a degree of focus in our attempt at conceptual integration. Indeed, understanding the way in which mental models support team-working practices and performance strikes us as being a critically important direction for future research. Moreover, as work in this area matures we are certain that the concept of a team mental model is one that will need to be entertained very seriously as part of any broader theoretical framework for capturing the nature of mental representations in work-based activity.

8. Conclusions

The literature that has been reviewed in this paper has led to the proposal that cognitive task performance fundamentally involves multiple mental representations manipulated in WM, which are informed by knowledge in LTM and information in the external environment. As such, there is a continuous interaction between external representations and internal cognition, which means that external components of the task must be taken seriously in theoretical accounts of goal-directed cognition. These proposals lead to the view that understanding human-machine interaction is central to an effective conceptual analysis of the nature of internal and external representations and the way that they play out in real-world, task-oriented activities, whether these arise in professional work domains such as those involving people using complex interactive technologies (e.g. in safety-critical, process-control contexts), or in more mundane everyday situations such as day-to-day human-computer interaction or object and furniture assembly.

Developing these proposals further, we have argued that it is possible to formulate a unified theoretical framework to capture the nature and inter-relations between mental representations and external representations that is based around an integration of the theories of Endsley (2000), Moray (1999) and Zhang (1997). Indeed, the degree of convergence between these three different approaches is such that the resulting Integrated Representations Framework that we propose appears to provide a more comprehensive account of the representations involved in task performance than either of the component theories can provide on its own. The Integrated Representations Framework that we present details internal cognitive mechanisms and representational constructs, whilst also providing a basis for considering human-task interaction in the context of a given external environment. We would further argue that any attempt

toward a unified approach to theory development is better served by testing a generic framework from alternative perspectives, as opposed to the alternative research strategy of creating and evaluating highly task-specific frameworks that do little to integrate concepts across multiple tasks, domains and research traditions. Paradoxically, however, it seems that much of the recent research on issues relating to mental representations and task performance has tended to pursue the more task-specific agenda, which we believe has led to considerable theoretical fragmentation. Indeed, the indication of the lack of a unified approach in the literature is the very failure by many researchers even to clarify and define what is meant by the terms that they use such as ‘mental model’.

The theorizing of Endsley (2000), Moray (1999) and Zhang (1997) is, perhaps, unique in its integrative stance, as well as its clear attempt to define and use representational terminology in a consistent way that is faithful to its origins in pioneering research. In drawing upon these authors’ theories, we have presented a summary of key proposals in the form of a diagrammatic overview that can inform an understanding of any task-based activity. Moreover, if a researcher needs to develop a detailed process-model of a particular task, then our framework can be consulted so as to inform an emerging task analysis. We conclude by reiterating that an integrated approach to representational issues associated with task performance has the key benefit of reducing the fragmentation and divergence that derives from developing highly specific frameworks for understanding particular tasks. Testing such a generic framework from a range of perspectives is, we believe, far more likely in the long run to produce a fully unified approach to issues of internal and external representation which

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underlie the human-machine interactions that are fundamental to ergonomics as a science.

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Figure 1. A simple assembly task.

Table 1. Examples of mental representation terminology.

Figure 2. Overview of Stage 3 of the cognitive model of machine comprehension by Narayanan and Hegarty (1998). Adapted to refer to object assembly.

Figure 3. An Integrated Representations Framework summarizing internal and external representations and SA in task performance. Adapted from Endsley (2000), Moray (1999), Zhang (1997).



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Term	Reference
Mental Representation	This is a generic concept that covers the full range of representational formats, including propositions, mental images and mental models (de Vega <i>et al.</i> 1996).
Internal Representation	Internal representation is a catchall term that is often used interchangeably with that of mental representation, but which is sometimes used as synonym for mental model (Wilson and Rutherford 1989).
Mental Image	Mental imagery is a potential medium for thought, whereby visual images are manipulated to perform mental simulations of physical objects (Kosslyn 1994, Denis 1991).
Proposition	Propositional representations are logic-like descriptions involving predicate-argument formalisms that encompass information in a way that has some resemblance to natural language (Pylyshyn 2002). As such, propositions are often taken as a way to encode verbal information (Paivio 1971), although they can encode visual information (Pylyshyn 2003).
Mental Model	Craik (1943) first proposed the notion of 'small-scale models' of reality, and Johnson-Laird (e.g. 1983) took up the term in a more restricted sense to refer to a specific type of mental representation held in <i>working memory</i> which is abstract and spatial but not visualizable (see also Johnson-Laird 2004). However, the term mental model has been freely applied by many researchers to denote virtually any representation of knowledge about devices (Tauber 1988). For example, Endsley (2000) discusses Situation Awareness theory in which mental models are associated with schemata in <i>long-term memory</i> .
User's Model	The idea that users have models of the operating characteristics of interactive systems or devices (e.g. computer-based technologies) is an instantiation of the mental models notion as described by Johnson-Laird (1983), and works along the same principles (Manktelow and Jones 1987).
Mental Simulation	Mental simulation is a term introduced by Einhorn and Hogarth (1981) to refer to a process where a sequence of events is consciously enacted (e.g. to determine cause-effect relationships or to predict outcomes).
Situation Model	Situation model is a term adopted by Situation Awareness theorists to refer to a model that guides attention, integrates perceived information and provides a mechanism for predicting future states of a system (Endsley 2000).
Operative Image	The operative image or model is a mental image of the device generated during the task interaction. It is dynamic and regulates activity (Oshanin 1966).
Conceptual Model	Welford's (1961) concept of a conceptual model is viewed as being an approximate, inexact, yet holistic mental image that is not task specific. In Activity Theory it is described as the 'inner idiosyncratic world of the operator' based on experience and instruction and held in long-term memory. As such, a conceptual model is static and resistant to change (Bedny <i>et al.</i> 2004).
Dynamic Model	The concept of a dynamic model, introduced in Activity Theory in the mid 1980s, is viewed as consisting of different aspects (including imagery) and is a representation created in working memory from operative thinking and information drawn from the conceptual model. A dynamic model can be related to the concepts of a situation model and an operative image (Bedny <i>et al.</i> 2004).
Conceptualization	This term has been used to refer to a person's mental representation of the hierarchy of subassemblies for an object (Baggett and Ehrenfeucht 1988).
Device Model	A device model is an individual's understanding of how a device works in terms of its internal structure and processes (Kieras and Bovair 1984).
Spatial Visualisation	Spatial visualisation is described as a type of representation that can be used to solve mechanical problems (Hegarty <i>et al.</i> 2003).
Shared Mental Model	Shared mental models are knowledge structures held by team members that enable task goals and team demands to be met (Cannon-Bowers <i>et al.</i> 1993; Levesque <i>et al.</i> 2001).
Team Mental Model	The concept of a team mental model draws on team-working theory and is claimed to be distinct from the notion of a shared mental model (Langan-Fox <i>et al.</i> 2004). Team mental models reflect an understanding of team goals and team-member skills. As such, they provide organized expectations for team performance, enabling timely and accurate predictions to be made regarding team-member behaviour (Langan-Fox <i>et al.</i> 2004).



