About the relationship between incongruity, complexity and informion : design implications for man-machie systems

About the Relationship between Incongruity, Complexity and Information: Design Implications for Man-Machine Systems

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Abstract

Information and information processing are one of the most important aspects of dynamic systems. The term 'information', that is used in various contexts, might better be replaced with one that incorporates novelty, activity and learning. Many important communications of learning systems are non-ergodic. The ergodicity assumption in Shannon's communication theory restricts his and all related concepts to systems that can not learn. For learning systems that interact with their environments, the more primitive concept of 'variety' will have to be used, instead of probability. Humans have a fundamental need for variety: he can't permanently perceive the same context, he can't do always the same things. The fundamental need for variety leads to a different interpretation of human behaviour that is often classified as "errors". Variety in the relationship between a learning system and his context can be expressed as incongruity. Incongruity is the difference between internal complexity of a learning system and external complexity of the context. Traditional concepts of information processing are models of homeostasis on a basic level without learning. Activity and the learning process are driving forces that cause permanently in-homeostasis in the relationship between a learning system and his context. A suitable model for information processing of learning systems must be conceptualised on a higher level: a homeostatic model of in-homeostasis. A concept to information processing is presented that derives an inverted U-shaped curve between incongruity and information. This concept leads to important design recommendations for man-machine systems.

1 Introduction

We live in a dynamic and irreversible changing world. We are information processing systems and have a huge learning potential. What happens to humans, if they have to behave in an approximately static environment? If we need growth (in a psycho-dynamic sense) and development, how long we are able to tolerate contexts that fix and constrain our activities? There is a lot empirical evidence that humans are getting bored if the context is characterized by repetitiousness, lack of novelty, and monotony (Smith 1981). Ulich (1987) differentiates between boredom and monotony. Boredom emerges from the feeling of not having enough possibilities to be active. Monotony emerges from the feeling of doing always the same things. "Monotony is a consequence of standardisation of the work process" (Ulich 1987, 8). On the other side, there is strong empirical evidence of stressed and over-loaded workers (Karmaus, Müller and Schienstock 1979).

We have to realize and to accept that humans do not stop learning after end of school. We are compelled to learn and to make experiences our whole life. Human information processing can not be independent of this life-long learning processes. In this sense, humans are open systems. In his law of requisite variety Asby (1958) pointed out, that for a given state of the environment, an open system has to be able to respond adaptively, otherwise the adaptability and the ability of the system to survive is reduced. A learning system, without input or with constant input, either decays or (in the best case) remains the same. Learning and the need for variety implies, that with constant input variety the requisite variety of the system tends to decay over time. This is a strong argument against 'one best way' solutions in work design on a structural level (see also Ulich 1987).

2 Concepts of Information

We can find in the literature different interpretations of the term 'information' (see Table 1). Several approaches from different point of views are done to clarify 'information' (e.g., TopsØe 1974, Dörner 1979, Völz 1991). If we try to apply information theory to human behaviour, then we have to integrate activity, perception, and learning. In this proposal we are looking for an interpretation of 'information', which is compatible with concepts of activity and learning. Going this way, we hope to avoid the paradox of 'new' information. Information before and after the reception of a message is not the same! Different concepts are introduced in the literature to 'solve' this paradox (see Table 2).

1.) Information as a message	(syntax)
2.) Information as the meaning of a message	(semantic)
3.) Information as the effect of a message	(pragmatic)
4.) Information as a process	
5.) Information as knowledge	
6.) Information as an entity of the world	

Table 1: Survey of six interpretations of 'information' found in the literature.

Streuffert and Streuffert (1978, 105) differentiate between 'information load' (the quantity of information per unit time), 'eucity' (the success component of information), and 'noxity' (the failure component of information). "Where noxity requires taking an action over again, thereby increasing current load by adding action requirements, eucity is likely to decrease load. Irrelevant information will be equivalent to load only with regard to some of the activities in which a person is engaging at the present time" (Streuffert and Streuffert 1978, 105).

before reception	after reception	Author
degree of freedom of the decision	content of the decision	HARTLEY 1928
uncertainty	certainty	SHANNON 1949
uncertainty	information	BRILLOUIN 1964
potential information	actual information	ZUCKER 1974
entropy	amount of information	TOPSØE 1974

Table 2: Terms to describe the amount of information of a message before and after reception.

The concept proposed in this paper assumes, that information processing is an interactive concept. We also try to enclose perceptual and behavioural aspects. We suppose further on, that the stimulus effects of the environment (or context) interact with the real or potential complexity of the receiver. The context can be the environment beyond the human skin, the neural stimuli of extremities (e.g., arm and leg movements, motor restlessness), and mental processes like 'daydreaming', etc. We call all perceivable stimuli that are generated inside the system, the 'internal source of stimulation' (see Fig. 1). So, the complexity of the context (CC) is the sum of the environmental complexity (EC) and of the bodily complexity (BC; e.g., measured by the level of arousal). The complexity of the receiver is limited to the internal complexity of his task related memory (MC). At least, we have a human in mind that is motivated to attend to the stimuli and is motivated to respond in some meaningful fashion to the situation of which the stimuli are a part. Attention as one perceptual aspect is closely coupled with arousal.

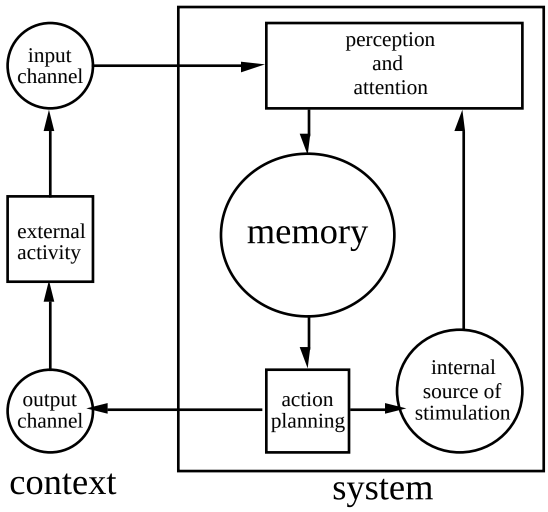

Fig. 1: Two different sources for perception: the 'input channel' of the context and the 'internal source of stimulation' of the system.

3 Arousal and Attention

The fundamental law that relates performance to arousal is the Yerkes-Dodson law (Yerkes and Dodson 1908). This 'law' stated that the quality of performance on any task is an inverted U-shaped function of arousal, and that the range over which performance improves with increasing arousal varies with task complexity. A simple task needs a higher amount of arousal than a more complex task to reach a maximal quality of performance. We can conclude that there is -- overall at the time -- a limited capacity to handle complexity. The limit is the sum of two parts: (1) the 'external' complexity CC (e.g., a given task complexity EC or a given level of arousal BC); and (2) the internal complexity MC. If the external complexity of the environment EC decreases and the incongruity remains under the individual threshold, then the complexity BC must increase to guarantee optimal quality of task performance. To increase BC, Smith (1981) describes various 'coping' strategies: drugs (e.g., caffeine, nicotine), motor restlessness, daydreaming. So, human perception of 'external' complexity can be affected either by the content of the external 'input channel', or by the content of the 'internal source of stimulation' (see Fig. 1). Now we can very easily relate the typical effects of drugs to three types of intended stimulation: (1) increase of action planning and activity (e.g., cocaine), (2) increase the internal stimulation (e.g., caffeine, nicotine), and (3) increase the perceptual range of the input channel (e.g., LSD).

On one side, the external complexity EC of the context can be increased through activity: exploration, response variability, and -- as last possibility -- withdrawal from boring situation. On the other side, Dörner et al (1988) assume that arousal correlates with the whole 'mental set of actual intentions' (MSI). If this assumption is correct, then we deduce that the complexity of MSI is an important part of BC. Stress through 'informational' overload is the increase of BC caused by the enhancement of MSI complexity.

The empirical evidence reviewed in Kahneman (1973, 28-42) suggests that a state of *high arousal* is associated with the following effects: "(1) narrowing of attention; (2) increased lability of attention; (3) difficulties in controlling attention by fine discriminations; and (4) systematic changes of strategy in various tasks." Kahneman relates attention only to the external 'input channel' (see Fig. 1). So, if the perceived complexity of the 'internal source of stimulation' (BC) is high (e.g., high arousal), then the perceptual capacity of the contextual 'input channel' (EC) is low (e.g., narrowing of attention, loss of fine discriminations).

On the other side, a state of extremely *low arousal* may cause: (1) a failure to adopt a task set; (2) a failure in the evaluation of one's performance, resulting in an insufficient adjustment of the investment of capacity to the demands of the task. We will see later, that humans in a state of extremely low arou sal primarily try to cope with this situation by increasing stimulation (external and/or internal) or, if an increase is not possible, escaping.

4 Attention and Activity

To determine the point of visual attention, several studies measured eye movements. There are much unsolved problems to correlate eye movements with higher psychological processes. But, 'eyes as output' are one of the best empirical sources. Kahneman (1973, 64-65) distinguishes three types of eye movements:

(1) *Spontaneous looking*, which is governed by the so-called 'collative' features of stimuli (novelty, complexity, incongruity). Responses to such stimuli are 'enduring dispositions', rooted in the innate tendency to respond to contours, and toward moving objects.

(2) *Task-relevant looking* is viewed as an allocation problem. It is a characteristic of the eye in that it has sharp vision at its centre or fovea, while peripheral vision is increasingly less distinct on outwards. Parafoveal vision is very sensitive to movements. Sharp vision occurs in sequential glances. The problem of where next to look is resolved through the interaction of task constraints and the visual context.

(3) Looking is a function of the *changing orientation of thought*. Eye movements of this type seem to reflect the overall transitions between stages of thought, even when the location, where the human is looking, cannot possibly offer any 'new' information. The eye movements during thought seem somehow to be related to the balance of activity between the two hemispheres, the rate of mental activity generally.

1.) *Basic information-processing mechanisms*, e.g., mechanisms governing the transfer of information from short-term memory storage to more permanent storage and comparisons of percepts with short- or long-term memory or expectancies derived therefrom.

2.) The *orienting response*, which involves information-processing mechanisms *plus* motor and physiological components such as changes in heart rate.

3.) Relatively *prolonged direction* of the receptors toward a source of stimulation (e.g., looking, listening, touching), which very likely involves the preceding processes plus motivational components such as those frequently denoted by terms like curiosity, boredom, monotony, aesthetic pleasantness.

4.) *Locomotor exploration*, which again involves the preceding but includes in addition the active movement of the organism toward a source of stimulation.

5.) *Manipulatory* or *investigatory behaviour*, which includes as a further component the effecting of some sort of change in the environment.

6.) *Integrated sequences* of the above, e.g., play in young organisms and various forms of artistic enterprise.

Table 3: Survey of activities classified along the dimension of "response-complexity" (from Brown & Gregory 1968, 810-811).

Brown and Gregory (1968, 810) concluded from their experimental results for attentional responses of humans to visual patterns, "that time spent viewing non-representational patterns: (a) increases as complexity, and especially the amount of contour defining the pattern, increases; and (b) roughly describes an inverted U-shaped function with increasing amounts of 'information' (a term which might better be replaced with one which incorporates novelty and related concepts with information-theoretic concepts), with the course and peak of the function being governed by the point(s) at which the observer alters the 'level of exactness' at which he abstracts the information."

The range of perceivable stimuli is divided into three parts: known structures and stimuli (KS), new structures and stimuli that are -- actually or potentially -- perceivable (NS), and unknown stimuli that are unknown and therefor not perceivable (US; see Fig. 2). At the moment it is unclear, how to get the dividing line between NS and US. The dividing line depends probably on the stored knowledge and learning strategies. What happens, if practice and learning increase KS by chunking? If we assume, that KS plus NS is about constant and KS increases over time, then NS must decrease. This seems to be not very attractive, even if this can sometimes happen. Perceptual chunking means to reduce complexity in NS and to increase complexity in KS. We call the range of KS plus NS the 'openness to the whole context': the perceptual range (PR). The attention controls the selection process of stimuli in PR. An empirically good validated effect runs as follows: the longer you are looking on something, the more you are going into details. The transfer rate from NS to KS is probably correlated with the learning rate.

Neisser (1976) distinguish between 'available information' and 'potential available information'. It is unclear, which mapping to our three parts is correct: (1) 'available information' is KS plus NS, and 'potential available information' is US, or (2) 'available information' is only KS, and 'potential available information' is NS plus US. The most interesting question is: how the transfer from US to NS looks? One possible answer is behavioural activity based on exploration or on supervised learning and training.

Attention depends strongly on our experience with the situation. Card (1982) could show that in man-computer interaction users form perceptual chunks as a result of practice. The same results are reported by Furst (1971). Möckl and Heemsoth (1984) proved the hypothesis that the degree of knowledge about a biological motion pattern (shot putting) determines the location of eye fixations. They found that the mean number of fixations at points with maximal information increased with increasing knowledge about the motion pattern. Points of maximal information were defined by an extra group of experts (coaches) about the performance of the motion. Thomas and Lansdown (1963) could show that radiologists have a more specific fixation pattern looking at a radiology picture than to unknown ink blots.

From these empirical results we can derive two possible conclusions: (1) the amount of socialisation and experience is negatively correlated with openness to the whole context; or, (2) the amount of socialisation and experience reduces complexity of new stimuli (NS) through chunking to keep the rest of the perceptual range (PR) free for new and unknown stimuli. Following the last interpretation we can say that humans are self optimising systems, which try to adapt to the context (Helson 1964). The different attractors for optima are constrained by the various kinds of contexts: culture, organisation, task (see Bainbridge 1994), and parts of our psycho-physiological and mental structure. The context determines what is important and what not, and where to turn attention to.

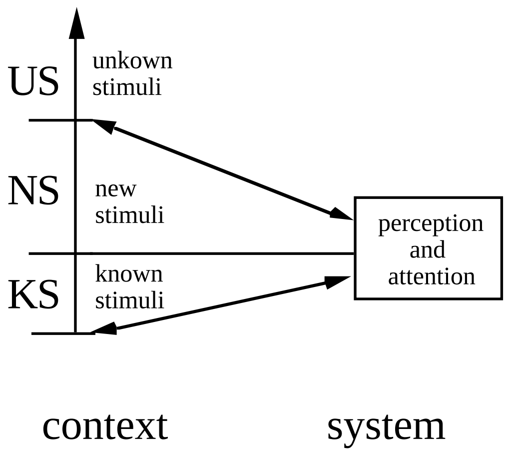

Fig. 2: The three parts of the context that relate to perception: known structures (KS), new structures (NS), and unknown structures (US).

In this paper we replace in a first step the term 'information' with the term 'incongruity' to incorporate novelty and other related concepts. Our second step is to define incongruity with complexity. Finally we present a suggestive relationship between incongruity and information based on behavioural activities.

5 Activity and Incongruity

Investigators of novelty assume, that living systems (like mammals, especially humans) are motivated by an information seeking behaviour. In situations, which are characterized by sensory deprivation, humans are intrinsically looking for stimulation. They increase the complexity of the context or the per ception of it. On the other side, humans try to avoid situations with a high amount of stimulation, dissonance, or stress. Hunt (1963) designated this amount of increased complexity as 'incongruity'.

If the complexity of the mental model MC is less complex than the complexity of the context CC, then humans try to optimise this positive incongruity. Seeking and explorative behaviour starts, when the positive incongruity sinks below an individual threshold or changes to negative incongruity (deprivation). Behaviour of avoidance can be observed, when the positive incongruity exceeds an individual threshold (dissonance, stimulation overflow). Most of daily situations can be characterised by a certain degree of positive incongruity.

We shift the semantic and theoretic problems from incongruity to complexity. Doing this, we can define incongruity in a more precise way. Incongruity is the difference of internal and external complexity (see Fig. 3). Now we have to look for a good definition of complexity (see the discussion in Rauterberg 1992).

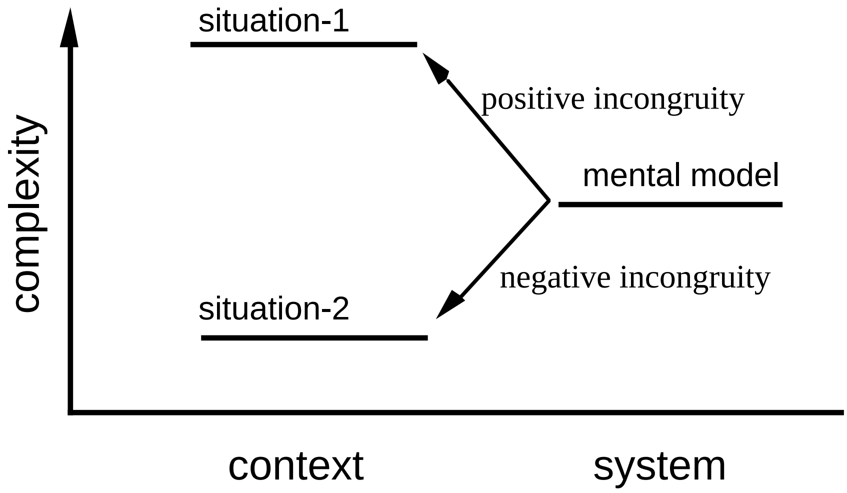

Fig. 3. The difference between the complexity of the mental model and the complexity of the context is called incongruity.

In man-computer interaction we are able to measure the complexity of human behaviour (e.g., explorative activities; see Rauterberg 1993). With some plausible assumptions we are also able to estimate the complexity of users' mental model (see Rauterberg 1992). The complexity of the context (the internal structure of the interactive software) can be measured. The next step is to look -- from the users' point of view -- for a good measure for the complexity of the *perceived* context. This problem is difficult, because we have to differentiate between the pre-structured part of perception based on learned mental schema (KS) and the unstructured and not predictable part, which enable the human to integrate new aspects into the stored knowledge (US). Attention and learning influences directly the shift from US to KS.

6 Learning and Activity

Learning is a permanent process that changes our long-term knowledge base in an irreversible way. The structure of our long-term memory changes to more complexity and higher abstraction. Bateson (1972) developed a hierarchical concept of four different learning categories that reflects different levels of abstraction. The basic idea of Bateson's concept is that the variety on one level can be reduced to the invariant structure. This invariant structure forms the next higher, more abstract level of learning. Learning implies abstraction. Humans under non standardised and fixed conditions evolve during their lifetime very abstract invariants. This fact is the basis of wisdom of old humans. Actual research is done under the topic of 'meta-cognition' and 'meta-learning' (Weinert and Kluwe 1984). Learning as a driving force for irreversible developments is the most underestimated factor in human behaviour, especially in the work and organisational context.

Neisser (1976) was one of the first researcher, who tried to integrate activity, perception, and learning. He emphasised that human experience depends on the stored mental schema, which guide explorative behaviour and the perception of external context. Learning increases constantly the complexity of the mental model. This is an irreversible process. One consequence is, that the contextual complexity must increase appropriately to fit the human needs for optimal variety.

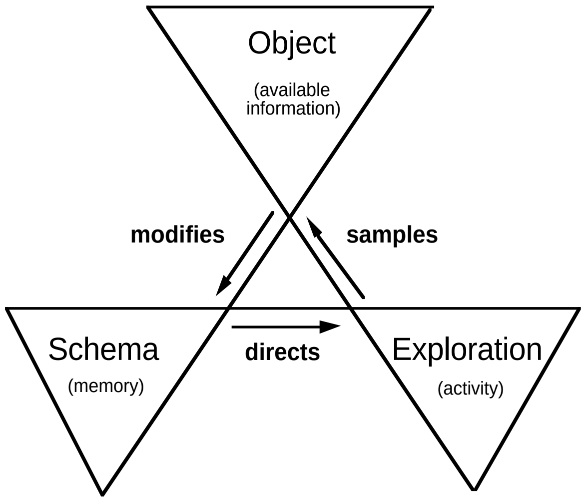

Fig. 4: The perceptual cycle (Neisser 1976, 21).

The empirical results in Rauterberg (1993) indicate, that the complexity of the observable behaviour of novices is larger than the complexity of experts. We concluded that the behavioural complexity is negatively correlated with the complexity of the underlying mental model. Thus it is possible to estimate the cognitive complexity based on the measurement of the behavioural complexity, the measurement of the system complexity and the measurement of the task complexity (for a more detailed discussion see Rauterberg 1992).

7 Activity and Information

Weizsäcker (1974) differentiated the concept of 'information' into two aspects: 'Singularity of the first time', and 'confirmation and redundancy'. For both aspects we can find two different research traditions in psychology: (1) novelty and curiosity (Berlyne 1960, Hunt 1963, Voss and Keller 1981), and (2) dissonance theory (Festinger 1957, Irle 1975, Frey 1981). Both research tracks are only loose coupled till today.

A context with sensory deprivation has not enough positive incongruity or even negative incongruity. On one side, a human will leave a context with very low incongruity (to little difference to context complexity), and on the other side with very high incongruity (to much context complexity; see Fig. 5). In between we have the range of positive emotions with behaviour, which increase novelty on one side, and on the other side that increase confirmation and redundancy, or reduce dissonance, resp.

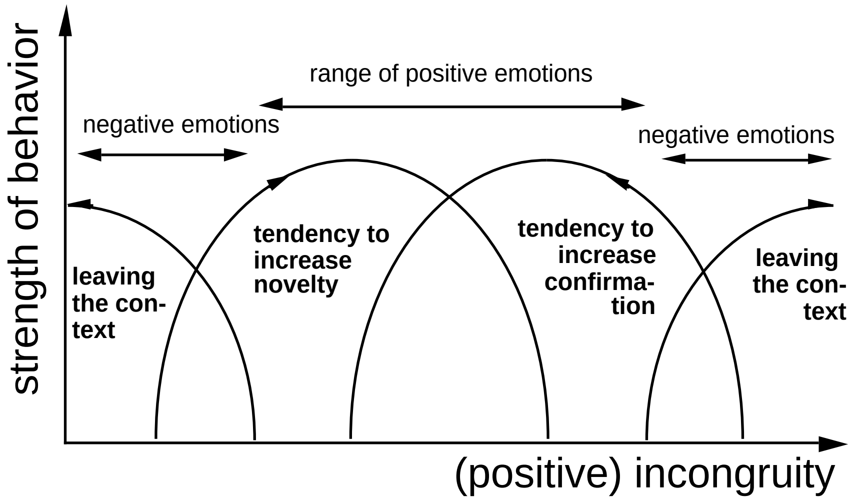

Fig. 5: The coherence between positive incongruity, emotions and observable behaviour (see also Streuffert & Streuffert 1978, 201).

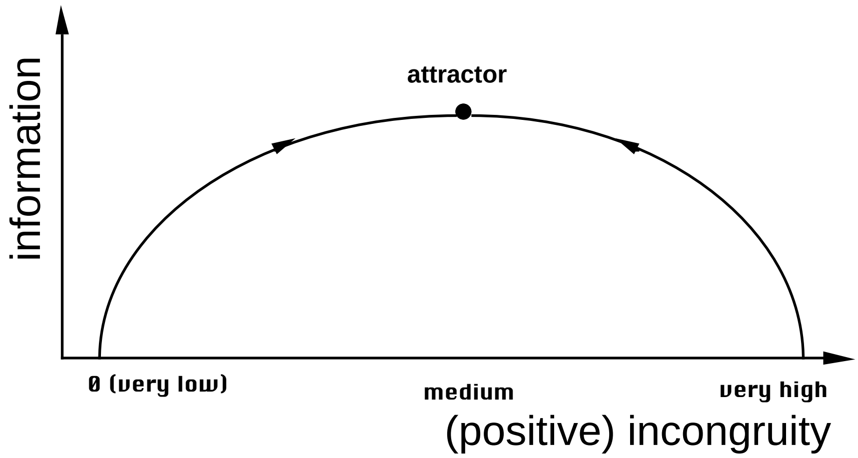

Fig. 6: The summarised coherence between positive incongruity and information.

Paritsis and Steward (1983) considered that the needs of "Natural Intelligent Systems" for information and variety can change according to the rate of their satisfaction. They argue that humans are seeking satisfaction and development, and that there is a *need for information* and variety, which facilitate development. This need for variety and the relationship to satisfaction is also valid in work contexts. "The most common source of interest is variety" (Walker and Marriott 1951, 182). Paritsis (1992) suggests that there is an optimum variety, which maximises the rate of development and evolution. Ulich (1974) expects the same relationship between task complexity and the efficiency of work. In particular for a given human, context and time is an optimum variety (and information) in the context, "which is a) as low to enable the organism to be adapted on the basis of its requisite variety, b) as high to allow and induce development, c) at the same time does not produce overload or under-load stress" (Paritsis 1992, 35).

Overall we assume a reverse u-curve as the summarised coherence between incongruity and information (see Fig. 6). If a human has to behave for a while in a total fixed and stabile context and he has a normal learning rate, then he must start to increase the incongruity. This can be done on two different ways: (1) increasing the complexity of the context or the perception of it, and/or (2) reducing the complexity of the mental model. Way (2) implies the possibility of 'forgetting' (decrease learning rate) or the manipulation of the perception mechanisms (suppression).

In an under-load situation we can conclude that operators try to increase their activities (see Table 3). If the sensory stimulation is too low and can not be increased in some other way (e.g., watching television or video), then operators tend to show locomotor exploration, manipulatory or investigatory beha viour (e.g., playing games). Task related actions, that could be classified as errors, are sometimes a subconscious, but a high rational strategy to increase external complexity.

In an over-load situation we can conclude that operators try to reduce their activities. The results of Moray and Rotenberg (1989, 1337) suggest "that operators prefer to work only one fault at a time and that this 'cognitive lock-up' hinders recognition of further faults."

8 Consequences for the Design of Man-Machine Systems

Bainbridge (1982) describes very clearly the problems arising when an operator has to take over a complex process during a monitoring task (the vigilance problem). To take-over process control is especially problematic when the system runs into an unknown state. Training in a simulator is one possible consequence, better is permanent on-line control in the real process. High skilled operators tend to lose the potential to be aware of the whole process. They need a special qualification to get open minded.

Boreham (1993, personal communication) described the different reactions of nurses and high qualified physicians in a monitoring task during anaesthetisation. Humans with lower cognitive complexity (e.g., nurses) are more able to be satisfied informational in a context with constant variety than humans with higher cognitive complexity (e.g., physicians). The optimal incongruity level depends on the complexity of the cognitive structure. If incongruity is too low, then humans try to increase the contextual complexity. This perspective allows us to have an alternative interpretation of human 'failures' in inescapable situations with information under-load (e.g., process monitoring in a steady-state). To increase the signal rate of the machine system artificially is not an appropriate design strategy for man-machine systems (Bainbridge 1982, 154). Job rotation and job enrichment can help to reduce information under-load, but not for a long time. Depending on the learning rate of the worker, we have to be aware of the monotony problematic.

The best solution is to involve the worker in the task solving process, especially when the task is a 'complete task' (Ulich et al 1992). Operators should have on-line control over the real process (Bainbridge 1982). Ulich (1983) formulated a global principle: differential and dynamic work design. There is no fixed 'one best way' for task solving processes. To satisfy the human need for variety (and optimal information) the work system must be flexible and individualisable. Following Ulich's dynamic work design principle we have to increase continuously -- but not abrupt (as in alarm situations) -- the task and context variability over time. Of course, this demand leads to difficulties in complex system design. But, neglecting this demand we run directly into most of the ironies described by Bainbridge (1982).

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