Processes underlying human performance

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There is a presumably revised version in the second edition of that Handbook, which I have never seen.

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Note on the Figures : this review was originally published on-line (late 90s) on a site which had a limit of 5MB on the entire site, so the figures are all of primitive minimal quality.

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This chapter was written in response to a request to cover the whole of cognitive ergonomics in 30 pages (I didn't succeed !) for a handbook of aviation human factors.

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INTRODUCTION

Two decades ago, a chapter on aviation with this title might have focused on physical aspects of human performance, on representing the control processes involved in flying. There has been such a fundamental change in our knowledge and techniques that this chapter will focus almost exclusively on cognitive processes. The main aims are to show that relatively few general principles underlie the huge amount of information relevant to interface design, and that context is a key concept in understanding human behaviour.

Classical interface human factors/ ergonomics consists of a collection of useful but mainly disparate facts and a simple model of the cognitive processes underlying behaviour - that these processes consist of independent information-decision-action or if-then units.

(I use the combined term human factors/ ergonomics, shortened to HF/E, because these terms have different shades of meaning in different countries.
'Cognitive' processing is the unobservable processing between [or before] arrival of stimuli at the senses and initiating an action.)

Classic HF/E tools are powerful aids for interface design, but they make an inadequate basis for designing to support complex tasks. Pilots and air traffic controllers are highly trained and able people. Their behaviour is organised and goal-directed, and they add knowledge to the information given on an interface in two main cognitive activities : understanding what is happening, and working out what to do about it.

As the simple models of cognitive processes used in classic HF/E do not contain reminders about all the cognitive aspects of complex tasks, they do not provide a sufficient basis for supporting HF/E for these tasks. The aim of this chapter is to present simple concepts which could account for behaviour in complex dynamic tasks and provide the basis for designing to support people doing these tasks. As the range of topics and data which could be covered is huge, the strategy will be to indicate key principles by giving typical examples, rather than attempting completeness. This chapter will not present a detailed model for the cognitive processes suggested, or survey HF/E techniques, and it does not discuss collective work. The chapter will be in three main sections on : simple use of interfaces; understanding, planning and multi-tasking; and learning, workload and errors. The conclusion will outline how the fundamental nature of human cognitive processes underlies the difficulties met by HF/E practitioners.

USING AN INTERFACE : CONTEXTUAL AND COGNITIVE PROCESSES UNDERLYING CLASSIC HF/E

This chapter distinguishes between cognitive functions or goals, **what** is to be done, and cognitive processes, **how** these are done. This section starts with simple cognitive functions and processes underlying the use of displays and controls, on the interface between a person and the device they are using. More complex functions of understanding and planning will be discussed in the next main section.

I take the view that simple operations are affected by the context within which they are done. Someone does not just press a button in isolation : for example, a pilot keys in a radio frequency as part of contacting air-traffic control, as part of navigation, which is multi-tasked with checking for aircraft safety, etc. From this point of view, an account of cognitive processes should start with complex tasks. However that is just too difficult. Here, I have started with the simple tasks involved in using an interface, and point out how even simple processes are affected by a wider context. The next main section builds up from this to discuss more complex tasks.

Five main cognitive functions are involved in using an interface :

* discriminating a stimulus from a background, or from other possible stimuli. The process usually used for this is decision making.
* perceiving 'wholes'. The main process here is integrating together parts of the sensory input.
* naming,
* choosing an action. The cognitive process by which these two functions are done (in simple tasks) is recoding, i.e. translating from one representation to another, such as (shape : name), or (display : related control).
* comparison, which may be done by a range of processes from simple to complex.

Because discriminating and integrating stimuli are usually done as the basis for naming or for choosing an action, it is often assumed that the processes for carrying out these functions are independent, input driven, and done in sequence. However, the discussion will show that these processes are not necessarily distinct, or done in sequence, and that they all involve use of context and knowledge.

This section will not discuss displays and controls separately, as both involve all the functions and processing types. Getting information may involve making a movement such as visual search or accessing a computer display format, while making a movement involves getting information about it. The four sub-sections here are on :

detecting and discriminating;
visual integration;
naming, and simple action choices;
action execution.

A. Detecting and Discriminating

It might be thought, because the sense organs are separate from the brain, that at least basic sensory effectiveness, the initial reception of signals by the sense organs, would be a simple starting point, before considering the complexities that the brain can introduce such as naming a stimulus or choosing an action. However sensing processes turn out not to be simple : there can be a large contribution of prior knowledge and present context.

This part of the chapter is in four sub-sections, on : detecting; discriminating one signal from others that are present, or not present (absolute judgement); and sensory decisions. It is artificial to distinguish between sensory detection and discrimination, although they are discussed separately here, because they both involve (unconscious) decision making about what a stimulus is. In many real tasks, other factors have more effect on performance than any basic limits to sensory abilities. Nevertheless, it is useful to understand these sensory and perceptual processes, because they raise points which are general to all cognitive processing.

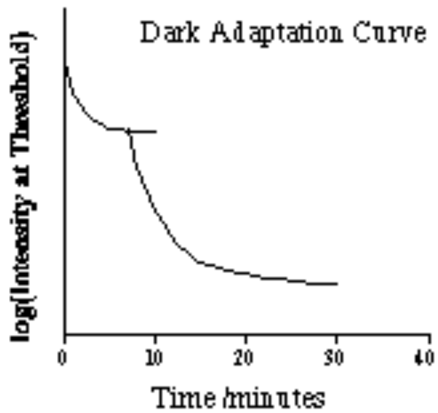

Figure 1 : The change in sensitivity of the eyes develops over a period of time in darkness. [After more time in darkness, people are able to detect dimmer lights.] There are two curves, corresponding to adaptation in colour vision [early] and in black-and-white vision at low light intensities [later].

1. **Detecting**
   'Detection' is one of those words which may be used to refer to different things. In this section I use it to mean sensing the presence of a stimulus against a blank background. Detecting the presence of light is an example. A human eye has the ultimate sensitivity to detect one photon of electromagnetic energy in the visible wavelengths. However, we can only detect at this level of sensitivity if we have been in complete darkness for about half an hour (Figure 1). The eyes adapt so they are sensitive to a range of light intensities around the average (Figure 2), this adaptation takes time. Adaptation allows the eyes to deal efficiently with a wide range of stimulus conditions, but it means that sensing is relative [to the context] rather than absolute.

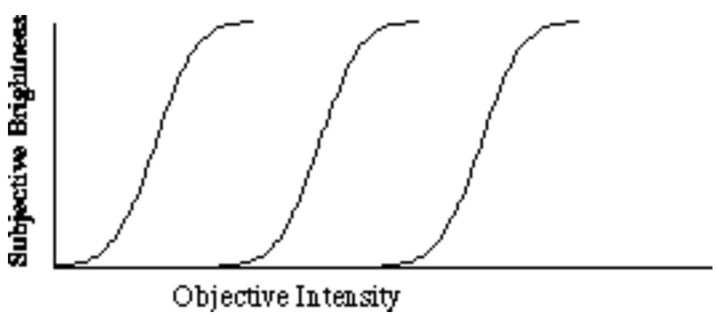

Figure 2 : The relation between objective light level, and subjective experienced light level, at three different levels of background illumination. At any particular level of adaptation, the eye is good at discrimination over a narrow range of intensities around that level. So a light which appears bright at one level of illumination may not be seen at another, and vice versa.

The two curves on the dark adaptation graph (Figure 1) indicate that the eyes have two different sensing systems, one primarily for use at high, and the other for use at low, light intensities. These two systems have different properties. At higher levels of illumination the sensing cells are sensitive to colour. There is one small area of the retina (the sensory surface inside the eye) which is best able to discriminate between spatial positions, and best able to detect stationary objects. The rest of the sensory surface (the periphery) is better at detecting moving than stationary objects. At lower levels of illumination intensity, the eyes see mainly in black and white, and peripheral vision is more sensitive for detecting position.

Therefore it is not possible to make a simple statement that 'the sensitivity of the eyes is...'. The sensitivity of the eyes depends on the environment (e.g. the average level of illumination) and on the stimulus (e.g. its movement, relative position, or colour). The sensitivity of sense organs adapts to the environment and the task, so sensitivity does not have an absolute value independent of these influences. This means it is difficult to make numerical predictions about sensory performance in particular circumstances, without testing directly.

However, it is possible to draw practical implications from the general trends in sensitivity. For example, it is important to design to support both dark and light visual sensing systems in tasks which may be done in both high and low levels of illumination, such as flying. It is also sensible to design so that the most easily detected stimuli (the most 'salient') are used for the most important signals. Visual salience depends not only on intensity but also on the colour, movement, and position of the stimulus. Very salient stimuli attract attention, they over-ride the usual mechanism for directing attention (see Section III). This means that very salient signals can either be useful as warning signals, or a nuisance as irrelevant distractions which interrupt the main task thinking.

2. Discriminating between stimuli

In this section I use the word 'discrimination' to mean distinguishing between two (or more) stimuli. As with detection, the limits to our ability to discriminate between stimulus intensities are relative rather than absolute.

The just noticeable difference between two stimuli is a ratio of the stimulus intensities. (There is a sophisticated modern debate about this, but it is not important for most practical applications). This ratio is called the Weber fraction. Again, the size of this ratio depends on the environmental and task context. For example, in visual intensity discriminations, the amount of contrast needed to distinguish between two stimuli depends on the size of the object (more contrast is needed to see smaller objects) and on the level of background illumination (more contrast is needed to see objects in lower levels of background illumination).

The Weber fraction describes the difference between stimuli which can just be discriminated. When stimuli differ by larger amounts, the time needed to make the discrimination is affected by the same factors : finer discriminations take longer, and visual discriminations can be made more quickly in higher levels of background illumination.

Issues of sensory discrimination do not only apply to visual stimuli.

Touch and feel (muscle and joint receptor) discriminations are made when using a control. For example, a person using a knob with tapered sides may make three times more positioning errors than when using a knob with parallel sides (Hunt & Warrick, 1957). Neither of the sides of a tapered knob actually points in the direction of the knob, so touch information from the sides is ambiguous.

Resistance in a control affects how easy it is to discriminate by feel between positions of the control. Performance in a tracking task, using controls with various types of resistance, shows that inertia makes performance worse, while elastic resistance can give the best results. This is because inertia is the same whatever the size of movement made, so it does not help in discriminating between movements. Elastic resistance, in contrast, varies with the size of movement, so gives additional information about the movements being made (Howland & Noble, 1955).

3. Absolute Judgement

The Weber fraction describes the limit to our abilities to discriminate between two stimuli when they are both present. When two stimuli are next to each other we can, at least visually, make very fine discriminations in the right circumstances. However, our ability to distinguish between stimuli when only one of them is present is much more limited. This process is called absolute judgement. The judgement limits to our sensory abilities are known in general, for many senses and dimensions (Miller, 1956). These limits can be affected by several aspects of the task situation, such as the range of possible stimuli which may occur (Helson, 1964).

When only one stimulus is present, distinguishing it from others must be done by comparing it with mental representations of the other possible stimuli. So absolute judgement must involve knowledge and/or working memory. This is an example of a sensory discrimination process which has some processing characteristics in common with what are usually considered much more complex cognitive functions. There is not always a clear distinction between 'simple' and 'complex' tasks in the aspects of processing involved.

Although our ability to make absolute judgements is limited it can be useful. For example, we can discriminate between 8 different positions within a linear interval. This means that visual clutter on scale-and-pointer displays can be reduced; it is only necessary to place a scale marker at every 5 units which need to be distinguished. But our ability is not good enough to distinguish between 10 scale units without the help of an explicit marker.

In other cases, the limitations need to be taken into account in design. For example, we can only distinguish between 11 different colour hues by absolute judgement. As we are very good at distinguishing between colours when they are next to each other, it can be easy to forget that colour discrimination is limited when one colour is seen alone. For example, a colour display might use green-blue to represent one meaning (e.g. main water supply) and purple-blue with another meaning (e.g. emergency water supply). It might be possible to discriminate between these colours, and so use them as a basis for identifying meaning, when the colours are seen together, but not when they are seen alone. (For some discussion of meaning, see Section C below.)

Again discrimination is a process in which the task context, in this case whether or not the stimuli occur together for comparison, has a strong effect on the cognitive processes involved and on our ability to make the discriminations.

4. Sensory decision making

Detections and discriminations involve decisions, about whether the evidence reaching the brain is sufficient to justify deciding that a stimulus (difference) is present. For example, detection on a raw radar screen involves deciding whether a particular radar trace is a 'blip' representing an aircraft, or something else which reflects radar waves. A particular trace may only be more or less likely to indicate an aircraft, so a decision has to be made in conditions of uncertainty. This sort of decision can be modelled by signal detection or statistical decision theory. Different techniques are now used in psychology, but this approach is convenient here because it distinguishes between the quality of the evidence and the observer's prior biases about decision outcomes.

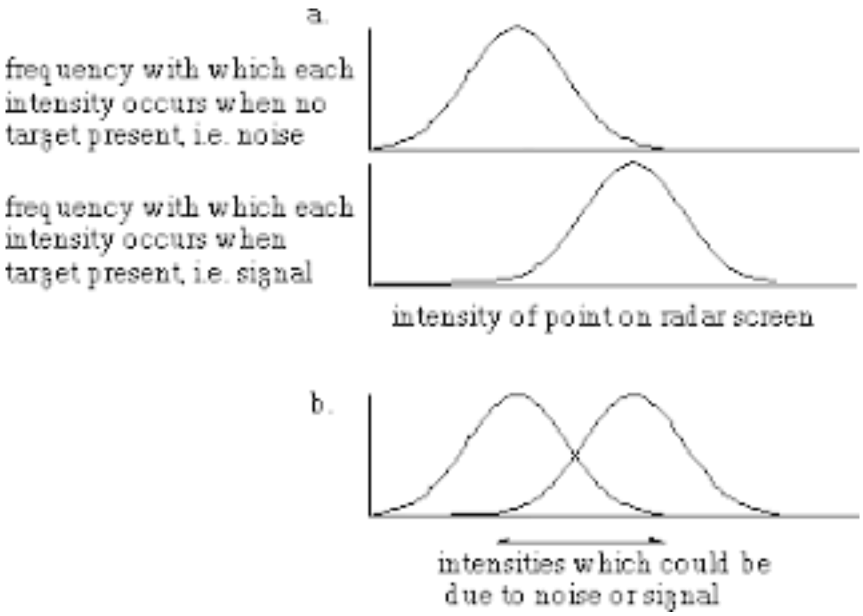

Figure 3 : Knowledge about the occurrence of screen intensities as evidence for different events, based on past experience.

Suppose that radar decisions are based on signal intensity, and that the frequencies with which different intensities have appeared on the radar screen when there was no aircraft present have been as shown in Figure 3.a.top, while the intensities which have appeared when an aircraft was present are shown in Figure 3.a.bottom. There is a range of intensities which occurred only when an aircraft was not present, a range of intensities which occurred only when an aircraft was present, and an intermediate range of intensities which occurred both when an aircraft was present and when it was not, Figure 3.b. How can someone make a decision when one of the intermediate intensities occurs ? The decision is made on the basis of signal likelihood. The height of the curve above a particular intensity indicates how likely that intensity was to occur when there was or was not an aircraft. At the mid point between the two frequency distributions, both possibilities are equally likely. Intensities less than this mid-point are more likely not to come from an aircraft, intensities greater than this mid-point are more likely to come from an aircraft.

Note that when a stimulus is in this intermediate range, it is not always possible to be right about a decision. A person can decide a trace is not an aircraft when it actually is (a 'miss'), or can decide it is an aircraft when it is not (a 'false alarm'). These ways of being wrong are not called 'errors', because it is not mathematically possible always to be right when making uncertain decisions. The number of wrong decisions, and the time to make the decision, increase when signals are more similar (overlap more).

Note that when the radar operator is making the decision, there is only one stimulus actually present, with one intensity. The two frequency distributions, against which this intensity is compared to make the decision, must be supplied from the operator's previous experience of radar signals, stored in their knowledge base. Decisions are made by comparing the input stimulus ('bottom up' [from the environment]) with stored knowledge about the possibilities ('top down' [from the person's knowledge of prior events]).

In addition to the uncertainty due to similarity between possible interpretations of a stimulus, the second major factor in this type of decision making is the importance or costs of the alternative outcomes. Above, the person's decision criterion, the intensity at which they change from deciding 'yes' to deciding 'no', was the point at which both possibilities are equally likely. But suppose it is very important not to miss a signal, for instance when radar watch keeping in an early warning system. Then it might be sensible to use the decision criterion in Figure 4. This would increase the number of hits. It would also increase the number of false alarms, but this might be considered a small price to pay compared with the price of missing a detection. Alternatively, imagine someone doing a job in which when they detect a signal they have to do a lot of work, but they are feeling lazy and not committed to their job. Then they might move their decision criterion in the other direction, to minimise the number of hits.

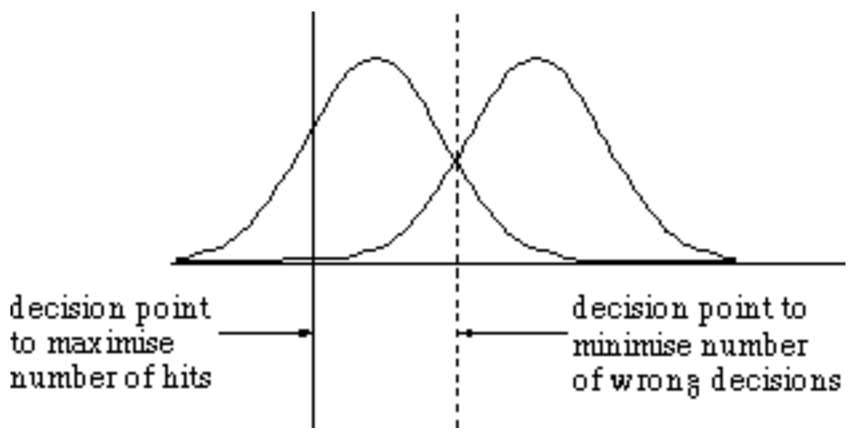

Figure 4 : An example of change in bias to account for different pay-offs. If rewarded for 'hits', the bias changes to increase hits, but 'false alarms' also increase.

This shift in decision criterion is called bias. Decision bias can be affected by probabilities and costs. The person's knowledge of the situation provides the task and personal expectations/ probabilities and costs which are used in setting the biases, so again top-down processing influences sensory decisions. There are limits to human ability to assess biases (Kahneman, Slovic & Tversky, 1992). At extreme probabilities we tend to substitute determinacy for probability. We may think something is sure to happen, when it is just highly likely. Some accidents happen because people see what they expect to see, rather than what is actually there (e.g. Davis, 1966). Inversely we may think something will never happen, when it is objectively of very low probability. For example, when signals are very unlikely, then it is difficult for a human being to continue to direct attention to watching for them (the 'vigilance' effect).

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B. Visual Integration

The effects of knowledge and context are even more evident in multi-dimensional aspects of visual perception, such as colour, shape, size, and movement, in which what is seen is an inference from combined evidence. This discussion is in sections on : movement, size, and colour; grouping processes; and shape. (There are also interesting auditory integrations, much involved in music perception, but these will not be discussed here.)

1. Movement, size and colour constancies

It is actually quite odd that we perceive a stable external world, given that we and other objects move, and the wavelength of the environmental light we see by changes, so the size, position, shape, and wavelength of light reflected from objects onto the retina all change. As we do perceive a stable world, this suggests our perception is relative rather than absolute : we do not see what is projected on the retina, but a construction based on this projection, made by combining evidence from different aspects of our sensory experience. The processes by which a wide variety of stimuli falling on the retina are perceived as the same are called 'constancies'.

When we turn our head the stimulation on the retina also moves. However, we do not see the world as moving, because information from the turning receptors in the ear is used to counteract the evidence of movement from the retina. The changes on the retina are perceived in the context of changes in the head rotation receptors. When the turning receptors are diseased, or the turning movements are too extreme for the receptors to be able to interpret quickly, then the person may perceive movement which is not actually occurring, as in some flying illusions.

There is also constancy in size perception. As someone walks away from us, we do not see them becoming smaller and smaller, although there are large changes in the size of the image of that person which falls on the retina. In interpreting the size of objects, we take into account all the objects which are at the same distance from the eye, and then perceive them according to their relative size. Size constancy is more difficult to account for than movement constancy, as it involves distance perception, itself a complex process (Gibson, 1950). Distance is perceived by combining evidence about texture, perspective, changes in colour of light with distance, and overlapping (itself a construct, see below). Information from the whole visual field is used in developing a percept which makes best overall sense of the combination of inputs. Cognitive psychology uses the concept that different aspects of stimulus processing are done simultaneously, unless an aspect is difficult and slows processing down. Each aspect of processing communicates its 'results so far' to the other aspects via a 'blackboard', and all aspects work together to produce a conclusion (Rumelhart, 1977).

Colour perception is also an integrative process which shows constancy. Research on the colour receptive cells in the retina suggests that there are only three types of cell, which respond to red, green and blue light wavelengths. The other colours we 'see' are constructed by the brain, based on combinations of stimulus intensities at these three receptors. The eyes are more sensitive to some colours, so if a person looks at two lights of the same physical intensity but different wavelengths, the lights may be of different experienced intensity (brightness). The effectiveness of the colour construction process is such that there are some visual demonstrations in which people see a range of colours, even though the display consists only of black and white plus one colour.
This constructive process also deals with colour constancy. The wavelength of ambient lighting can change quite considerably, so the light reflected from objects also changes in wavelength, but objects are perceived as having stable colour. The wavelengths of light from all the objects change in the same

way, and colour is perceived from the relative combinations of wavelengths, not the actual wavelengths. This constancy process is useful for perceiving a stable world despite transient and irrelevant changes in stimuli, but it does make designing colour displays more difficult. As with our response to stimulus intensity, our perception of colour is not a fixed quantity which can easily be defined and predicted. Instead it depends on the interaction of several factors in the environment and task contexts, so it may be necessary to make colour perception tests for a particular situation.

2. Grouping processes

Another type of perceptual integration occurs when several constituents of a display are grouped together and perceived as a 'whole'. The Gestalt psychologists in the 1920s first described these grouping processes, which can be at several levels of complexity.

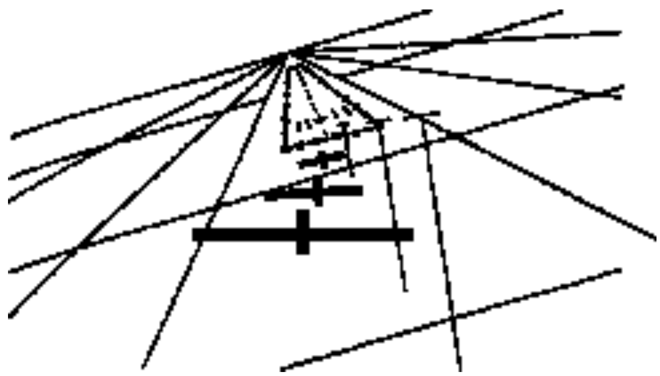

Figure 5 : An example of grouping processes in the interpretation of a display. A Head-Up predictor display for aircraft landing, proposed by Gallaher et al (1977). [Lines with the same qualities are grouped by a person viewing this. In use, lines which move together are grouped.]

1. Separate elements can be seen as linked into a line or lines. There are four ways in which this can happen : when the elements are close together, similar, lie on a line, or define a contour. The grouping processes of proximity and similarity can be used in the layout of displays and controls on a conventional interface, to show which items go together.
2. When separate elements move together they are seen as making a whole. This grouping process is more effective if the elements are also similar. This is used in the design of Head Up Displays and predictor displays, as in Figure 5.
3. Something which has uniform colour or a connected contour is seen as a 'whole', e.g. the four sides of a square are seen as a single square, not as four separate elements.
4. The strongest grouping process occurs when the connected contour has a 'good' form, that is, a simple shape. For example, a pull-down menu on a computer screen is seen as a distinct unit in front of other material, because it is a simple shape, and the elements within the shape are similar and (usually) different from the elements on the rest of the screen. When the visual projections of two objects are touching, then the one with the simplest shape is usually seen as in front of (overlapping) the other.

The visual processes by which shapes and unities are formed suggest recommendations for the design of symbols and icons which are easy to see (Easterby, 1970).

3. Shape constancy

Visual integrative processes ensure that we see a unity when there is an area of the same colour, or a continuous contour. The shape we see depends on the angles of the contour lines (there are retinal cells which sense angle of line). Again there are constancy processes. The shape perceived is a construction, taking into account various aspects of the context, rather than a simple mapping of what is projected from the object onto the retina. Figure 6 shows a perspective drawing of a cube, with the same ellipse placed on each side. The ellipse on the front appears as an ellipse on a vertical surface. The ellipse on the top appears to be wider and sloping at the same angle as the top. The ellipse on the side is ambiguous - is it rotated, or not part of the cube at all ? The ellipse on the top illustrates shape 'constancy'. It is perceived according to knowledge about how shapes look narrower when they are parallel to the line of sight, so a flat narrow shape is inferred to be wider. Again, the constancy process shows that knowledge about the properties of the surrounding context (in this case the upper quadrilateral) affects how particular stimuli are seen.

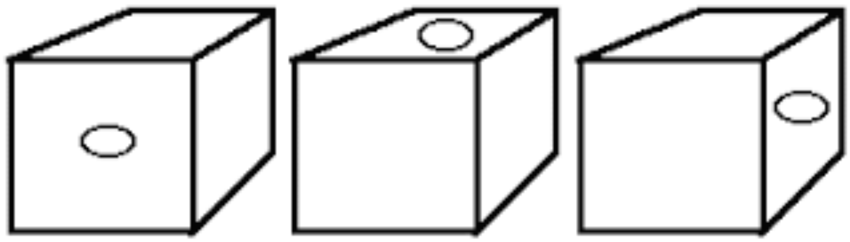

Figure 6 : Shape and size 'constancy' : the same cube with the same ellipse in three different positions. The three ellipses are computer generated duplicates.

The Gestalt psychologists provided dramatic examples of the effects of these inference processes, in their reversible figures as in Figure 7. The overall interpretation which is given to this drawing affects how particular elements of it are grouped together and named, for example whether they are seen as parts of the body or pieces of clothing. It is not possible to see both interpretations at the same time, but it is possible to change quickly from one to the other. As the interpretation given to an object affects how parts of it are perceived, this can cause difficulty with the interpretation of low quality visual displays, for example from infrared cameras or on-board radar.

Figure 7 : The 'wife/mother-in-law' reversible figure

C. Naming, and simple action choices

The next functions to consider are identifying name, status, or size, and choosing the nature and size of actions. These cognitive functions may be met by a process of recoding (association) from one form of representation to another, such as :

shape : converted to . . . . name
colour . . . . level of danger
spatial position of display . . . . name of variable
name of variable . . . . spatial position of its control
length of line . . . . size of variable
display . . . . related control
size of distance from target . . . size of action needed

Identifications and action choices which involve more complex processing than this recoding will be discussed in the section on complex tasks. This section will discuss : interdependence of the processes and functions; identifying name and status : shape, colour, and location codes; size : size codes; and recoding/ reaction times. Computer displays have led to the increased use of alpha-numeric codes, which are not discussed here (see Bailey, 1989).

1. Interdependence of the functions

Perceiving a stimulus, naming it, and choosing an action are not necessarily independent. Figure 7 above shows that identification is interrelated with perception. This section gives three examples which illustrate other HF/E issues.

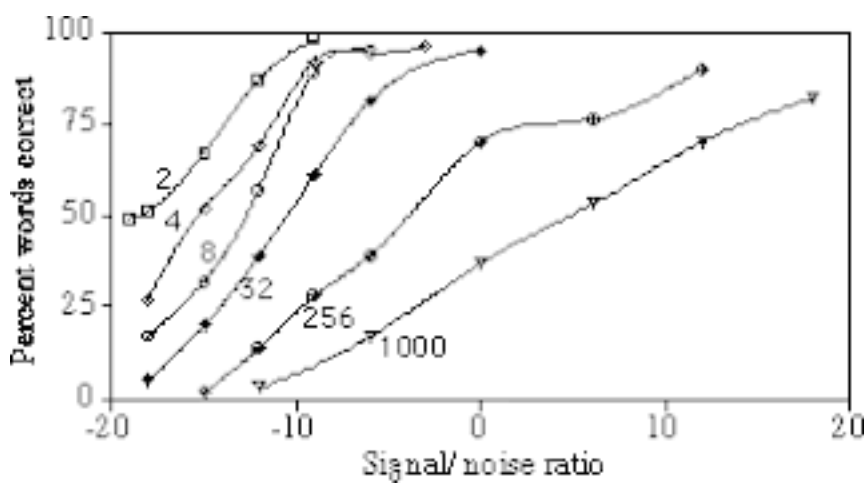

Figure 8 : Percent words heard correctly in different levels of noise, from vocabularies of various sizes, e.g. the top line presents the results from tests in which only two different words might occur (Miller, Heise and Lichten, 1951).

Naming difficulties can be based on discrimination difficulties. Figure 8 shows the signal/noise ratio needed to hear a word against background noise. The person listening has not only to detect a word against the noise background, but also to discriminate it from other possible words. The more alternatives there are to distinguish, the better the signal/noise ratio needs to be. This is the reason for using a minimum number of standard messages in speech communication systems, and for designing these messages to maximise the differences between them, as in the International Phonetic alphabet, and standard air-traffic control language (Bailey, 1989).

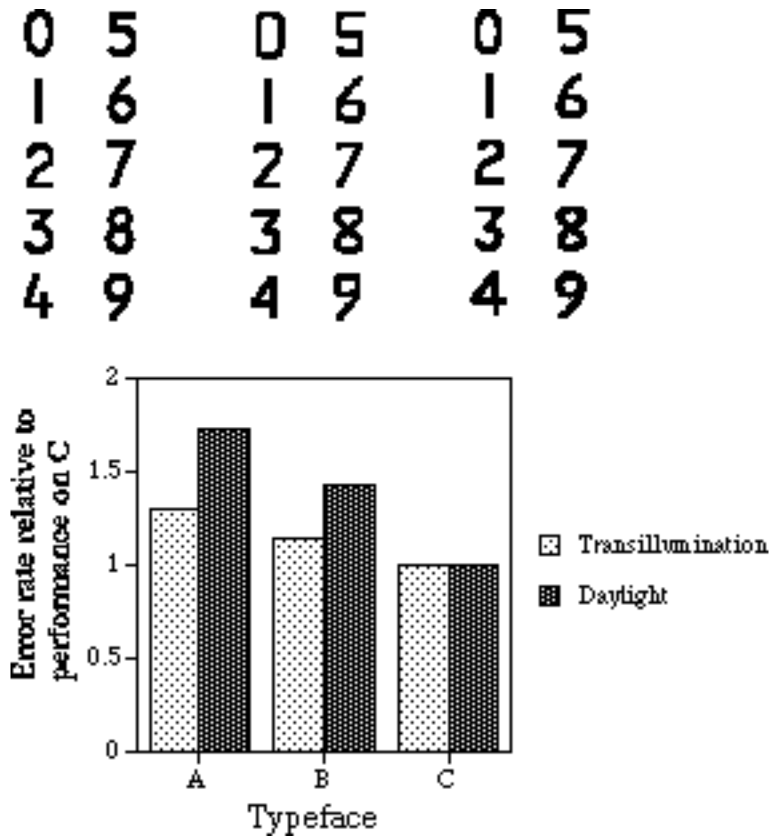

Figure 9 : Relative reading accuracy with three different digit designs (Atkinson et al , 1952). The differences between the digits are not very clear in this low quality figure.

An important aspect of maximising differences between signals can be illustrated by a visual example. Figure 9 shows some data on reading errors with different digit designs. Errors can be up to twice as high with design A than with design C. At a quick glance, these digit designs do not look very different, but each digit in C has been designed to maximise its difference from the others. Digit reading is a naming task based on a discrimination task, and the discriminations are based on differences between the straight and curved elements of the digits. It is not possible to design an '8' which can be read easily, without considering the need to discriminate it from 3, 5, 6 and 9, which have elements in common. As a general principle, design for discrimination depends on knowing the ensemble of alternatives to be discriminated, and maximising the differences between them.

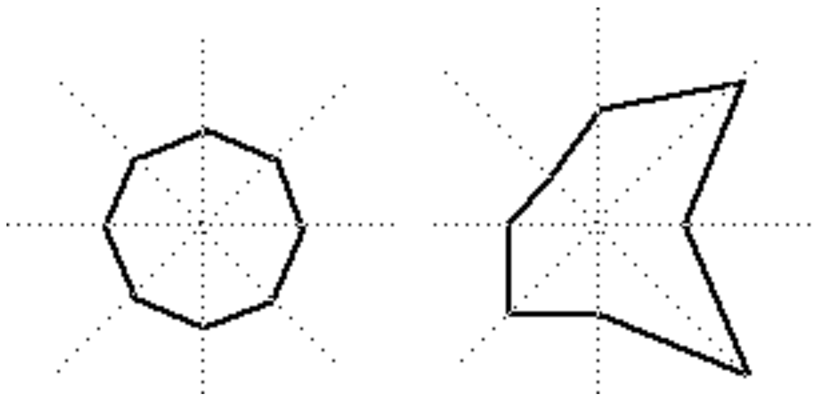

Figure 10 : 'Iconic' display : Eight variables are displayed, measured outwards from the centre. When all eight variables are on target, the display has an octagon shape. It is easy to detect that there is a distortion in the shape, much more difficult to remember what problem is indicated by any given distorted shape.

However ease of detection/ discrimination does not necessarily make naming easy. Figure 10 shows an 'iconic' display. Each axis displays a different variable, and when all 8 variables are on target, the shape is symmetrical. It is easy to detect a distortion in the shape, to detect that a variable is off target. However studies show that people have difficulty with discriminating one distorted pattern from another by memory, and with identifying which pattern is associated with which problem. This display supports detection, but not discrimination or naming. It is important in task analysis to note which of the cognitive functions are needed, and that the display design supports them.

2. Shape, colour, and location codes for name and status

Conventional interfaces all too often consist of a sea of displays or controls which are identical both to sight and touch. The only way of discriminating between and identifying them is to read the label [often dirty] or learn the position. Even if labels have well designed typeface, abbreviations, and position, they are not ideal. What is needed is an easily seen 'code' for the name or status, which is easy to recode into its meaning. The codes used most frequently are shape, colour, and location. (Felt texture can be an important code in the design of controls.) The codes need to be designed for ease of discrimination, and for ease of making the translation from code to meaning.

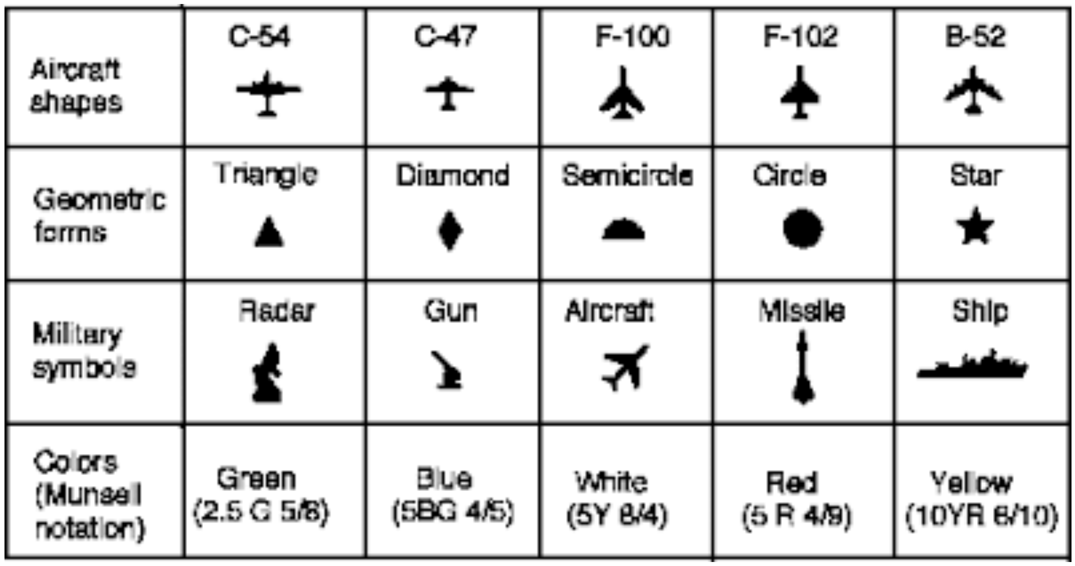

Figure 11 : Shapes used in discrimination tests (Smith and Thomas, 1964).

Shape codes
Good shape codes are 'good' figures in the Gestalt sense, and also have features which make the alternatives easy to discriminate. However, ease of discrimination is not the primary criterion in good shape code design. Figure 11 shows the materials used in discrimination tests between sets of colours, military look-alike shapes, geometric forms, and aircraft look-alike shapes [like the a/c, not like each other] . Colour discrimination is easiest, military symbols are easier to distinguish than aircraft symbols because they have more different features, and geometric forms are discriminated more easily than aircraft shapes. (Geometric forms are not necessarily easier to discriminate. For example the results would be different if the shapes included an octagon as well as a circle.)
The results from naming tests rather than discrimination tests would be different, if geometric shapes or colours had to be given a military or aircraft name. Naming tests favour look-alike shapes, as look-alike shapes can be more obvious in meaning.

Nevertheless, using a look-alike shape (symbol or icon) does not guarantee obviousness of meaning. That people make the correct link from shape to meaning needs to be tested carefully. People can be asked, for each possible shape : what they think it is a picture of; what further meaning, such as an action, they think it represents; and, given a list of possible meanings, which of these meanings they choose as the meaning of the shape.
To minimise confusions when using shape codes, it is important not to include in the coding vocabulary any shape which is assigned several meanings, or several shapes which could all be assigned the same meaning. Otherwise there could be high error rates in learning and using the shape codes. It is also important to test these meanings on the appropriate users, naive or expert people, or an international population. For example, in Britain a favoured symbol for 'delete' would be a picture of a space villain from a children's TV series, but this is not understood by people from other European countries !

As well as the potential obviousness of their meaning, look-alike shapes have other advantages over geometric shapes. They can act as a cue to a whole range of remembered knowledge about this type of object (see below on knowledge). Look-alike shapes can also vary widely, while the number of alternative geometric shapes which are easy to discriminate is small. An interface designer using geometric shape as a code runs out of different shapes quite quickly, and may have to use the same shape with several meanings. The result of this is that a person interpreting these shapes has to notice when the context has changed to one in which a different shape-meaning translation is used, and then to remember this different translation, before they can work out what a given shape means [see example below on the meaning of colour]. This multi-stage process can be error-prone, particularly under stress. Some computer based displays have the same shape used with different meanings in different areas of the same display. A person using such a display has to remember to change the coding translation they use, every time they make an eye movement.

Colour codes
Using colour as a code poses the same problems as using geometric shape. Except for certain culture based meanings, such as red = danger, the meanings of colours have to be learned specifically, rather than being obvious. And only a limited number of colours can be discriminated by absolute judgement. The result is that a designer, who thinks colour is easy to see, rapidly runs out of different colours, and has to use the same colour with several meanings. There are computer based displays on which colour is used simultaneously with many different types of meaning, such as :

colour . . means . . substance (steam, oil, etc.)
colour . . . . status of item (e.g. on, off)
colour . . . . function of item
colour . . . . sub-system item belongs to
colour . . . . level of danger
colour . . . . attend to this item
colour . . . . click here for more information
colour . . . . click here to make an action

A user has to remember which of these coding translations is relevant to a particular point on the screen, with a high probability of confusion errors.

Location codes
The location of an item can be used as a basis both for identifying an item, and for indicating its links with other items.

People can learn where a given item is located on an interface, and then look or reach to it automatically, without searching. This increases the efficiency of behaviour. [See also 'acquisition' movements, below.] But this learning is effective only if the location : identity mapping remains constant, otherwise there can be a high error rate. For example Fitts and Jones (1947a), in their study of pilot errors, found that 50% of errors in operating aircraft controls were choosing the wrong control. The layout of controls on three of the aircraft used at that time shows why it was easy to be confused :

Aircraft	*Position of Control*		
	left	*centre*	*right*
B-25	throttle	prop	mixture
C-47	prop	throttle	mixture
C-82	mixture	throttle	prop

Suppose a pilot had flown a B-25 sufficiently frequently to be able to reach to the correct control without thinking or looking. If he then transferred to a C-47, two thirds of his automatic reaches would be wrong, if to a C-82 all of them. As with other types of coding, location-to-identity translations need to be consistent and unambiguous. Locations will be easier to learn if related items are grouped together, such as items from the same part of the device, with the same function, or the same urgency of meaning.

Locations can sometimes have a realistic meaning, rather than an arbitrary learned one. Items on one side in the real world should be on the same side when represented on an interface. (Ambiguity about the location of left/ right displays could have contributed to the Kegworth air crash, Green, 1990). Another approach is to put items in meaningful relative positions. For example, in a mimic/ schematic diagram or an electrical wiring diagram, the links between items represent actual flows from one part of the device to another. On a cause-effect diagram, links between the nodes of the diagram represent causal links in the device. On such diagrams relative position is meaningful, and inferences can be drawn from the links portrayed (see below on knowledge).

Relative location can also be used to indicate which control goes with which display. When there is a one-to-one relation between displays and controls, then choice of control is a recoding which can be made more or less obvious, consistent, and unambiguous by the use of spatial layout. Gestalt proximity processes link items together if they are next to each other. But the link to make can be ambiguous, such as in the layout : o o o o x x x x. Which x goes with which o ? People bring expectations about code meanings to their use of an interface. If these expectations are consistent among a particular group of people, the expectations are called 'population stereotypes'. If an interface uses codings which are not compatible with a person's expectations, then the person is likely to make errors.

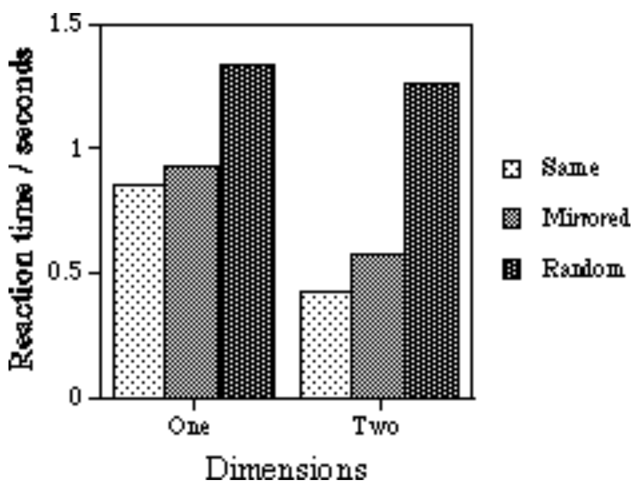

Figure 12 : Effect of relative spatial layout (same, reversed, random) of signal lights and response buttons on response time (Fitts and Deininger, 1954).

If two layouts to be linked together are not the same, then studies show that reversed but regular links are easier to deal with than random links (Figure 12). This suggests recoding may be done, not by learning individual pairings, but by having a general rule from which the person can work out the linkage.

In multiplexed computer based display systems, in which several alternative display formats may appear on the same screen, there are at least two problems with location coding. One is that each format may have a different layout of items. We do not know whether people can learn locations on more than one screen format sufficiently well to be able to find items on each format by automatic eye movements rather than by visual search. If people have to search a format for the item they need, studies suggest this could take at least 25 seconds. This means that every time the display format is changed, performance will be slowed down while this search process interrupts the thinking about the main task (see also below on short-term memory). It may not be possible to put items in the same absolute position on each display format, but one way of reducing the problems caused by inconsistent locations is to locate items in the same relative positions on different formats.

The second location problem in multiplexed display systems is that people need to know the search 'space' of alternative formats available, where they currently are in it, and how to get to other formats. It takes ingenuity to design so that the user of a computer based interface can use the same sort of 'automatic' search skills for obtaining information that are possible with a conventional interface.

In fact there can be problems with maximising the consistency and reducing the ambiguity of all types of coding used on multiple display formats (Bainbridge, 1991). Several of the coding vocabularies and coding translations used may change between and within each format (beware the codes used in Figures in this chapter). The cues a person uses to recognise which coding translations are relevant need to be learned, and are also often not consistent. A display format may have been designed so the codes are obvious in meaning for a particular sub-task, when the display format and the sub-task are tested in isolation. But when this display is used in the real task, before and after other formats used for other sub-tasks, each of which uses different coding translations, then a task-specific display may not reduce either the cognitive processing required or the error rates.

3. Size : size codes

Usually, on an analogue interface, length of line is used to represent the size of a variable. The following arguments apply both to display scales and to the way control settings are shown. There are three aspects : the ratio of the size on the interface to the size of the actual variable; the way comparisons between sizes are made; and the meaning of the direction of a change in size.

Interface size : actual size ratio

An example of the interface size to actual size ratio is that, when using an analogue control (such as a throttle), a given size of action has a given size of effect. Once people have learned this ratio, they can make actions without having to check their effect, which gives increased efficiency (see below).
The size ratio and direction of movement are again codes used with meanings which need to be consistent. Size ratios can cause display reading confusions if many displays are used, which all look the same but differ in the scaling ratio used. Similarly, if many controls which are similar in appearance and feel are used with different control ratios, then it may be difficult to learn automatic skills in using them to make actions of the correct size. This confusion could be increased by using one multi-purpose control, such as a mouse or tracker ball, for several different actions each with a different ratio.

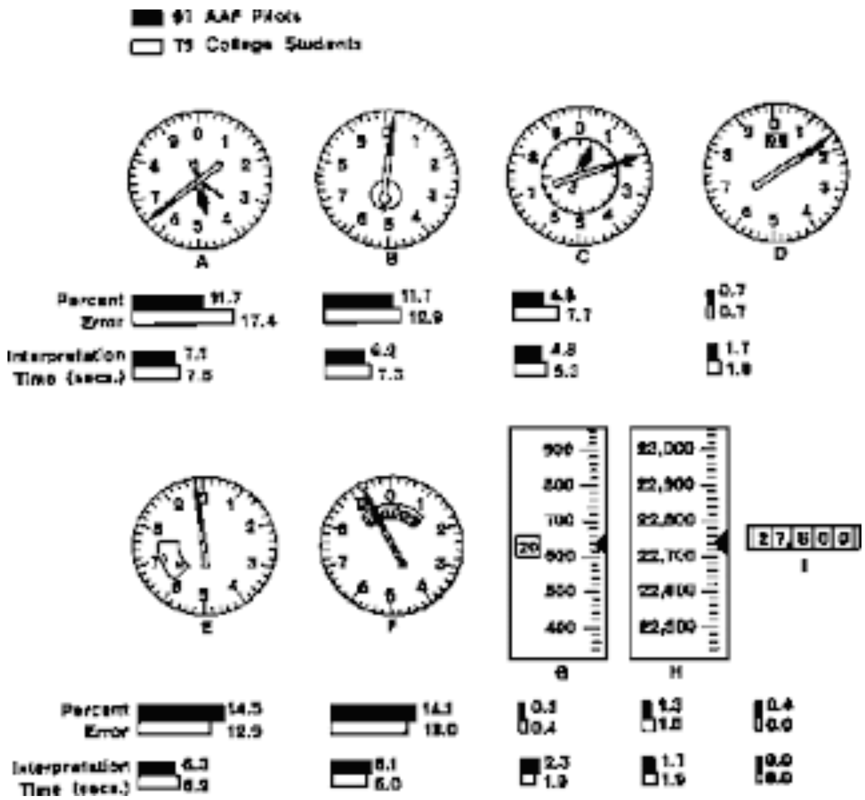

Figure 13 : Speed and accuracy of reading different altimeter designs (Grether, 1949). The reading times and error rates are shown by horizontal bars.

A comparison of alternative altimeter designs is an example which also raises some general HF/E points. The designs were tested for reading speed and accuracy (Figure 13). The digital display gives the best performance, and the 3-pointer design (A) is one of the worst. The 3 pointer altimeter poses several coding problems for someone reading it. The three pointers are not clearly discriminable. Each pointer is read against the same scale using a different scale ratio, and the size of pointer and size of scale ratio are inversely related (the smallest pointer indicates the largest scale, 10,000s, the largest pointer 100s).

Despite these results, a digital display is not now used.
A static reading test (from which the above results were obtained) is not a good reflection of the real flying task. In the real task, altitude changes rapidly so a digital display would be unreadable. And the user also needs to identify rate of change, for which angle of line is an effective display. Unambiguous combination altimeter displays are now used, with a pointer for rapidly changing small numbers, and a digital display for slowly changing large numbers (D).
Before this change, many hundreds of deaths were attributed to misreadings of the three-pointer altimeter, yet the display design was not changed until these comparative tests were repeated two decades later.
This delay occurred for two reasons, which illustrate that HF/E decisions are made in several wider contexts. First the technology : in the 1940s, digital instrument design was very much more unreliable than the unreliability of the pilot's instrument readings. Secondly, cultural factors influence the attribution of responsibility for error. There is a recurring swing in attitudes, between saying that a user can read the instrument correctly so the user is responsible for incorrect readings, to saying that if a

designer gives users an instrument which it is humanly impossible to read correctly reliably, then the responsibility for misreading errors lies with the designer.

Making comparisons between sizes

There are two important comparisons in control tasks : is the variable value acceptable/ within tolerance (a check reading) ? and if not, how big is the error ? These comparisons can both usually be done more easily on an analogue display. Check readings can be made automatically (i.e. without processing that uses cognitive capacity) if the pointer on a scale is in an easily recognisable position when the value is correct. And linking the size of error to the size of action needed to correct it can be done easily if both are coded by length of line.

An example shows why it is useful to distinguish cognitive functions from the cognitive processes used to meet them. Comparison is a cognitive function which may be done either by simple recoding or by a great deal of cognitive processing, depending on the display design. Consider the horizontal bars in Figure 13 above as a display from which an HF/E designer must get information about the relative effectiveness of the altimeter designs. The cognitive processes needed involve searching for the shortest performance bar by comparing each of the performance bar lines, probably using iconic (visual) memory, and storing the result in working memory, then repeating to find the next smallest, and so on. Visual and working memory are used as temporary working spaces while making the comparisons : working memory is also used to maintain the list of decision results.

This figure is not the most effective way of conveying a message about alternative designs, because most people do not bother to do all this mental work. The same results are presented in Figure 14. For a person who is familiar with graphs, the comparisons are inherent in this representation.

A person looking at this does not have to do cognitive processing which uses processing capacity and is unrelated to and interrupts the main task of thinking about choice of displays. (See below for more on memory interruption, and on processing capacity.) It is very obvious that the 3-pointer altimeter is a poor display, and the digital and simple combined displays are the best
This point applies in general to analogue and digital displays. For many comparison tasks, digital displays require more use of cognitive processing and working memory.

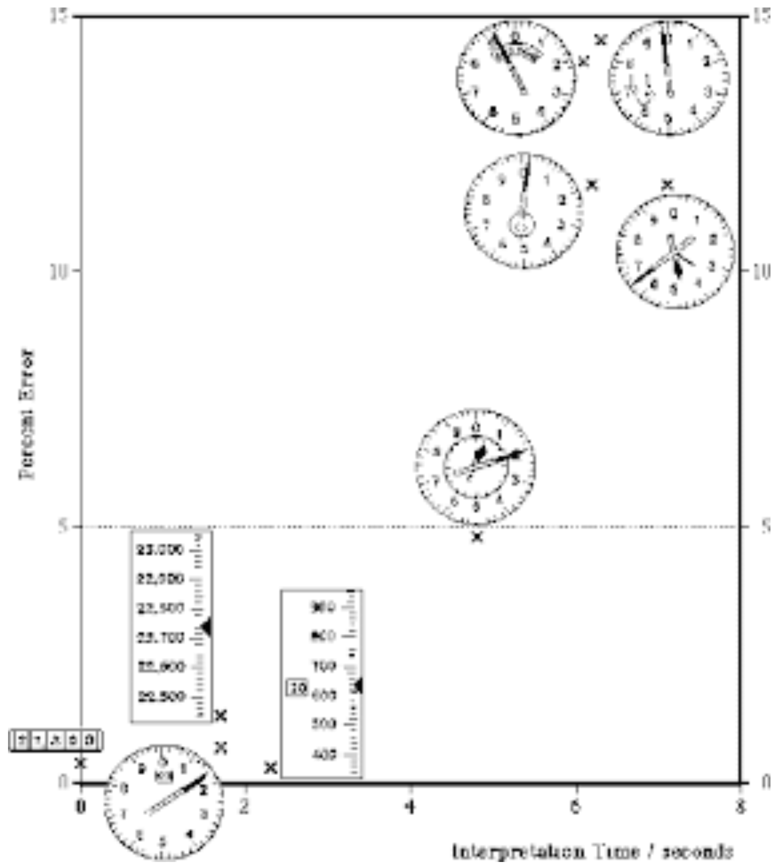

Figure 14 : The results from Figure 13, presented on a co-ordinate graph.
Horizontal axis : reading time. Vertical axis : % reading error.

Direction of movement to meaning

The second aspect to be learned about interface sizes is the meaning of the direction of a change in size. Cultural learning is involved here, and can be quite context specific. For example, people in technological cultures know that clockwise movement on a display indicates increase, but on a tap or valve control means closure, therefore decrease. Again there can be population stereotypes in the expectations people bring to a situation, and if linkages are not compatible with these assumptions, error rates may be at least doubled.

Directions of movements are often paired. For example, making a control action to correct a displayed error involves two directions of movement, on the display and on the control. It can be straightforward to make the two movements compatible in direction if both are linear, or both are circular.

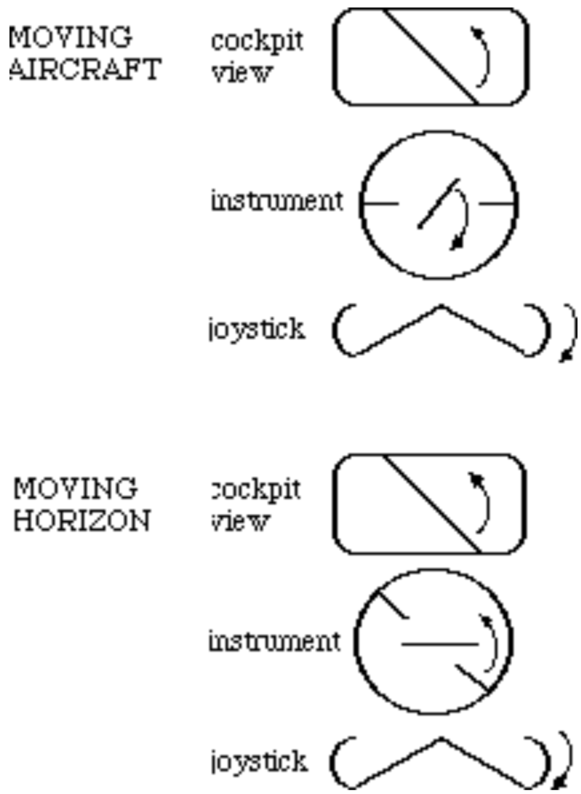

Figure 15 : Two possible designs for the aircraft attitude indicator, showing incompatible movements.

It is in combining three or more movements that it is easy to get into difficulties with compatibility. One classic example is the aircraft attitude indicator. In Fitts and;Jones' (1947b) study of pilots' instrument reading errors, 22% of errors were either reversed spatial interpretations, or attitude illusions. In the design of the attitude indicator, four movements are involved : of the external world, of the display, of the control, and of the pilot's turning receptors, see Figure 15. The attitude instrument can show a moving aircraft, in which case the display movement is the same as the joystick control movement but opposite to the movement of the external world. Or the instrument can show a moving horizon, which is compatible with the view of the external world but not with the movement of the joystick. There is no solution in which all three movements are the same, so some performance errors or delays are inevitable. Similar problems arise in the design of moving scales and of remote control manipulation devices.

4. Reaction times

Evidence about recoding difficulties comes from both *error rates* and the *time taken* to translate from one code representation to another. Teichner and Krebs (1974) reviewed the results of reaction time studies. Figure 16 shows the effect of the number of alternative items and the nature of the recoding. The effect of spatial layout was illustrated in Figure 12. Teichner and Krebs also reviewed evidence that, although unpractised reaction times are affected by the number of alternatives to choose between, after large amounts of practice this effect disappears, all choices are made equally quickly. This suggests that response choice has become automatic, it no longer requires processing capacity.

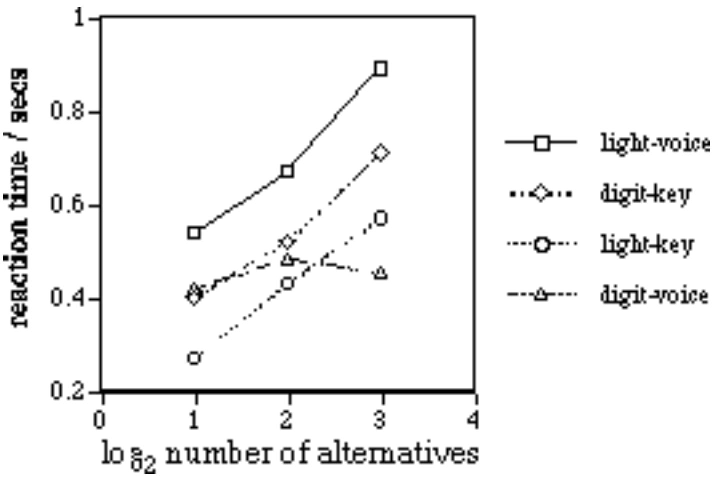

Figure 16 : Response times are affected by the number of alternatives to be responded to, the nature of the 'code' linking the signal and response, and the amount of practice [over-learned digit-voice translation is not affected by number of alternatives]. (Teichner and Krebs, 1974).

The results show the effect of different code translations : using spatial locations of signals and responses (light, key) or symbolic ones (visually presented digit, spoken digit i.e. voice). The time taken to make a digit to voice translation is constant, but this is already a highly practised response for the people tested. Otherwise, making a spatial link (light to key) is quickest. Making a link which involves a change of code type, between spatial and symbolic, (digit to key, or light to voice) takes longer. (So these data show it can be quicker to locate than to name.) This coding time difference may arise because spatial and symbolic processes are handled by different areas of the brain, and it takes time to transmit information from one part of the brain to another. The brain does a large number of different types of coding translation (e.g. Barnard, 1987).

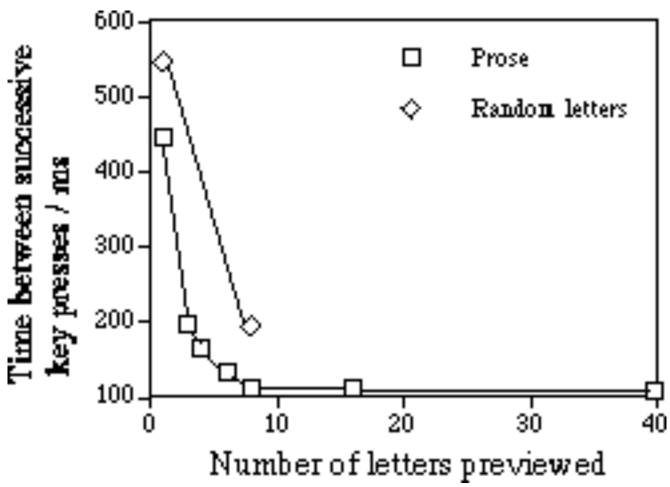

Figure 17 : Effect of preview and type of material on response time. These data come from a study of expert typists, given more or less preview, and typing either random letters or prose (Shaffer, 1973). (Another Figure, see 18 and 21, where location codes are reversed on the graph and the code index. Graphing software may do this.)

The findings presented so far come from studies of reacting to signals which are independent and occur one at a time. Giving advance information about the responses which will be required, which allows people to anticipate and prepare their responses, reduces response times. There are two ways of doing this, illustrated in Figure 17. One is to give preview, allowing people to see in advance the responses needed. This can more than halve reaction time. The second method is to have sequential relations in the material to be responded to. Figure 16 showed that reaction time is affected by the number of alternatives : the general effect underlying this is that reaction time depends on the probabilities of the alternatives. Sequential effects change the probabilities of items. One way of introducing sequential relations is to have meaningful sequences in the items, such as prose rather than random letters.

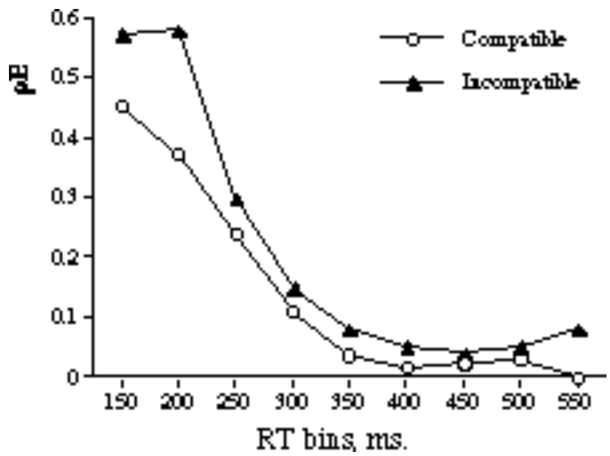

Figure 18 : The speed-accuracy tradeoff : error rates at different response times (unpublished results, see also Rabbitt and Vyas, 1970). [Another figure (see Fig.21) which confuses 2 spatial layouts - filled triangles are above on the graph, below in the code listing.]

Reaction time and error rate are interrelated. Figure 18 shows that when someone reacts very quickly, they choose a response at random. As they take a longer time, and can take in more information before initiating a response, there is a tradeoff between time and error rate. At longer reaction times there is a basic error rate which depends on the equipment used.

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D. Action execution

This chapter does not focus on physical activity, but this section will make some points about cognitive aspects of action execution. The section will be in two parts, on acquisition movements, and on continuous control or tracking movements.

The speed, accuracy and power a person can exert in a movement depend on its direction relative to the body position. Human biomechanics and its effects on physical performance, and the implications for workplace design, are large topics which will not be reviewed here (Pheasant, 1991). Only one point will be made. Workplace design affects the amount of physical effort needed to make an action, and the amount of postural stress a person is under. These both affect whether a person is willing to make a particular action, or to do a particular job. So workplace design can affect performance in cognitive tasks. Factors which affect what a person is or is not willing to do are discussed more in the section on workload.

1. Acquisition movements

When someone reaches to something, or puts something in place, this is an 'acquisition' movement : reaching a particular end point or target is more important than the process of getting there. The relation between the speed and accuracy of these movements can be described by Fitts Law (1954), in which movement time depends on the ratio of movement length to target width. However, detailed studies show that movements with the same length-width ratio are not all carried out in the same way.

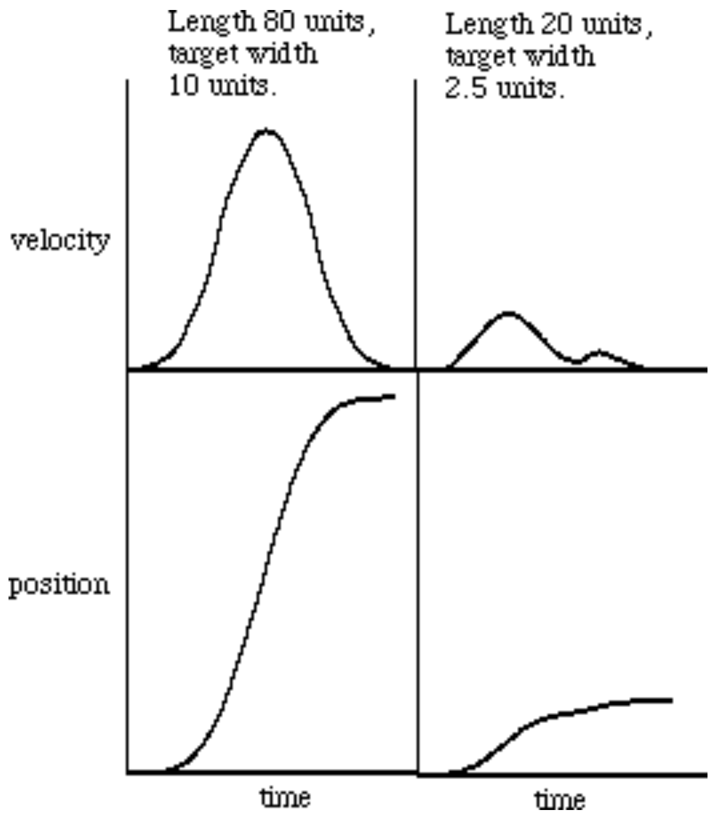

Figure 19 : Detailed evidence about the execution of two movements, both with the same movement length to target size ratio (8 : 1) and the same overall movement time (Crossman and Goodeve, 1963).

Figure 19 shows that an 80/ 10 movement is made with a single pulse of velocity. A 20 /2.5 movement has a second velocity pulse, suggesting the person has sent a second instruction to their hand about how to move. Someone making a movement gives an initial instruction to their muscles about the direction, force and duration needed, then monitors how the movement is being carried out, by vision and/ or feel. If necessary they send a corrected instruction to their muscles, to improve the performance, and so on. This monitoring and revision is called using feedback. A finer movement involves feedback to and a new instruction from the brain. A less accurate movement can be made with one instruction to the hand, without needing to revise it. An unrevised movement ('open-loop' or 'ballistic') probably involves feedback within the muscles and spinal cord, but not visual feedback to and a new instruction from the brain.

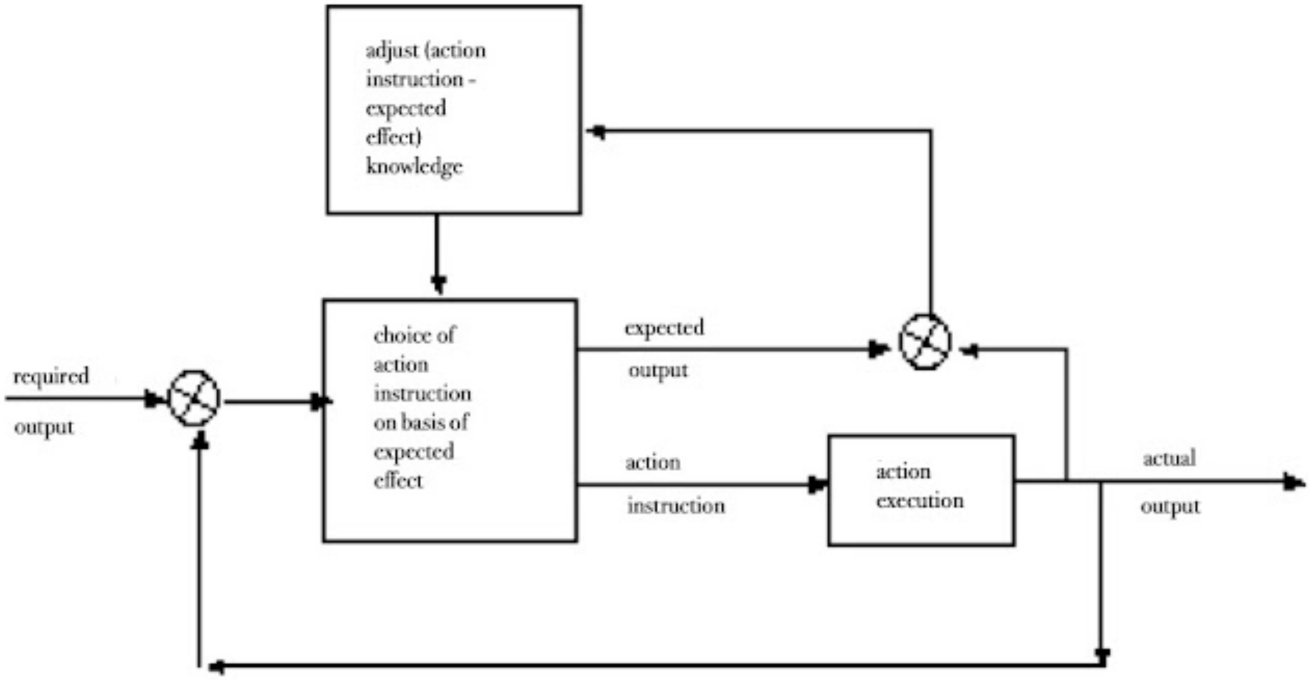

Figure 20 : Double use of feedback in learning to make movements (Bainbridge, 1978). One feedback loop [lower in diagram] is used in adjusting the movement while it is being made, the other [upper] loop adjusts the way successive actions are made, as the result of learning.

Movements which are consistently made the same way can be done without visual feedback, once learned, as mentioned in the section on location coding. Figure 20 indicates the double use of feedback in this learning. A person chooses an action instruction which they expect will have the effect they want. If the result turns out not to be as intended, then the person needs to adjust their knowledge about the expected effect of an action. This revision continues each time they make an action, until the expected result is the same as the actual result. Then the person can make an action with minimal need to check that it is being carried out effectively. This reduces the amount of processing effort needed to make the movement. Knowledge about expected results is a type of meta-knowledge. Meta-knowledge is important in activity choice, and will be discussed again.

2. Control or tracking movements

Control movements are ones in which someone makes frequent adjustments, with the aim of keeping some part of the external world within required limits. They might be controlling the output of an industrial process, or keeping an aircraft straight and level. In industrial processes, the time lag between making an action and its full effect in the process may be anything from minutes to hours, so there is usually time to think about what to do. By contrast in flying, events can happen very quickly and human reaction time plus neuromuscular lag, adding up to half a second or more, can have a considerable effect on performance. So different factors may be important in the two types of control task.

There are two ways of reducing the human response lag (cp. Figure 17). Preview allows someone to prepare actions in advance and therefore to overcome the effect of the lag. People can also learn something about the behaviour of the track they are following, and can then use this knowledge to anticipate what the track will do and so prepare their actions [soccer and hockey goal-keepers can have surprising ability to do this !].

There are two ways of displaying a tracking task. In a pursuit display, the moving target and the person's movements are displayed separately. A compensatory display system computes the difference between the target and the person's movements, and displays this difference relative to a fixed point. Many studies show human performance is better with a pursuit display, e.g. Figure 21. As mentioned above, people can learn about the effects of their actions, and about target movements, and both types of learning lead to improved performance. On the pursuit display, the target and human movements are displayed separately, so a person using this display can do both types of learning. In contrast, the compensatory display only shows the difference between the two movements. It is not possible for the viewer to tell which part of a displayed change is due to target movements and which is due to their own movements, so these are difficult to learn.

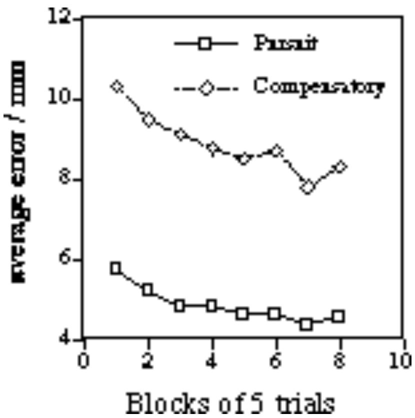

Figure 21 : Errors in tracking performance when using pursuit and compensatory displays (Briggs and Rockway, 1966).
[This is a good example of confused location coding - in the code menu - pursuit is above, in the results it is below. This makes it take longer correctly to interpret the figure.]

A great deal is known about human fast tracking performance (Sheridan and Ferrell, 1974; Rouse, 1980). A person doing a tracking task is acting as a controller. Control theory provides tools for describing some aspects of the track to be followed and how a device responds to inputs. This has resulted in the development of a 'human transfer function', a description of a human controller as if they were an engineered control device. The transfer function contains some components which describe human performance limits, and some which partially describe human ability to adapt to the properties of the device they are controlling. This function can be used to predict combined pilot - aircraft performance. This is a powerful technique with considerable economic benefits. However it is not relevant to this chapter as it describes performance, not the underlying processes, and it only describes human performance in compensatory tracking tasks. It also focuses attention on an aspect of human performance which can be poorer than that of fairly simple control devices. This encourages the idea of removing the person from the system, rather than appreciating what people can actively contribute, and designing support systems to overcome their limitations.

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E. Summary and implications

Theory

The cognitive processes underlying classic HF/E can be relatively simple, but not so simple that they can be ignored. Cognitive processing is carried out to meet cognitive functions. Five cognitive functions were discussed in this section of this chapter : distinguishing between stimuli; building up a percept of an external world containing independent entities with stable properties; naming; choosing an action; and comparison.

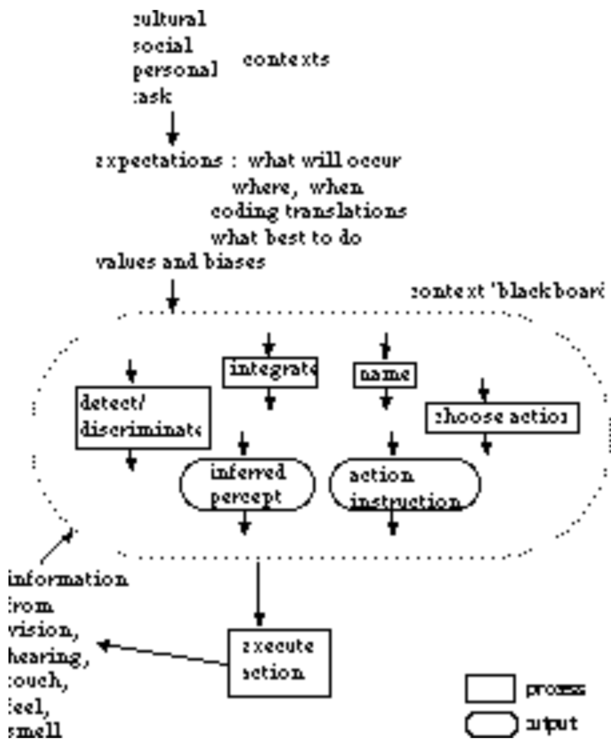

Figure 22 : A contextual overview of cognitive processes in simple tasks. [Interpreting the meaning of external stimuli and choosing an appropriate action is done within the context of knowledge and expectations about the situation.]

This section suggests these functions could be met in simple tasks by three main cognitive processes. (What happens when these processes are not sufficient has been mentioned briefly and is discussed in the next main section.) The three processes are :
- deciding between alternative interpretations of the evidence;
- integrating data from all sensory sources, together with knowledge about the possibilities, into an inferred percept which makes best sense of all the information;
- recoding, i.e. translating from one type of code to another.

Five other key aspects of cognitive processing have been introduced :
1. Sensory processing is relative rather than absolute.
2. The cognitive functions are not necessarily met by processes in a clearly distinct sequence. Processes which are 'automated' may be done in parallel. The processes communicate with each other via a common 'blackboard', which provides the context within which each process works, as summarised in

Figure 22. As processing is affected by the context in which it is done, behaviour is adaptive. However, for HF/E practitioners this has the disadvantage that the answer to any HF/E question is always 'it depends'.
3. The processing is not simply input driven : all types of processing involve the use of knowledge relevant in the context. (It can therefore be misleading to use the term 'knowledge based' to refer to one particular mode of processing.)
4. Preview and anticipation can improve performance.
5. Actions have associated meta-knowledge about their effects, which improves with learning.

Practical aspects
The primary aim of classic HF/E has been to minimise unnecessary physical effort. The points made here emphasise the need to minimise unnecessary cognitive effort.
Task analysis should not only note which displays and controls are needed, but might also ask such questions as : What cognitive functions need to be carried out ? by what processes ? Is the information used in these processes salient ?
In discrimination and integration : What is the ensemble of alternatives to be distinguished ? Are the items designed to maximise the differences between them ? What are the probabilities and costs of the alternatives ? How does the user learn these ?
In recoding : What coding vocabularies are used (shape, colour, location, size, direction, alpha-numeric):
- in each sub-task ?
- in the task as a whole ?
- are the translations unambiguous, unique, consistent, and if possible obvious ?
Do reaction times limit performance, and if so can preview or anticipation be provided ?

II. Complex tasks

Using an interface for a *simple task* entails the functions of distinguishing between stimuli, integrating stimuli, naming, comparing, and choosing and making simple actions [see the previous section]. When the interface is well designed, these functions can be carried out by decision making, integration, and recoding processes. These processes use knowledge about the alternatives which may occur, their distinguishing features, probabilities and costs, and the translations to be made.

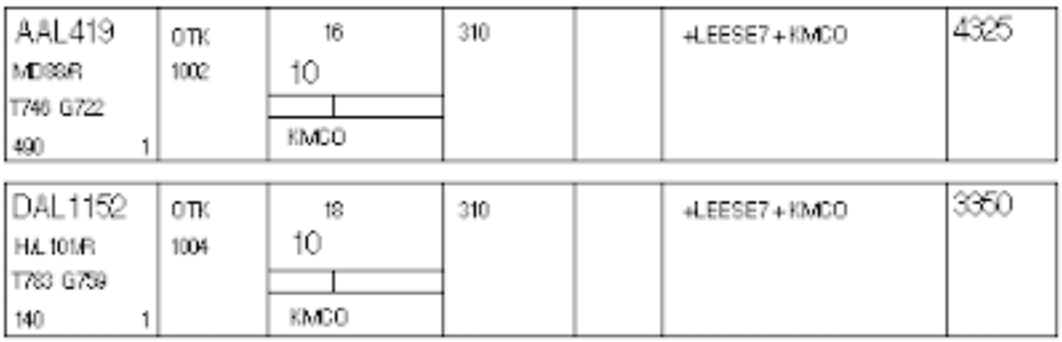

Figure 23 : Flight strips describing two aircraft, AAL419 and DAL152, which are flying at the same flight level (310 hundred feet [4th box from left]) from fix OTK [2nd box] to fix LEESE7 [6th box]. DAL1152 is estimated to arrive at LEESE7 two minutes after AAL419 (18-16 [3rd box, top row]), and is travelling faster (T783-T746 [1st box, 3rd row]).
[Air-traffic controllers had well over-learned this location coding. There were considerable problems with designing new displays for controllers because the eye-movements etc. used in reading and sorting these strips were so integral to an expert controllers' activities.]

Doing a more *complex task* uses more complex knowledge, in more complex functions and processes. For example, suppose an air-traffic controller is given the two flight strips in Figure 23. Commercial aircraft fly from one fix point to another. These two aircraft are flying at the same level (31,000 ft) from fix OTK to fix LEESE7. DAL1152 is estimated to arrive at LEESE7 two minutes after AAL419 (18-16), and is travelling faster (783-746). So DAL1152 is closing on AAL419 relatively fast and the controller needs to take immediate action, to tell one of the aircraft to change flight level. The person telling the aircraft to change level is doing more than simply recoding the given information. They use strategies for searching the displays and for comparing the data about the two aircraft, plus a simple dynamic model of how an aircraft changes position in time, to build up a mental picture of the relative positions of the aircraft, with one overtaking the other so a collision is possible. They then use a strategy for optimising the choice of which aircraft to instruct to change.

The overall cognitive functions or goals involved are :
- to understand what is happening,
- and to plan what to do about it.

In complex dynamic tasks these two main cognitive needs are met by subsidiary cognitive functions such as :
- infer/ review present state.
- predict/ review future changes/ events.

- review/ predict task performance criteria.
- evaluate acceptability of present or future state.
- define sub-tasks (task goals) to improve acceptability.
- review available resources/ actions, and their effects.
- define possible (sequences of) actions (and enabling actions) and predict their effects.
- choose action / plan.
- formulate execution of action plan (including monitor the effects of actions, which may involve repeating all the above).

These cognitive functions are interdependent. They are not carried out in a fixed order but are used as necessary. Lower level cognitive functions implement higher level ones. At the lowest levels, the functions are fulfilled by cognitive processes such as searching for the information needed, discrimination, integration, and recoding. So the processing is organised within the structure of cognitive goals/ functions.

An overview is built up in working storage by carrying out these functions. This overview represents the person's understanding of the current state of the task and their thinking about it. The overview provides the data the person uses in later thinking, as well as the criteria for what best to do next and how best to do it. There is a cycle : processing builds up the overview, which determines the next processing, which updates the overview, and so on, see Figure 24. Figure 22 [previous section] showed an alternative representation of context, as nested rather than cyclic. (For more about this mechanism, see Bainbridge 1993a.)

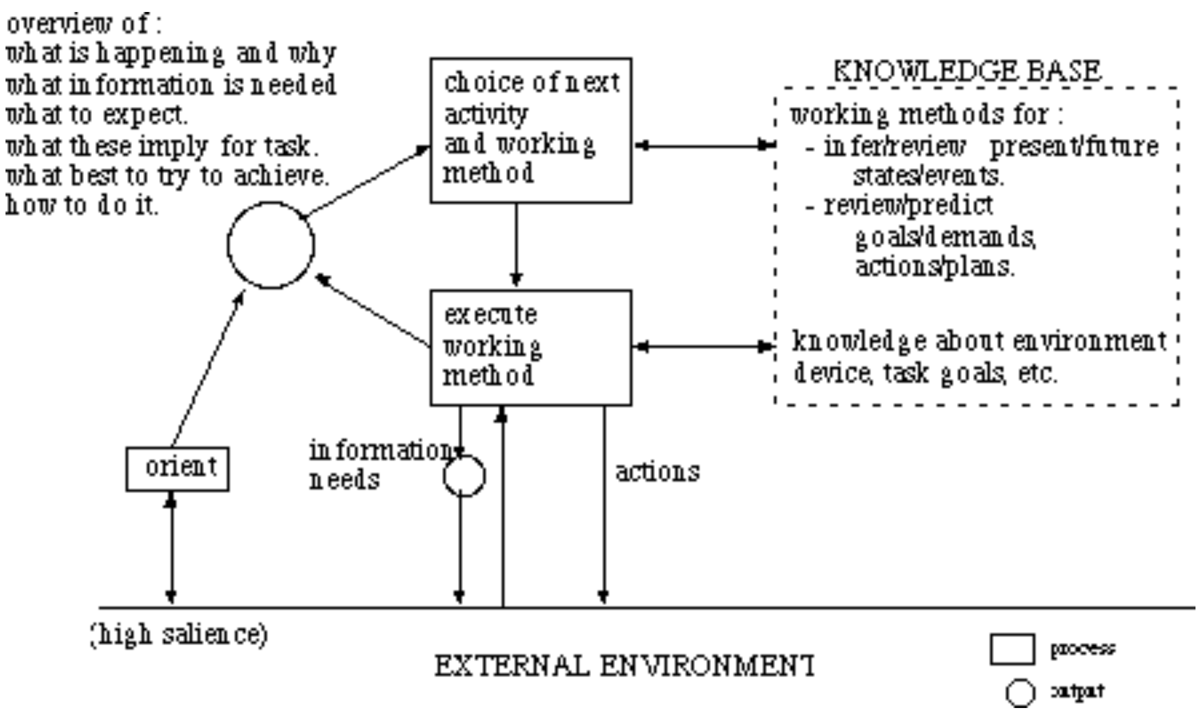

Figure 24 : The cycle of processing. Cognitive activity builds up the person's understanding and planning in working storage [top left circle]. The contents of working storage then affect the choice of the next best behaviour to carry out, and how to do it, and so on.

The main cognitive processes discussed in the previous section were decision making, integrating stimuli, and recoding. Additional modes of processing are needed in complex tasks, such as :
- carrying out a sequence of recoding transformations, and temporarily storing intermediate results in working memory.
- building up a structure of inference, an overview of the current state of understanding and plans, in working storage, using a familiar working method.
- using working storage to mentally simulate carrying out a cognitive or physical strategy.
- deciding between alternative working methods on the basis of meta-knowledge.
- planning and multi-tasking.
- developing new working methods.

These complex cognitive processes are not directly observable. The classic experimental psychology method, which aims to control all except one or two measured variables, and to vary one or two variables so their effects can be studied, is well suited to investigating discrimination and recoding processes. It is not well suited to investigating cognitive activities in which many inter-related processes may occur without any observable behaviour.
Studying these tasks involves special techniques : case studies, videos, verbal protocols, or distorting the task in some way, perhaps slowing it down or making the person do extra actions to get information (Wilson and Corlett, 1995). Both setting up and analysing the results of such studies can take years of effort. The results tend to be as complex as the processes studied, so they are difficult to publish in the usual formats. Such studies do not fit well into the conventions about how research is done, so there are unfortunately not many of this type. However, the rest of this section will give some evidence about the nature of complex cognitive processes, to support the general claims made so far. The sub-sections are on : sequences; language understanding; inference and diagnosis; working storage; planning, multi-tasking, and problem solving; and knowledge.

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A. Sequences of transforms

After decision making, integrating and recoding, the next level of complexity in cognitive processing is carrying out a sequence of recoding translations or transforms. The result of one step in the sequence acts as the input to the next step, and so has to be kept temporarily in working memory. Here the notion of recoding needs to be expanded to include transforms such as simple calculations and comparisons, and conditions leading to alternative sequences.
Note that in this type of processing the goal of the behaviour, the reason for doing it, is not included in the description of how it is done. Some people call this type of processing 'rule based'. There are two typical working situations in which behaviour is not structured relative to goals.

When a person is following instructions which do not give them any reason for why they have to do each action, then they are using this type of processing. This is usually not a good way of presenting instructions as, if anything goes wrong, the person has no reference point for identifying how to correct the problem.

The second case can arise in a stable environment, in which behaviour can be done in the same way each time. If a person has practised often, the behaviour may be done without needing to check it, or to think out what to do or how to do it (see below). Such over-learned sequences give a very efficient way of behaving, in the sense of using minimal cognitive effort. But if the environment does change, then over-learning is maladaptive and can lead to errors (see next section on learning and errors).

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B. Language processing

This section will cover two issues : using language to convey information and instructions, and the processes involved in language understanding. Although language understanding is not the primary task of either pilot or air traffic controller, it does provide simple examples of some key concepts in complex cognitive processing.

1. Written instructions
Providing written instructions is often thought of as a way of making a task easy, but this is not guaranteed. Reading instructions involves interpreting the words in order to build up a plan of action. The way the instructions are written may make this processing more or less difficult. Video recorder operating manuals are notorious for this.

Various techniques have been used for measuring the difficulty of processing different sentence types. Some typical results are (Savin and Perchonock, 1965) :

Sentence type	*Example*	*% Drop in Performance*
kernel	The pilot flew the plane	0
negative	The pilot did not fly the plane.	-16
passive	The plane was flown by the pilot	-14
negative passive	The plane was not flown by the pilot	-34

Such data suggest that understanding negatives and passive involves two extra and separate processes. This suggests it is best in general to use active positive forms of sentence. But when a negative or restriction is the important message, it should be the most salient and come first. For example, 'No smoking' is more effective than 'Smoking is not permitted'. Though using a simple form of sentence does not guarantee that a message makes good sense. I recently enjoyed staying in a hotel room with a notice on which the large letters said:
Do not use the elevator during a fire.
Read this notice carefully.

Connected prose is not necessarily the best format for showing alternatives in written instructions. Spatial layout can be used to show the groupings and relations between phrases, by putting each phrase on a separate line, by indenting to show items at the same level, and by using flow diagrams to show the effect of choice between alternatives (e.g. Oborne, 1995, Chapter 4). When spatial layout is used to convey meaning in written instructions, it is a code and should be used consistently, as discussed in the previous section.

Instructions also need to be written from the point of view of the reader : 'if you want to achieve this, then do this'. Instruction books are often written the other way round : 'if you do this, then this happens'. The second approach requires from the reader much more understanding, searching and planning to work out what to do. Note that the effective way of writing instructions is goal oriented. In complex tasks, methods of working are in general best organised in terms of what is to be achieved; this will be discussed again below.

2. Language understanding

In complex tasks, many of the cognitive processes and knowledge used are only possible because the person has considerable experience of the task.

Language understanding is the chief complex task studied by experimental psychologists (e.g. Ellis, 1993), because it is easy to find experts to test. Some examples illustrate processes which are also used in other complex tasks.

When someone is listening to or reading language, each word evokes learned expectations. For example :

The : *can only be followed by : a descriptor, or a noun.*

The pilot : *depending on the context, either :*

1. will be followed by the word 'study', or :

2. a. evokes general knowledge (scenarios) about aircraft or ship pilots.

2. b. can be followed by :

2. b. i. a descriptive clause, containing items relevant to living things/ animals/ human beings/ pilots, or

2. b. ii. a verb, describing possible actions by pilots.

Each word leads to expectations about what will come next, each constrains the syntax (grammar) and semantics (meaning) of the possible next words. To understand the language, a person needs to know the possible grammatical sequences, the semantic constraints on what words can be applied to what types of item, and the scenarios. During understanding, a person's working storage contains the general continuing scenario, the structure of understanding built up from the words received so far, and the momentary expectations about what will come next. (Many jokes depend on not meeting these expectations.)

The overall context built up by a sequence of phrases can be used to disambiguate alternative meanings, such as :

The Inquiry investigated why
the pilot turned into a mountain.
or : **In this fantasy story**
the pilot turned into a mountain.

The knowledge base/ scenario is also used to infer missing information. For example :

The flight went to Moscow.
The stewardess brought her fur hat.

Answering the question 'Why did she bring her fur hat ?' involves knowing that stewardesses go on flights and about the need for and materials used in protective clothing, which are not explicitly mentioned in the information given.

Understanding language does not necessarily depend on the information being presented in a particular sequence. Although it requires more effort, we can understand someone whose first language uses a different word order from English, such as :

The stewardess her fur hat brought.

We do this by having a general concept that a sentence consists of several types of unit (noun phrases, verb phrases, and so on) and we make sense of the input by matching it to the possible types of unit. This type of processing can be represented as being organised by a 'frame with slots', where the frame co-ordinates the slots for the types of item expected, which are then instantiated in a particular case, as in :

Noun phrase	Verb	Noun phrase
The stewardess	**brought**	**her fur hat**

(As language has many alternative sequences, this is by no means a simple operation, Winograd 1972.)

The understanding processes used in complex control and operation tasks show the same features that are found in language processing.
The information obtained evokes both general scenarios and specific moment to moment expectations. The general context, and additional information, can be used to decide between alternative interpretations of the given information. A structure of understanding is built up in working storage. Frames or working methods suggest the types of information the person needs to look for to complete their understanding. These items can be obtained in a flexible sequence. And knowledge is used to infer whatever is needed to complete the understanding but which is not supplied by the input information. There is an important addition in control/ operation tasks, which is that the structure of understanding is built up in order to influence the state of the external world, to try to get it to behave in a particular way.

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C. Inference and diagnosis

To illustrate these cognitive processes in an aviation example, this section uses an imaginary example so the presentation can be short. Later sections describe real evidence on pilot and air traffic controller behaviour which justifies the claims made here.

Suppose that an aircraft is in flight and the 'engine oil low' light goes on. What might be the pilot's thoughts ? The pilot needs to *infer the present state* of the aircraft (cognitive functions here are indicated by italics). This involves considering alternative hypotheses which could explain the light, such as that there is an instrument fault, or there genuinely is an engine fault, and then choosing between the hypotheses according to their probability (based on previous experience of this or other aircraft) or by looking for other evidence which would confirm or disprove the possibilities. The pilot could *predict the future changes* which will occur as a result of the chosen explanation of events. Experienced people's behaviour in many dynamic tasks is future oriented. A person takes anticipatory action, not to correct the present situation, but to ensure that predicted unacceptable states or events do not occur. Before *evaluating the predictions for their acceptability*, the pilot needs to *review the task performance criteria*, such as the relative importance of arriving at the original destination quickly, safely or cheaply. The result of comparing the predictions with the criteria will be to *define the performance needs to be met*. It is necessary to *review the available resources*, such as the state of the other engines or the availability of alternative landing strips. The pilot can then *define possible alternative action sequences and predict their outcomes*. A *review of action choice criteria*, which includes the task performance criteria plus others such as the difficulty of the proposed procedures, is needed as a basis for *choosing an action sequence / plan*, before beginning to *implement the plan*. Many of these cognitive functions must be based on incomplete evidence, for example about future events or the effects of actions, so risky decision making is involved.

A pilot who has frequently practised these cognitive functions may be able to carry them out 'automatically', without being aware of the need for intermediate thought. And an experienced pilot may not be aware of thinking about the functions in separate stages, for example (predict + review criteria + evaluation) may be done together.

Two modes of processing have been used in this example :
- 'automatic' processing (i.e. recoding),
- using a known working method which specifies what thinking to carry out.

Other modes of processing will be suggested later. The mode of processing needed to carry out a function depends on the task situation and the person's experience (see next section on learning). An experienced person's knowledge of the situation may enable them to reduce the amount of thinking they have to do, even when they do need to think things out explicitly. For example, it may be clear early in the process of predicting the effects of possible actions that some will be not acceptable and so need not be explored further (see below on planning).

Nearly all the functions and processing mentioned have been supplied from the pilot's knowledge base. In the example, the warning light evoked working methods for explaining the event and for choosing an action plan, as well as knowledge about the alternative explanations of events and suggestions of relevant information to look for. The combination of (working method + knowledge referred to in using this method + mental models for predicting events) is the scenario. Specific scenarios may be evoked by particular events, or by particular phases of the task (phases of the flight).

This account of the cognitive processes is goal oriented. The cognitive functions or goals are the means by which the task goals are met, but are not the same as them. Task and personal goals act as constraints on what it is appropriate and useful to think about when fulfilling the cognitive goals.

The cognitive functions and processing build up a structure of data (in working storage) which describes :
- the present state and the reasons for it,
- predicted future changes,
- task performance and action choice criteria,
- resources available,
- possible actions,
- evaluations of the alternatives,
- the chosen action plan.

This data structure is an overview which represents the results of the thinking and deciding done so far, and provides the data and context for later thinking. As an example, the result of reviewing task performance criteria is not only an input to evaluation, it could also affect what is focused on in inferring the present state, or in reviewing resources, or in action choice. The overview ensures that behaviour is adapted to its context.

The simple example above described reaction to a single unexpected event. Normally flying and air traffic control are ongoing tasks. For example, at the beginning of shift an air traffic controller has to build up their understanding of what is happening and what actions are necessary, from scratch. After this, each new aircraft which arrives is fitted into the controller's ongoing mental picture of what is happening in the airspace; the thinking processes do not start again from the beginning. Aircraft usually arrive according to schedule and are expected, but the overview needs to be updated and adapted to changing circumstances (see below on planning and multi-tasking

There are two groups of practical implications of these points.

One is that cognitive task analysis should focus on the cognitive functions involved in a task, rather than simply pre-specifying the cognitive processes by which they are met.

The second is that designing specific displays for individual cognitive functions may be unhelpful. A person doing a complex task meets each function within an overall context, the functions are interdependent, and the person may not think about them in a pre-specified sequence. Giving independent interface support to each cognitive function, or sub-task within a function, could make it more difficult for the person to build up an overview which interrelates the different aspects of their thinking.

Diagnosis

The most difficult cases of inferring what underlies the given evidence may occur during fault diagnosis. A fault may be indicated by a warning light or, for an experienced person, by a device not behaving according to expectations. Like any other inference, fault diagnosis can be done by several modes of cognitive processing, depending on the circumstances. If a fault occurs frequently, and has unique symptoms, it may be possible to diagnose the fault by visual pattern recognition, i.e. pattern on interface indicates fault identity (e.g. Marshall, Scanlon, Shepherd and Duncan, 1981). This is a type of recoding. But diagnosis can also pose the most difficult issues of inference, for example by reasoning based on the physical or functional structure of the device (e.g. Hukki and Norros, 1993).

In-flight diagnosis may need to be done at speed. Experienced people can work rapidly using 'recognition primed decisions', in which situations are assigned to a known category with a known response, on the basis of similarity. The processes involved in this are discussed by Klein (1989). The need for rapid processing emphasises the importance of training for fault diagnosis.

Amalberti (1992, Expt. 4) studied fault diagnosis by pilots. Two groups of pilots were tested, one group were experts on the Airbus, the other group were experienced pilots beginning their training on the Airbus. They were asked to diagnose two faults specific to the Airbus, and two general problems. In 80% of responses, the pilots gave only one or two possible explanations. This is compatible with the need for rapid diagnosis. Diagnostic performance was better on the Airbus faults, which the pilots had been specifically trained to watch out for, than on the more general faults.

One of the general problems was a windshear on take-off. More American than European pilots diagnosed this successfully. American pilots are more used to windshear as a problem, so are more likely to think of this as a probable explanation of an event. People's previous experience is the basis for the explanatory hypotheses they suggest.

In the second general fault there had been an engine fire on take-off, during which the crew forgot to retract the landing gear, which made the aircraft unstable when climbing. Most of the hypotheses suggested by the pilots to explain this instability were general problems with the aircraft, or were related to the climb phase. Amalberti suggested that when the aircraft changed the phase of flight, from take-off to climb, the pilots changed their scenario providing the appropriate events, procedures, mental models and performance criteria for use in thinking. Their knowledge about the previous phase of flight became less accessible, and so was not used in explaining the fault.

D. Working Storage

The inference processes build up the contextual overview or situation awareness in working storage. This is not the same as short-term memory, but short-term memory is an important limit to performance, and will be discussed first.

1. Short-term memory

Figure 25 shows some typical data on how much is retained in short-term memory after various time intervals. Memory decays over about 30 seconds, and is worse if the person has to do another cognitive task before being tested on what they can remember.

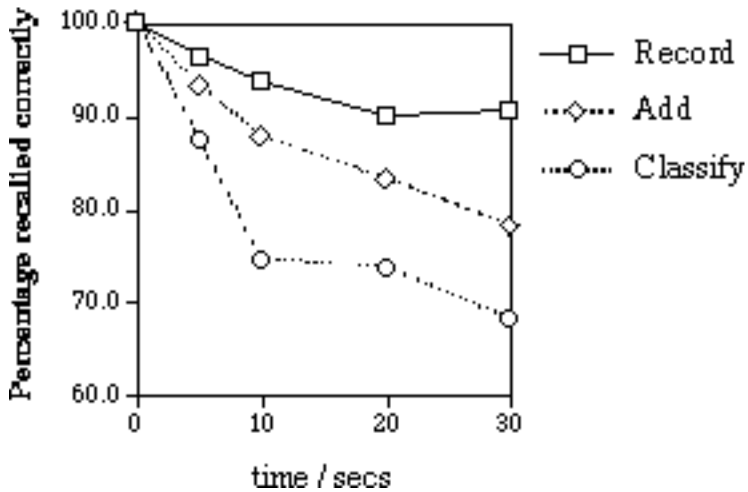

Figure 25 : Decay in short-term memory over a short period of time. Memory decays more if there is a more complicated other task to be done while the item is in memory (adapted from Posner and Rossman, 1965).

This memory decay is important in the design of computer based display systems in which different display formats are called up in sequence on a screen. Suppose the user has to remember an item from one display, for use with an item on a second display. Suppose that the second display format is not familiar, so the person has to search for the second item : this search may take about 25 seconds. The first item must then be recalled after doing the cognitive processes involved in calling up the second display and searching it. The memory data suggest that the person may have forgotten the first item on 30% of occasions.

The practical implication is that, to avoid this source of errors, it is necessary to have sufficient display area so that all the items used in any given cognitive processing can be displayed simultaneously. Minimising non-task-related cognitive processes is a general HF/E aim, to increase processing efficiency. In this case it is also necessary in order to reduce errors. This requirement emphasises the need to identify what display items are used together, in a cognitive task analysis.

2. The overview in working storage

Although there are good reasons to argue that the cognitive processes in complex dynamic tasks build up a contextual overview of the person's present understanding and plans (Bainbridge 1993a), not much is known about this overview. This section will make some points about its capacity, its content, and the way items are stored.

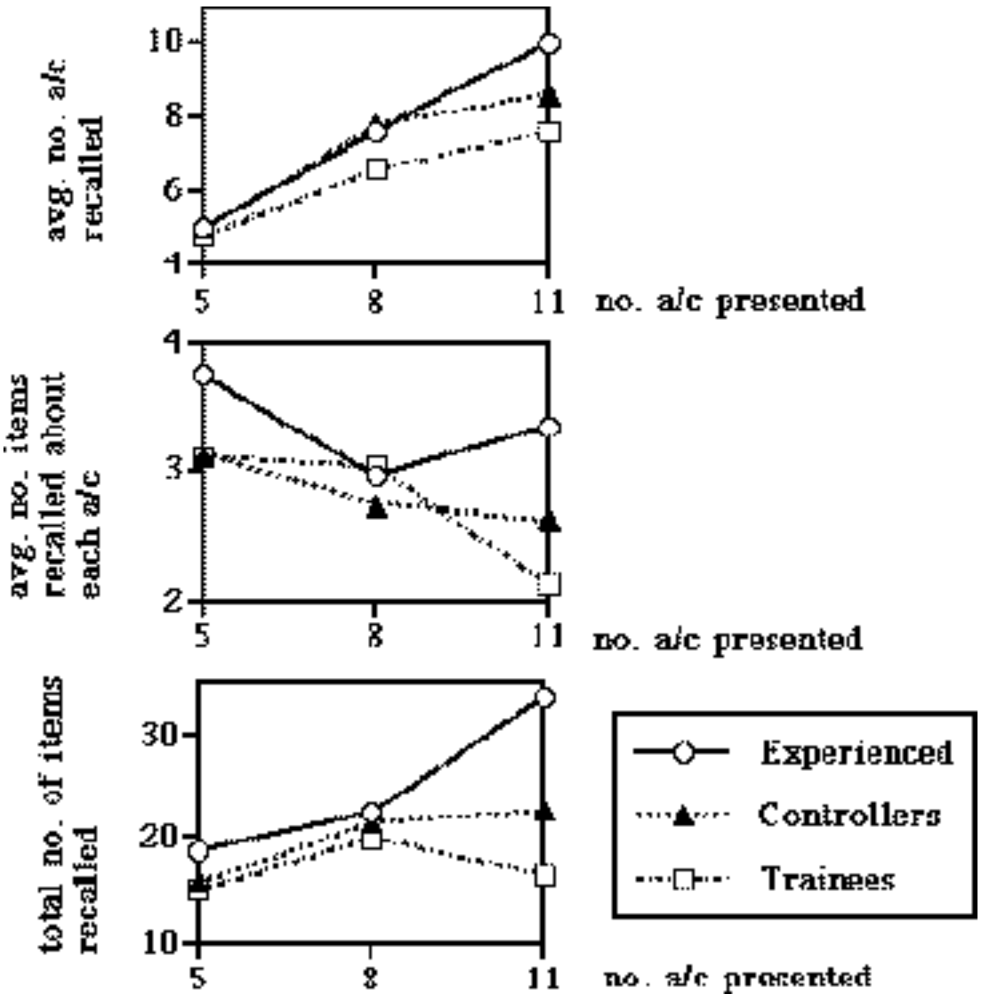

Figure 26 : Number of aircraft (a/c) remembered, and number of items remembered about each aircraft, by air-traffic controllers with three different levels of experience and at three different levels of workload. (data in personal communication from Bisseret, based on Bisseret, 1970).

Capacity

Bisseret (1970) asked air traffic area controllers, after an hour of work, what they remembered about the aircraft they had been controlling. Three groups of people were tested : trainee controllers, people who had just completed their training, and people who had worked as controllers for several years. Figure 26 shows the number of items recalled. The experienced controllers could remember on average 33 items. This is a much larger figure than the 7+/-2 chunk capacity for static short-term memory (Miller 1956) or the 2 items capacity of running memory for arbitrary material (Yntema and Mueser, 1962). Evidently a person's memory capacity is improved by doing a meaningful task and by experience. A possible reason for this will be given below.

Content

Bisseret also studied which items were remembered. The most frequently remembered items were flight level (33% of items remembered), position (31%) and time at fix (14%). Leplat and Bisseret (1965) had previously identified the strategy the controllers used in conflict identification (checking whether aircraft are a safe distance apart). The frequency with which the items were remembered matches the sequence in which they were thought about : the strategy first compared aircraft flight levels, then position, then time at fix, and so on.

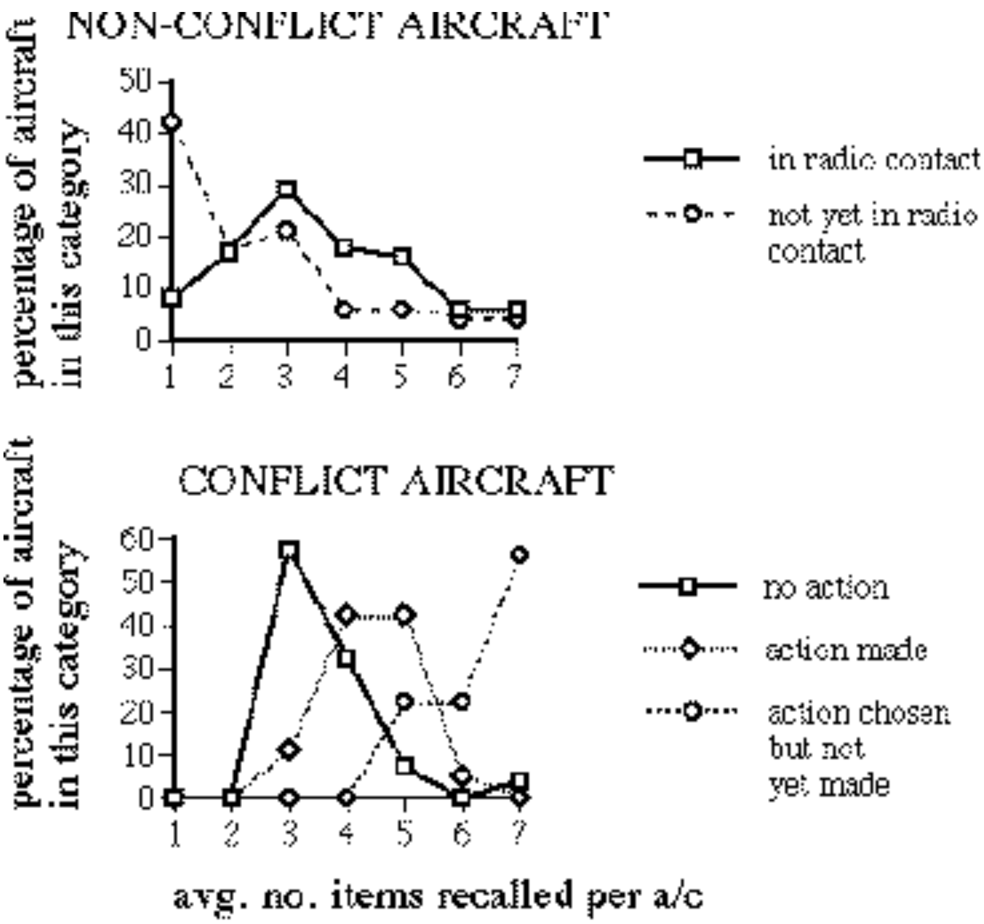

Figure 27 : Number of items remembered about aircraft with different status for the air-traffic controller (data from Sperandio, 1970).
[e.g. top graph : For a/c not in conflict with others, and not yet in radio contact, the controllers remembered 1 item about more than 40% of the a/c, 3 items about another 20% of the a/c.
e.g. bottom graph : For a/c in conflict with others, for which the controllers had decided what to do but not yet made the action, the controllers remembered more than 6 items about more than 50% of the a/c in this category. While, for a/c which they have already done something about, they remember 4 or 5 items about 80% of those.]

Sperandio (1970) studied another aspect (Figure 27). He found that more items were remembered about aircraft involved in conflict than ones which were not. For non-conflict aircraft, more was remembered about aircraft which had been in radio contact. For conflict aircraft, more was remembered about aircraft on which action had been taken, and most was remembered about aircraft for which an action had been chosen but not yet made.

These results might be explained by two classic memory effects.
One is the *rehearsal* or repetition mechanism by which items are maintained in short-term memory. The more frequently the item or aircraft has been considered by the controllers when identifying potential collisions and acting on them, the more likely it is to be remembered.
The findings about aircraft in conflict could be explained by the *recency* effect, that items which have been rehearsed most recently are more likely to be remembered.
These rehearsal and recency mechanisms make good sense as mechanisms for retaining material in real as well as in laboratory tasks.

The form in which material is retained
The controllers studied by Bisseret *op cit* remembered aircraft in pairs or threes : 'there are two flying towards DIJ, one at level 180, the other below at 160', 'there are two at level 150, one passed DIJ towards BRY several minutes ago, the other should arrive at X at 22', or 'I've got one at level 150 which is about to pass RLP and another at level 170 which is about 10 min behind'. The aircraft were not remembered by their absolute positions, but in relation to each other. Information was also remembered relative to the future, many of the errors put the aircraft too far ahead.
These sorts of data suggest that, while rehearsal and recency are important factors, the items are not remembered simply by repeating the raw data, as in short term memory laboratory experiments. What is remembered is the outcome of working through the strategy for comparing aircraft for potential collisions. The aircraft are remembered in terms of the key features which bring them close together, whether they are at the same level, or flying towards the same fix point, etc.

A second anecdotal piece of evidence is that air traffic controllers talk about 'losing the picture' as a whole, not piecemeal. This implies that their mental representation of the situation is an integrated structure. It is possible to suggest that experienced controllers remember more because they have better cognitive skills for recognising the relations between aircraft, and the integrated structure makes items easier to remember.

The only problem with this integrated structure is that the understanding, predictions and plans can form a 'whole' which is so integrated and self-consistent that it becomes too strong to be changed. People may then only notice information which is consistent with their expectations, and it may be difficult to change the structure of inference if it turns out to be unsuccessful or inappropriate (this rigidity in thinking is called 'perceptual set').

Some practical implications
Some points have already been made about the importance of short-term memory in display systems. The interface also needs to be designed to support the person in developing and maintaining their overview. It is not yet known whether an overview can be obtained directly from an appropriate display, or whether the overview can only be developed by actively understanding and planning the task, with a good display enhancing this processing but not replacing it. It is important, in display systems in which the data needed for the whole task are not all displayed at the same time, to ensure there is a permanent overview display and it is clear how the other possible displays are related to it.

Both control automation (replacing the human controller) and cognitive automation (replacing the human planner, diagnoser, and decision maker) can cause problems with the person's overview. A person who is expected to take over manual operation or decision making will only be able to make informed decisions about what to do after they have built up an overview of what is happening. This may take 15-30 minutes to develop. So the system design needs to allow for this sort of delay before a person can take over effectively (Bainbridge, 1983). Also the data above show that a person's ability to develop a wide overview depends on experience. This means that, to be able to take over effectively from an automated system, they need to practise building up this overview. So practise opportunities should be allowed for, in the allocation of functions between computer and person, or in other aspects of the system design such as refresher training.

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E. Planning, multi-tasking and problem solving

Actions in complex dynamic tasks are not simple single units. A sequence of actions may be needed, and it may be necessary to deal with several responsibilities at the same time. Organisation of behaviour is an important cognitive function, which depends on and is part of the overview. This section will be in three inter-related parts, on : planning future sequences of action; multi-tasking - dealing with several concurrent responsibilities including sampling; and problem solving - devising a method of working when a suitable one is not known.

1. Planning

It may be more efficient to think out what to do in advance - if there is a sequence of actions to carry out, or multiple constraints to satisfy, or it would be more effective to anticipate events. Alternative actions can be considered and the optimum ones chosen, and the thinking is not done under time pressure. The planning processes may use working storage, for testing the alternatives by mental simulation, and for holding the plan as part of the overview.

In aviation, an obvious example is preflight planning. Civilian pilots plan their route in relation to predicted weather. Military pilots plan their route relative to possible dangers and the availability of evasive tactics. In high speed low level flight there is not time to think out what to do during the flight, so the possibilities need to be worked out beforehand. The plan then needs to be implemented, and adjusted if changes in circumstances make this necessary. So this section will be in two parts, on preplanning, and on-line revision of plans.

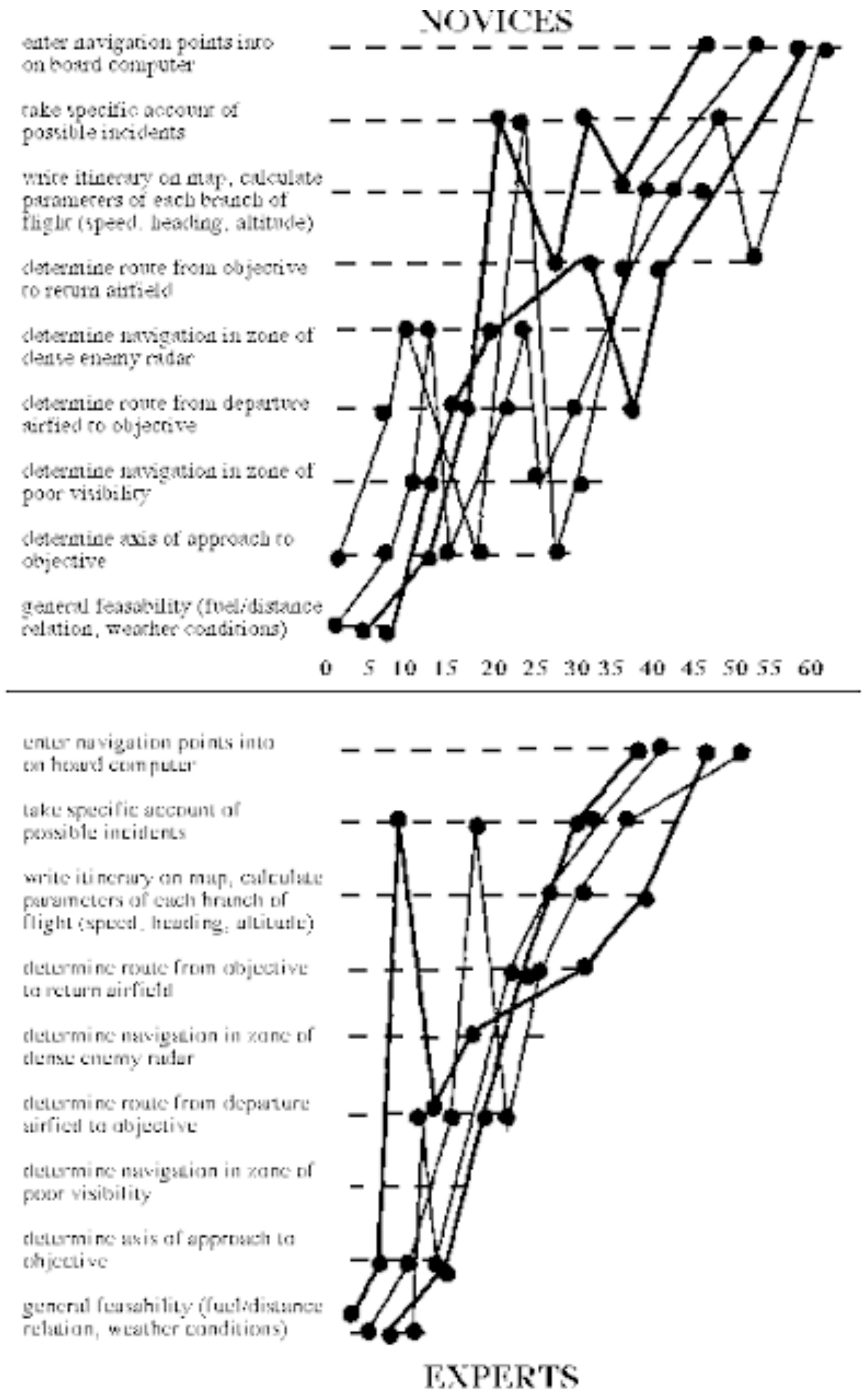
NOVICES
enter navigation points into on board computer
take specific account of possible incidents
write itinerary on map, calculate parameters of each branch of flight (speed, heading, altitude)
determine route from objective to return airfield
determine navigation in zone of dense enemy radar
determine route from departure airfied to objective
determine navigation in zone of poor visibility
determine axis of approach to objective
general feasability (fuel/distance relation, weather conditions)
0 5 10 15 20 25 30 35 40 45 50 55 60
EXPERTS

Figure 28 : Stages of planning by pilots (translated with permission from Amalberti, 1992). This figure shows the differences between novice and expert pilots.
[X axis : time during planning, Y axis : type of planning activity. Continuous lines on right show how 4 pilots in each group changed from one planning activity to another over time.]

Preplanning
Figure 28 shows results from a study of preflight planning by Amalberti (1992, Expt. 2). Pilots thought out the actions to take at particular times or geographical points. Planning involves thinking about several alternative actions, and choosing the best compromise given several constraints. Some of the constraints the pilots consider are the level of risk of external events, the limits to manoeuvrability of the aircraft, and their level of expertise to deal with particular situations, as well as the extent to which the plan can be adapted, and what to do if circumstances mean that major changes in plan are needed.

Amalberti studied 4 novice pilots, who were already qualified but at the beginning of their careers, and 4 experts. The cognitive aims considered during planning are listed on the left of Figure 28. Each line on the right represents one pilot, and shows the sequence in which he thought about the cognitive functions.
The results show that novice pilots took longer to do their planning, and that each of the novice pilots returned to reconsider at least one point he had thought about earlier. Verbal protocols collected during the planning showed that novices spent more time mentally simulating the results of proposed actions to explore their consequences.
The experts did not all think about the cognitive functions in the same sequence, but only one of them reconsidered an earlier point. Their verbal protocols showed they prepared fewer responses to possible incidents than the novices.

One of the difficulties with planning is that later in planning the person may think of problems which mean that parts of the plan already devised need to be revised. Planning is an iterative process. The topics are interdependent, for example the possibility of incidents may affect the best choice of route to or from the objective. What is chosen as the best way of meeting any one of the aims may be affected by, or affect, the best way of meeting other aims. As the topics are interdependent, there is no one optimum sequence for thinking about them. The results suggest that experts have the ability, when thinking about any one aspect of the flight, to take into account its implications for other aspects, so it does not need to be revised later.

The experts have better knowledge about the scenario, about possible incidents and levels of risk. They know more about what is likely to happen, so they need to prepare fewer alternative responses to possible incidents. The experts also know from experience the results of alternative actions, including the effects of actions on other parts of the task, so they do not need to mentally simulate making the actions to check their outcomes. They also have more confidence in their own expertise to deal with given situations. All these are aspects of their knowledge about the general properties of the things they can do, how risky these are, how good they are at them, and so on. This 'meta knowledge' was introduced in the section above on actions, and is also central to multi-tasking and in workload and learning (see next section).

On-line adaptation of plans
In the second part of Amalberti's study, the pilots carried out their mission plan in a high fidelity simulator. The main flight difficulty was that they were detected by radar. The pilots responded immediately to this. The response had been preplanned, but had to be adapted to details of the situation

when it happened. The novice pilots showed much greater deviations from their original plan than the experts. Some of the young pilots slowed down before the point at which they expected to be detected, as accelerating was the only response they knew for dealing with detection. This acceleration led to a deviation from their planned course, so they found themselves in an unanticipated situation. They then made a sequence of independent reactive short-term decisions, because there was not time to consider the wider implications of each move. The experts made much smaller deviations from their original plan, and were able to return to the plan quickly. The reason for this was that they had not only preplanned their response to radar, they had also thought out in advance how to recover from deviations from their original plan. Again experience, and therefore training, plays a large part in effective performance.

In situations in which events happen less quickly, people may be more effective in adapting their plans to changing events at the time. The current best model for the way that people adapt their plans to present circumstances is probably the opportunistic planning model of Hayes-Roth and Hayes-Roth (1979, see also Hoc, 1988).

2. Multi-tasking

If a person has several concurrent responsibilities, each of which involves a sequence of activities, then inter-leaving these sequences is called multi-tasking. Doing this involves an extension of the processes mentioned under planning. Multi-tasking involves working out in advance what to do, combined with opportunistic response to events and circumstances at the time.

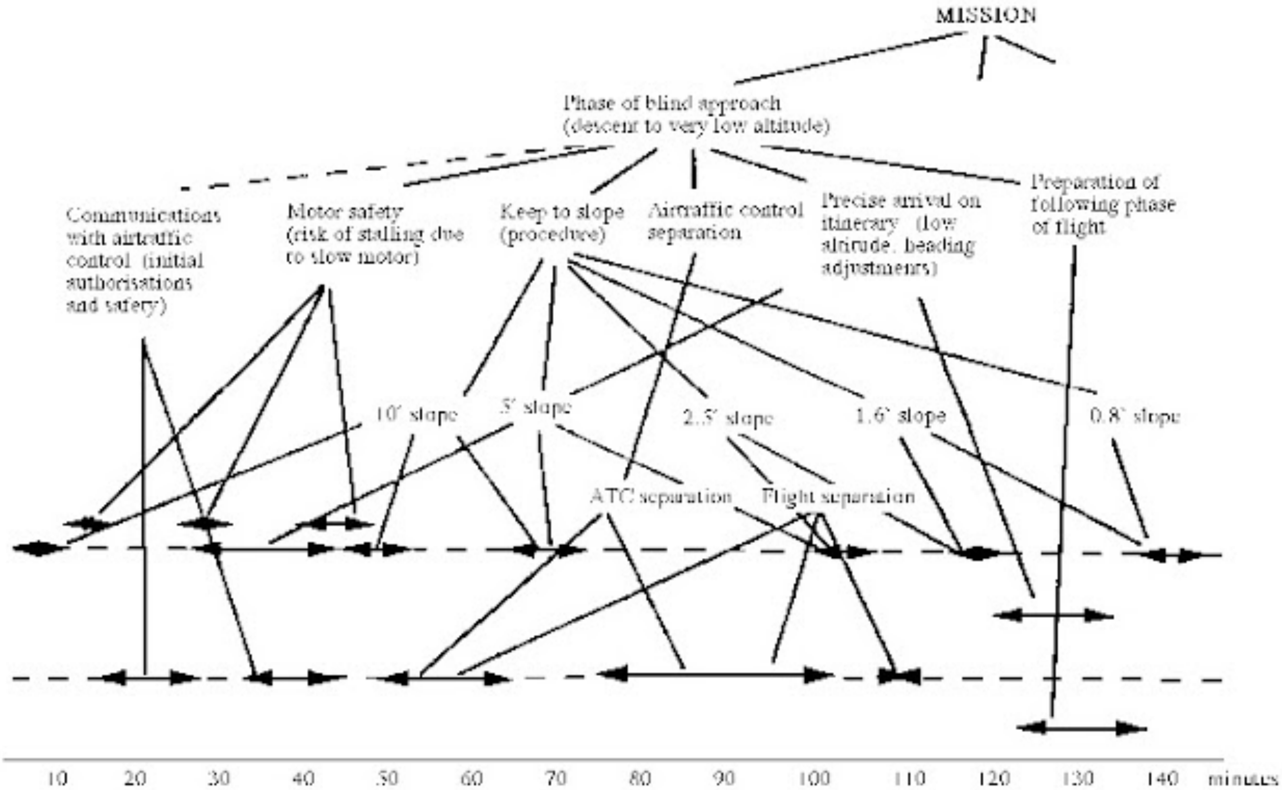

Figure 29 : Multi-tasking by a pilot during one phase of a mission (translated with permission from Amalberti, 1992). This figure shows that the activities are inter-leaved.
[Above (angled lines) - hierarchy of tasks and sub-tasks.
Below (horizontal dashed lines) - each line represents a particular activity, double headed arrows show the times during which the pilot did that activity. Sub-tasks which he returns to several times are : motor safety, slope control, communications with AirTrafficControl.]

Examples of multi-tasking
Amalberti (1992, Expt.1) studied military pilots during a simulated flight. Figure 29 shows part of his analysis, of one pilot's activities during descent to low level flight. The bottom line in this Figure is a time line.
The top part of the figure describes the task as a hierarchy of task goals and sub-goals.
The parallel double-headed arrows beneath represent the time which the pilot spent on each of the activities. These arrows are arranged in five parallel lines which represent the five main tasks in this phase of flight : maintain engine efficiency at minimum speed; control angle of descent; control heading; deal with air traffic control; and prepare for the next phase of flight.
Figure 29 shows how the pilot allocated his time between the different tasks.
Other principal tasks which occurred in other phases of flight were : keep to planned timing of manoeuvres; control turns; check safety.

Sometimes it is possible to meet two goals with one activity. The pilot does not necessarily complete one sub-task before changing to another. Indeed this is not often not possible in a control task, in which states and events develop over time. Usually the pilot does one thing at a time. However, it is possible for him to do two tasks together when they use different cognitive processing resources. For example, controlling descent, which uses eyes + motor co-ordination, can be done at the same time as communicating with air traffic control, which uses hearing + speech (see also below on workload - in the third section of this chapter).

Some multi-tasking examples are difficult to describe in a single figure. For example, Reinartz (1989), studying a team of three nuclear power plant operators, found they might work on nine to ten different goals at the same time.

Other features of multi-tasking have been observed by Benson (1990):

- *Multi-tasking may be planned ahead* (a process operator studied by Beishon, 1974, made plans for up to 1.5 hours ahead). These plans are likely to be partial, and incomplete in terms of timing and detail. Planned changes in activity may be triggered by times or events. When tasks are done frequently, much of the behaviour organisation may be guided by habit.
- *Executing the plan*. Interruptions may disrupt planned activity. The preplan is incomplete, and actual execution depends on details of the situation at the time. Some tasks may be done when they are noticed in passing (Beishon *op cit* first noticed this, and called it serendipity.) This is opportunistic behaviour. The timing of activities of low importance may not be preplanned, but may be fitted in spare moments. The remaining spare moments are recognised as spare time.
- *Effects of probabilities and costs*. In a situation which is very unpredictable, or when the cost of failure is high, people may make the least risky commitment possible. If there is a high or variable workload, people may plan to avoid increasing their workload, and use different strategies in different workload conditions (see below on workload - in the third section of this chapter).

A possible mechanism

Sampling is a simple example of multi-tasking in which people have to monitor several displays to keep track of changes on them. Mathematical sampling theory has been used as a model for human attention in these tasks. In the sampling model, the frequency of attending to an information source is related to the frequency of changes on that source. This can be a useful model of how people allocate their attention when changes to be monitored are random, as in straight and level flight, but this model is not sufficient to account for switches in behaviour in more complex phases of flight.

Amalberti *op cit* made some observations about switching from one task to another. He found that :

- before changing to a different principal task the pilots review the normality of the situation, by checking that various types of redundant information are compatible with each other.
- before starting a task that will take some time, they ensure that they are in a safe mode of flight. For example, before analysing the radar display, they check that they are in the appropriate mode of automatic pilot.
- while waiting for feedback about one part of the task, pilots do part of another task, which they know is short enough to fit into the waiting time.
- when doing high risk high workload tasks, pilots are less likely to change to another task.

These findings suggest that, at the end of a sub-section of a principal task, the pilots check that everything is alright. They then decide (not necessarily consciously) what next to devote effort to, by combining their preplan with meta-knowledge about the alternative tasks, such as how urgent they are, how safe or predictable they are, how difficult they are, how much workload they involve, and how long they take (see below on workload - in third section of paper).

Practical implications
Multi-tasking can be preplanned, and involves meta-knowledge about alternative behaviours. Both planning and knowledge develop with experience, which underlines the importance of practice and training.

The nature of multi-tasking also emphasises the difficulties which could be caused by task specific displays. If a separate display was used for each of the tasks combined in multi tasking, then the user would have to call up a different display, and perhaps change coding vocabularies, each time they changed to a different main task. This would require extra cognitive processing and extra memory load, and could make it difficult to build up an overview of the tasks considered together. This suggests an extension to the point made in the section above on working storage. All the information used in all the principal tasks which may be interleaved in multi-tasking needs to be available at the same time, and easily cross-referenced. If this information is not available, then co-ordination and opportunistic behaviour may not be possible.

3. Problem solving
A task is familiar to a person who knows :
- the appropriate working methods,
- the associated reference knowledge about the states which can occur,
- the constraints on allowed behaviour,
- the scenarios, mental models, etc. which describe the environmental possibilities within which the working methods must be used.

Problem solving is the general term for the cognitive processes a person uses in an unfamiliar situation, which they do not already have an adequate working method or reference knowledge for dealing with. Planning and multi-tasking are also types of processing which are able to deal with situations which are not the same each time. However, both take existing working methods as their starting point, and either think about them as applied to the future, or work out how to interleave the working methods used for more than one task. In problem solving, a new working method is needed.

There are several ways of devising a new working method. Some are less formal techniques which do not use much cognitive processing, such as trial-and-error, or asking for help. There are also techniques which should not need much creativity, such as reading an instruction book.
People may otherwise use one of three techniques for suggesting a new working method. Each of these uses working methods recursively, it uses a general working method to build up a specific working method.
1.*Categorisation*. This involves grouping the problem situation with similar situations for which a working method is available. The working method which applies to this category of situation can then be used. This method is also called 'recognition primed decision making'. The nature of 'similarity' and the decisions involved are discussed by Klein (1989).

2. *Case-based reasoning*. This involves thinking of a known event (a 'case') which is similar or analogous to the present one, and adapting the method used then for use in the present situation. This is the reason why stories about unusual events circulate within an industry. They provide people in the industry with exemplars for what they could do themselves if a similar situation arose, or with opportunities to think out for themselves what would be a better solution.

3. *Reasoning from basic principles*. In the psychological literature, the term 'problem solving' may be restricted to a particular type of reasoning in which a person devises a new method of working by building it up from individual components (e.g. Eysenck and Keane, 1990, Chapters 11, 12). This type of processing may be called 'knowledge based' by some people.

A general problem solving strategy consists of a set of general cognitive functions, which have much in common with the basic cognitive functions in complex dynamic tasks (see introduction to this section). Problem solving for example could involve understanding the problem situation, defining what would be an acceptable solution, and identifying what facilities are available. Meeting each of these cognitive needs can be difficult, because the components need to be chosen for their appropriateness to the situation and then fitted together. This choice could involve : identifying what properties are needed from the behaviour; searching for components of behaviour which have the right properties (according to the meta-knowledge which the person has about them); and then combining them into a sequence.

The final step in developing a new working method is to test it, either by mental simulation, or by trial-and-error. This mental simulation could be similar to the techniques used in planning and multi-tasking. So working storage may be used in problem solving in two ways : to hold both the working method for building up a working method and the proposed new method; and to simulate carrying out the proposed working method to test whether its processing requirements and outputs are acceptable.

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F. Knowledge

Knowledge is closely involved in all modes of cognitive processing. Even in simple tasks, it provides the probabilities, utilities and alternatives considered in decision making, and the translations used in recoding. In complex tasks it provides the working methods and reference knowledge used in thinking about cognitive functions, and the meta-knowledge.
Different strategies may use different types of reference knowledge. For example, a strategy for diagnosing faults by searching the physical structure of the device uses one type of knowledge, while a strategy which relates symptoms to the functional structure of the device uses another. The reference knowledge may include scenarios, categories, cases, mental models, performance criteria, and other knowledge about the device the person is working with. Some knowledge may be used mainly for answering questions, for explaining why events occur or actions are needed. This basic knowledge may also be used in problem solving.

There are many interesting fundamental questions about how these different aspects of knowledge are structured, inter-related and accessed (Bainbridge, 1993b), but these issues are not central to this chapter. The main questions here are the relation between the type of knowledge and how it can best be displayed, and what might be an optimum general display format.

Knowledge and representation.
Any display for a complex task can show only a sub-set of what could be represented. Ideally, the display should make explicit the points which are important for a particular purpose, and provide a framework for thinking. The question of which display format is best for representing what aspect of knowledge has not yet been thoroughly studied, and most of the recommendations about this are assumptions based on experience (Bainbridge, 1988). For example, the following formats are often found :

Aspect of knowledge	*Form of display representation*
geographical position	map
topology, physical structure	mimic/schematic, wiring diagram
cause-effect, functional structure	cause-effect network, mass-flow diagram
task goal-means structure	hierarchy
sequence of events or activities	flow diagram
analogue variable values and limits	scale+ pointer display
evolution of changes over time	chart recording

Each of these aspects of knowledge might occur at several levels of detail, for example in components, sub-systems, systems, and the complete device. And knowledge can be at several levels of distance from direct relevance, for example it could be about a specific aircraft, about all aircraft of this model, about aircraft in general, about aerodynamics, or about physics.

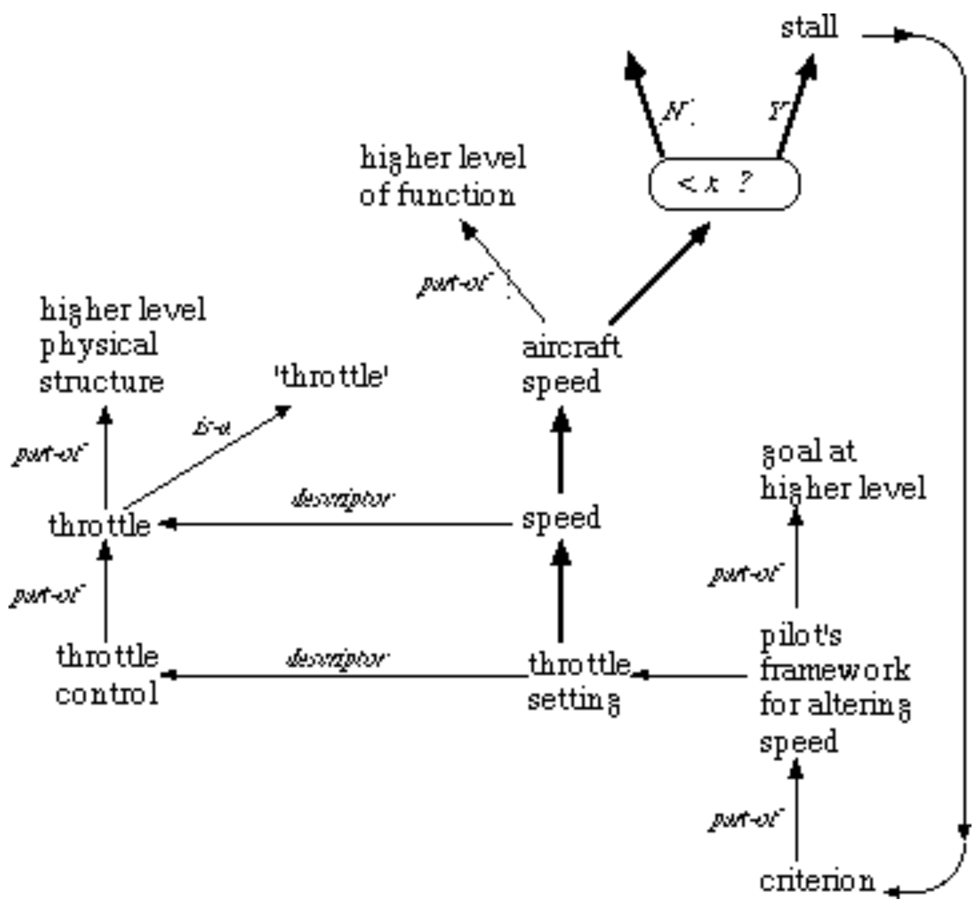

Figure 30 : Relations between different types of knowledge in a small part of a pilot's knowledge base (adapted from Bainbridge, 1991). 'Part-of' relations, 'is-a/category" relations, and cause-effect relations (shown by the thick arrows), are all interrelated.

Knowledge-display recommendations raise three sorts of question.
One arises because each aspect of knowledge is one possible 'slice' from the whole body of knowledge. All the types of knowledge are interrelated, but there is not a simple one-to-one relation between them. Figure 30 illustrates some links between different aspects of knowledge. Any strategy is unlikely to use only one type of knowledge, or to have no implications for aspects of thinking which use other types of knowledge. It might mislead the user to show different aspects of knowledge with different and separate displays which are difficult to cross-refer between, as this might restrict the thinking about the task. Knowledge about cross links is difficult to display, and is gained by experience. This emphasises training.

A second question is concerned with salience. Visual displays emphasise (make more salient) the aspects which can easily be represented visually. (For example, see the discussion at the end of the third section of this paper on the limitations of Figures 22 and 24 as models of behaviour.) It might be unwise to make some aspects of knowledge easy to take in simply because they are easier to display, rather than because they are important in the task. There are vital types of knowledge which are not easy to display visually, such as the associations used in recoding, or the categories, cases, scenarios, and meta-knowledge used in complex thinking. These are all learned by experience. The main approach to supporting non-visual knowledge is to provide the user with reminder lists about the alternatives (see below on cued recall). Display design and training are interdependent, as they are each effective at providing different types of knowledge. It could be useful to develop task analysis techniques which identify different aspects of knowledge, as well as to do more research on how types of knowledge, and the links between them, can best be presented.

The third issue about all these multiple possible display formats repeats the questions raised previously about efficient use of codes. If a user was given all the possible display types listed above, each of which would use different codes, possibly with different display formats using the same code with different meanings (for example a network with nodes could be used to represent physical, functional or hierarchical relations between items), the different codes might add to the user's difficulties in making cross connections between different aspects of knowledge.

An optimum format ? [cued recall]
These issues suggest the question : is there one or a small number of formats which subsume or suggest the others ? This is a question which has not yet been much studied.
A pilot study (Brennan, 1987) asked people to explain an event, given either a mimic or a cause-effect diagram of the physical device involved. The people tested either did or did not already know how the device worked. The results suggested that people who did not know how the device worked were most helped by a cause-effect representation (which does show how it worked), while experts were best with the mimic representation.
Contextual cues can greatly aid memory performance (e.g. Eysenck and Keane, 1990, Chapter 6). A cue is an aid to accessing the items to be recalled. The reason for expert performance with mimic displays might be that the icons and flow links on this type of display not only give direct evidence about the physical structure of the device, they also act as cues to or reminders about other knowledge the person has about the device - they evoke other parts of the scenario. This is an example from only one type of cognitive task, but it does point to the potential use of contextual cued recall in simplifying display systems. Cued recall can however only be effective with experienced people, who can recognise the cues and know what they evoke.

III. Mental workload, learning, and errors

Workload, learning, and errors are all aspects of the efficiency of cognitive processing. There are limits to human processing capacities but these are difficult to define, because of the adaptability of human behaviour. As a result of learning, processing becomes more efficient and adapted to what is required. As efficiency increases, so mental workload may decrease. Error rates can be affected by both expertise and workload, and errors are closely involved in the processes of learning. There is a huge wealth of material which could be discussed, so the aim here is only to give a brief survey.

A. Mental Workload

There is a large number of issues involved in accounting for mental workload and how it is affected by different aspects of a task. This section will mention three main topics : whether people can only do one task at a time; factors affecting processing capacity; and the ways in which people typically respond to overload.

1. Single or multi-channel processing

Many types of evidence, including the example of multi-tasking in Figure 29, show that people usually do one task at a time. This section will look at how people attend to one source of stimuli among many, and under what circumstances people can do more than one task at a time. As usual, the findings show how adaptable human beings are, and that there is not yet a full account of the processes involved.

Focused attention

People have the ability to pick out one message against a background of others, visual or auditory. Studies show however that a person does not only process one of the stimulus sources, but takes in enough about the other possible signals to be able to separate them. This chapter has already used the notion of 'depth' of processing, as in discrimination, recoding, sequences of recoding, and building up an overview. This notion is also involved here. Separation of two signal sources requires the least processing if they can be discriminated by physical cues, such as listening to a high voice while a low voice also speaks, or reading red lettering against a background of green letters. The sorts of factors discussed in Section I on discrimination affect how easy it is to do this separation. If stimuli cannot be distinguished by physical cues, then 'deeper' processing may be involved. For example, Gray and Wedderburn (1960) found that messages presented to the ears as :

left ear	:	mice	5	cheese
right ear	:	3	eat	4

were heard as 354 mice eat cheese

In that case, the items might be grouped by recognising their semantic category.

In some tasks 'deeper' processing for meaning may be needed, that is, building up an overview.
Try reading the **bold** words in this passage [this test was originally done using colour, which is more effective] :

It is important that the subject man **be** car **pushed** house **slightly** boy **beyond** hat **his** shoe **normal** candy **limits** horse **of** tree **competence** pen **for** be **only** in **phone** this **cow** way **book** can **hot** one **tape** be **pin** certain **stand** that **snaps** he **with** is **his** paying **teeth** attention **in** to **the** the **empty** relevant **air** task **and** hat **minimal** shoe **attention** candy **to** horse **the** tree **second or peripheral task**.
(from Lindsay and Norman, 1972)

Note that if the cue used becomes ineffective, this is disconcerting. It then takes time, and a search for clues about what would be effective, before the person can orient to a new cue and continue with the task. There is also an interplay of 'depths' of processing : when the physical cue becomes inadequate for following the message, then the reader uses continuity of meaning as a basis for finding a new physical cue. This account fits in with several points made earlier. The person is using active attention for what they want to take in, not passive reception of signals. The task setting provides the cue which can be used to minimise the effort needed to distinguish between signal sources. This cue then acts as a perceptual frame for searching for relevant inputs.

The concept of 'depth' of processing was first introduced by Craik and Lockhart (1972) to explain results in some memory experiments. The word 'depth' is in inverted commas here to distinguish it from depth in the organisation of behaviour, as in goal/ sub-goal, etc.

Parallel processing
The criteria defining whether or not people are able to do two tasks at the same time have so far proved elusive to identify.
Figure 16 shows that, after high levels of practice, choice time is not affected by number of alternatives. Such tasks are said to be 'automated', or to require 'no conscious attention'. They can be done at the same time as something else, unless both tasks use the same peripheral resources such as vision or hand movement. Wickens (e.g. 1984) has done a series of studies showing that people can use different peripheral resources at the same time. People can also learn to do some motor tasks so that movements are monitored by feel rather than visually; then movements can be made at the same time as looking at or thinking about something else.
In practice the possibility of multiple processing means that care is needed in designing tasks. One might, for example, think it would reduce unnecessary effort for an air traffic controller to have the flight strips printed out, rather than expecting the controller to write the strips by hand. However if the controller, while writing, is simultaneously thinking out how the information fits into their overview, then printing the flight strips might deprive them of useful attention and thinking time.

Whether or not two tasks which both involve 'central' processing can be done at the same time is less clear. This is partly because what is meant by 'central' processing has not been clearly defined. People can do two tasks at the same time if the tasks are processed by different areas of the brain, for example a music task and a language task (Allport, Antonis and Reynolds, 1972), though both tasks need to be simple and perhaps done by recoding. Going to 'deeper' levels of processing, there does seem to be a limit to the extent to which people can build up distinct overviews for two different tasks at the same time. Whether or not an overview is needed to do a task may be part of the question. As a couple of anecdotal examples : people playing multiple chess games may have very good pattern recognition skills and so react to each game by recognition primed decisions as they return to it, rather than having to keep in mind a separate and continuing overview for each of the games they are playing. Most experienced drivers can drive and hold a conversation on a different topic at the same time, when the driving task is simple, but they stop talking when the driving task becomes more difficult.

This is an area in which it is challenging to identify the limits to performance, and it is probably beyond the competence of HF/E at the moment, either to define the concepts, or to investigate and measure the processing involved. Fortunately in practice the issue can often be simplified. When predicting performance, the conservative strategy is to assume that people cannot do two tasks at the same time. This will always be the worst case performance.

2. Factors influencing processing capacity

The amount of mental work a person can do in a given time is not a simple quantity to specify. If it is assumed that a person can only do one thing at a time, then every factor which increases the time taken to do a unit task will decrease the number of those tasks which can be done in a given time interval, and so decrease performance capacity. So every factor in interface design might affect performance capacity.

Focusing on performance time emphasises performance measures of workload effects. Other important measures of workload are physiological, such as the rate of secretion of stress chemicals, and subjective, such as moods and attitudes. Any factor could be considered a 'stressor' if its effect is that performance levels, stress hormone secretion rates, or subjective feelings, deteriorate. The approach in this section will be to indicate some key general topics, rather than to attempt a full review.
The points made here are concerned with : the capacities of different mental processes; extrinsic and intrinsic stressors; individual differences; and practical implications.

Capacities of different cognitive resources

Different aspects of cognitive processing have different capacities. For a review of processing limits see Sage (1981). The capacity of different processes may be affected differently by different factors. Figure 31 shows time-of-day effects on performance in four tasks : serial search, verbal reasoning (working memory) speed, immediate retention, and alertness. The different performance trends in these tasks suggests that each task uses a different cognitive resource which responds differently to time-of-day stress. It is difficult to make reliable analyses of these differences, but some other tasks in which performance may differ in this way are coding and syllogisms (Folkhard, 1990).

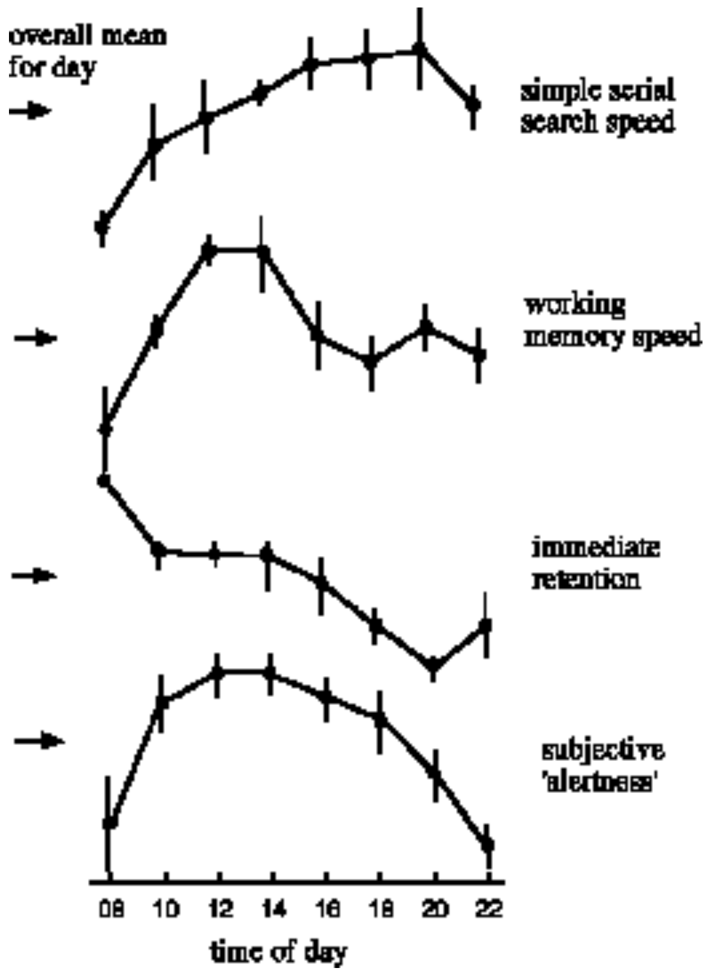

Figure 31 : Time-of-day effects show a different pattern in four different tasks, suggesting that these tasks all use different processing resources (Folkhard, 1990)
[horizontal scale - time of day, vertical scale - performance achieved in this task.]

Extrinsic and intrinsic stressors
Extrinsic stressors are stressors which apply to any person working in a particular environment, whatever task they are doing. Time-of-day, as in Figure 31, is extrinsic in this sense. Some other extrinsic stressors which can affect performance capacity are noise, temperature, vibration, fumes, and organisational culture.

Intrinsic stressors are factors which are local to a particular task. All the HF/E factors which affect performance speed or accuracy come in this category.

The effect of task difficulty interacts with motivation. Easy tasks may be done better with high motivation, while difficult tasks are done better at lower levels of motivation. This can be explained by assuming that stressors affect a person's 'arousal' level, and that there is an inverted-U relation between arousal level and performance, see Figure 32.

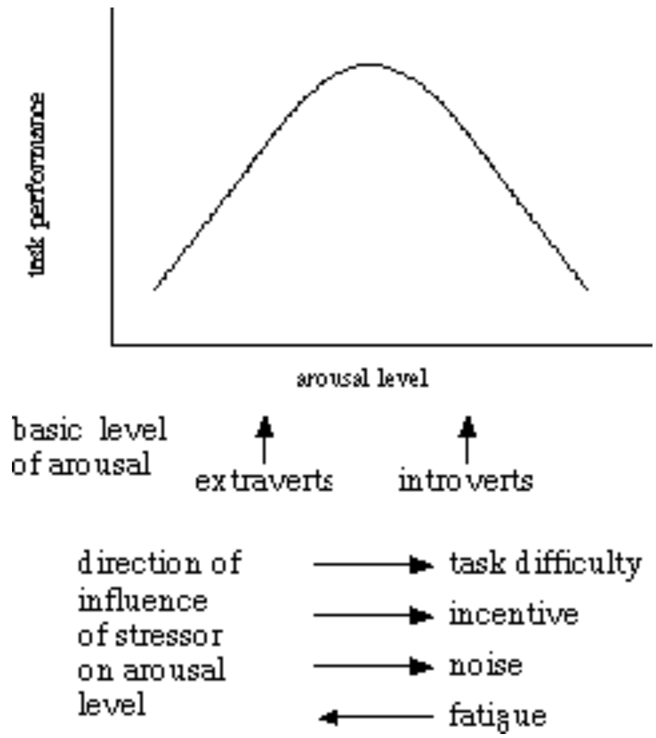

Figure 32 : An 'inverted U' relation between arousal level and task performance, and the effect of various stressors (only some stressors can be accounted for in this way).

Measures of stress hormones and of workforce attitudes show that several factors to do with the pacing of work, and the amount of control over their work that a person feels they have, can be stressors (e.g. Johansson, Aronsson and Linström, 1978). Such aspects are of more concern in repetitive manufacturing jobs than in work such as flying or air traffic control.

Individual differences

Individual differences affect a person's capacity for a task, and their willingness to do it. Aspects of individual differences fall into at least five groups.

1. Personality. Many personality dimensions, such as extroversion/ introversion, sensitivity to stimuli, need for achievement or fear of success, and preference for facts/ ideas or for regularity/ flexibility, can affect a person's response to a particular task.
2. Interests and values. A person's interests and values affect their response to various factors in the task and the organisational climate, which influence their willingness and commitment to do or learn a given task. People differ in their response to incentives or disincentives such as money, power, status, or transfer to a job which does not use their skills.
3. Talent. Different people have different primary senses, different cognitive styles, and different basic performance abilities (e.g. Fleishman, 1975). For example, very few of us have the ability to fly high-speed aircraft.
4. Experience. The rest of us may be able to develop higher levels of performance though practice. Even the few who can fly high-speed aircraft have millions spent on their training. The effects of training on cognitive capacities will be discussed more in the section below on learning.
5. Non-work stressors. There may be non-work stressors on an individual which affect their ability to cope with their work, such as illness, drugs, or home problems.

Practical implications
There are so many factors affecting the amount of effort any particular individual is able or willing to devote to a particular task at a particular time, that performance prediction might seem impossible. Actually the practical ways of dealing with this variety are familiar. There are two groups of issues, in HF/E design and in performance prediction.

Nearly all HF/E design recommendations are based on measures of performance capacity. Any factor which has a significant effect on performance should be improved, as far as is economically justifiable. Design recommendations could be made about all the intrinsic and extrinsic factors mentioned above, and individual differences might be considered in selection.

However it is easier to predict that a design change will improve performance than to predict the size of the improvement. Numerical performance predictions may be needed in order to assess whether a task can be done in the time available, or with the available people, or to identify the limits to speed or accuracy on which design investment should best be concentrated. Obviously it is not practical to include all the possible effective factors when making such predictions. Three simplifying factors can reduce the problem.

One is that, while smaller performance changes may give important clues about how to optimise design, from the point of view of performance prediction these factors may only be important if they make an order of magnitude difference to performance. Unfortunately our data relevant to this issue are far from complete.

The second point is that only conservative performance predictions are needed. For these purposes it may be valid to extrapolate from performance in simple laboratory tasks in which people with no relevant expertise react to random signals, which is the worst case. To predict minimum levels of performance, it may not be necessary to include the ways in which performance can improve when experienced people do tasks for which they know the redundancies, can anticipate, etc.

The third point is that, in practice, many of the techniques for performance prediction which have been devised have the modest aim of matching expert judgements about human performance in a technique which can be used by someone less expert, rather than attempting high levels of accuracy or validity.

3. Response to overload
If people doing a simple task have too much to do, they only have the options of omitting parts of the task or of accepting a lower level of accuracy in return for higher speed (Figure 18). People doing more complex tasks may have more scope for responding to increased workload while maintaining acceptable task performance. This section will discuss : increasing efficiency; changing strategy; and practical implications.

Increasing efficiency
Complex tasks often offer the possibility of increasing the efficiency with which a task is done. For example, Sperandio (1972) studied the radio messages of air traffic approach controllers. He found that when they were controlling one aircraft they spent 18% of their time in radio communication. When there were nine aircraft, they spent 87% of their time on the radio. In simple models of mental workload :
total workload = workload in one task x *number of tasks*

Evidently that relation does not apply here, or the controllers would spend 9 x 18 = 162% of their time on the radio.
Sperandio found that the controllers increased the efficiency of their radio messages in several ways. There were fewer pauses between messages. Redundant and unimportant information were omitted. And conversations were more efficient : the average number of conversations per aircraft decreased but the average number of messages per conversation increased, so fewer starting and ending procedures were necessary.

Changing strategy
The controllers studied by Sperandio *op cit* did not only alter the efficiency of their messages, the message content also altered. The controllers used two strategies for bringing aircraft into the airport (this is a simplification so the description can be brief). One strategy was to treat each aircraft individually. The other was to standardise the treatment of aircraft by sending them all to a stack at a navigation fix point, from which they could all enter the airport in the same way. When using the individual strategy, the controllers asked an aircraft about its height, speed, and heading. In the standard strategy they more often told an aircraft what height and heading to use. The standard strategy requires less cognitive processing for each aircraft. Sperandio found that the controllers changed from using only the individual strategy when there were three or fewer aircraft, to using only the standard strategy when there were eight or more aircraft. Expert controllers changed their strategy at lower levels of workload. Sperandio argued that the controllers change to a strategy which requires less cognitive processing, in order to keep the total amount of cognitive processing within achievable limits, see Figure 33A.

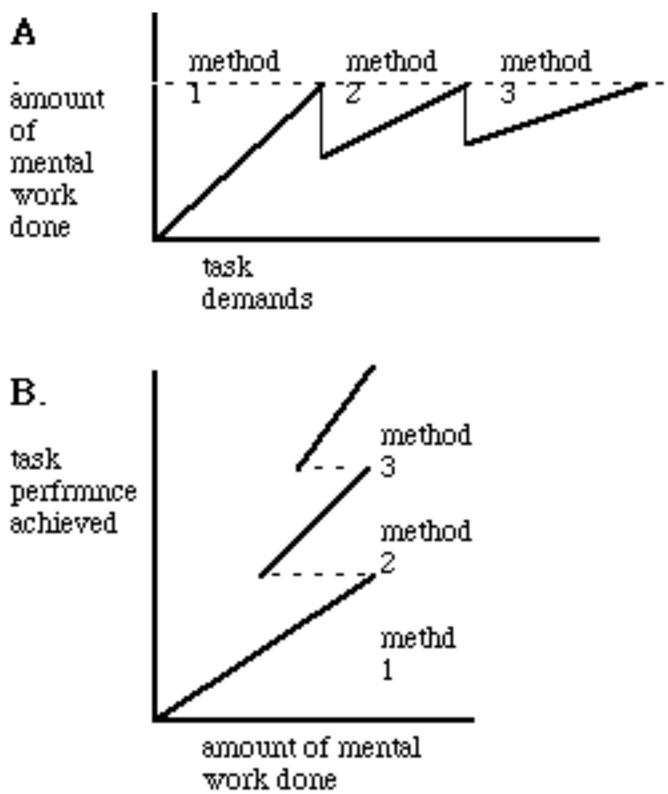

Figure 33 : The effect of changing task strategy on the mental workload experienced, and task performance achieved (Figure A from Sperandio, 1972). The figure is a simplification, in practice the use of methods overlap so there are not discontinuities.

The relation between task performance and workload is therefore not the same in mental work as it is in physical work. In physical work, conservation of energy ensures there is a monotonic relation between physical work and task performance. In mental workload, if there are alternative working methods for meeting given task demands, then there is not necessarily a linear relation between the task performance achieved and the amount of mental work needed to achieve it. By using different methods, the same amount of mental effort can achieve different amounts of task performance, see Figure 33B.

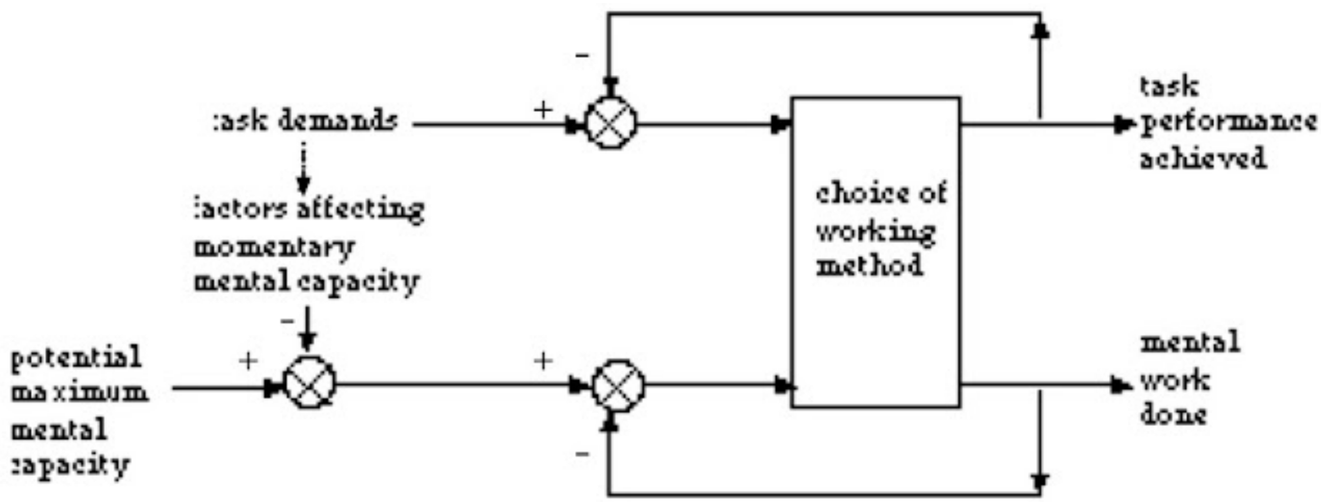

Figure 34 : Adaptation of choice of strategy to achieve a balance between task demands and mental capacities (Bainbridge, 1974).

In choosing an optimum working method, two adaptations are involved. A person must choose a method which meets the task demands (upper feedback loop in figure). The person must also choose a method which maintains mental workload at an acceptable level (lower loop). Whichever method is chosen will affect both the task performance achieved and the mental workload experienced, as indicated in Figure 34.
There needs to be a mechanism for this adaptive choice of working method. This is another contextual effect which could be based on meta-knowledge. Suppose that the person knows, for each method, both how well it meets various task demands and what mental workload demands it poses. The person could then compare this meta-knowledge with the demands of the task and mental context, to choose the best method for the circumstances (Bainbridge, 1978).

Practical implications
This flexibility of working method has several practical implications. It is not surprising that many studies have found no correlation between task performance and subjective experience of mental workload. There are also problems with predicting mental workload, similar to the problems of predicting performance capacity mentioned above.

A person can only use several alternative working methods if the performance criteria do not strictly constrain what method must be used. For example, in air traffic control, safety has much higher priority than the costs of operating the aircraft. Task analysis could check that alternative methods are possible, and perhaps what these methods are (it may not be possible to pre-define all methods, see Section II on problem solving and below on learning).

Adaptive use of working methods suggests that strategy specific displays should not be provided, as they could remove the possibility of this flexibility for dealing with varying levels of workload. It could also be useful to train people to be aware of alternative methods and of the use of meta-knowledge in choosing between them.

When decision support systems are introduced with the aim of reducing workload, it is necessary to consider a wider situation. Decision support systems can increase rather than decrease mental workload, if the user does not trust the decision support system and so frequently checks what it is doing (Moray, Hiskes, Lee and Muir, 1995).

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B. Learning

Learning is another potentially huge topic. All the expertise of psychology on learning, of HF/E on training, and of educational psychology on teaching cognitive skills and knowledge, could be included. As this chapter focuses on cognitive processes, this section will primarily discuss cognitive skill and knowledge. The coverage will only attempt a brief mention of some key topics, which indicate how learning inter-relates with other aspects of cognitive processing rather than being a separate phase of performance.

This section will use the word 'skill' in the sense in which it is used in psychology and in British industry. There are two key features of skilled behaviour in this sense :
Processing can be done with increased efficiency, either because special task related abilities have been developed which would not be expected from the average person, or because no unnecessary movements or cognitive processing are used.
And behaviour is adapted to the circumstances. Choices, about what best to do next and how to do it, are adapted to the task and personal context.
In this general sense, any type of behaviour and any mode of cognitive processing can be 'skilled', so it can be confusing to use the word 'skill' as the name for one mode of processing.
This section will be in three main parts, with brief notes on : changes in behaviour with experience; learning processes; and relations between mode of processing and appropriate training method.

1. Changes within a mode of processing
This section will briefly survey the modes of processing which have formed one framework of this chapter, and indicate the ways in which each can change by introducing new aspects of processing or losing inefficient ones. This is a summary of points made before and is by no means complete. Learning can also lead to changes from one mode of processing to another, discussed later.

Physical movement skills. By carrying out movements in a consistent environment, people can learn :
- which movement has which effect (i.e. they develop their meta-knowledge about movements, Figure 20). This means they do not need to make exploratory actions, and their movements do not oscillate around the target. People can then act with increased speed, accuracy and co-ordination, and can reach to the correct control or make the correct size of action without checking.

People can also learn :
- to use kinaesthetic rather than visual feedback.
- the behaviour of a moving target, so its movements can be anticipated.
Changes in performance may extend over very long periods. For example Crossman (1959) studied people doing the manually dexterous task of rolling cigars, and found that performance continued to improve until people had made about five million items.

Perceptual skills : discriminations and integrations. People learn :
- the discriminations, groupings, and size, shape and distance inferences to make.
- the probabilities and biases to use in decision making.
- the appropriate items to attend to.
- the eye movements needed to locate given displays.

Re-codings. The person connects from one item to another by association, without intermediate reasoning. These associations may need to be learned as independent facts, or there may be some general rule underlying a group of re-codings, such as 'choose the control with its location opposite to the location of the display'. Many people need a large number of repetitions before they can learn arbitrary associations.
Sequence of re-codings. Two aspects of learning may be involved :
- when a sequence is the same each time, so that the output of one recoding and the input of the next recoding are consistent, then a person may learn to 'chunk' these re-codings together, to carry them out as a single unit without using intermediate working memory.
- when a goal/ function can be met in the same way each time, then choosing a working method which is adapted to circumstances is not necessary. A previously flexible working method may then reduce to a sequence of transforms which does not include goals or choice of working method.

Familiar working methods. People need to learn :
- appropriate working method(s).
- the reference knowledge needed during use of each method. When this reference knowledge has been learned while using the method, then it may be accessed automatically, without having to think out explicitly what knowledge is needed in a particular situation.
- how to build up an integrated overview.
- meta-knowledge about each working method, which is used in choosing the best method for a given context.

Planning and multi-tasking. People can become more skilled in planning and multi-tasking. They can learn a general method for dealing with a situation, and the subsidiary skills for dealing with parts of it (Samurçay and Rogalski, 1988).

Developing new working methods. The process of developing new working methods can itself be more or less effective. Skill here lies in taking an optimum first approach to finding a new working method. There are several possible modes of processing for doing this.

Recognition primed decisions. People can only make recognition primed decisions about which working method to use once they have learned the categories of working method. Several aspects of learning are involved :
- the features defining a category, and how to recognise that an instance has these features so is a member of the category.

- the members of a category, and their properties (such as, for each category of situation : what to do in it).
- how to adapt a category method to specific circumstances.

Case based reasoning. Cases (or, more distant from a particular task, analogies) provide examples as a basis for developing the knowledge or working method needed. To be able to do this, people need to know :
- cases,
- how to recognise which case is appropriate to which circumstances.
- how to adapt the method used in one case to different circumstances.

Reasoning from basic principles. For this sort of reasoning, people need to have acquired an adequate base of knowledge about the task and the device(s) they are using, with associated meta-knowledge. The same type of knowledge may also be used for explaining both events and actions.

2. Learning processes

Little is know about how changes in processing take place during learning, except for the very simplest. Similar processes may be involved in developing and maintaining physical and cognitive skills. This section will indicate some mechanisms : repetition; meta-knowledge and feedback; independent goals-means; and changing modes of processing.

Repetition

Repetition is crucial for acquiring and maintaining skills. The key aspects are that, each time a person repeats a task : some aspects of the environment are the same as before, and knowledge of results is given. This knowledge of results has two functions : it gives information about how and how well the task was done, and it acts as a reward.

Meta-knowledge and feedback

As described in Section I on movement execution, learning of motor skills involves learning both how to do an action and meta-knowledge about the action. Actions have associated expectations about their effect (meta-knowledge). Feedback about the actual effect provides information which can be used to refine the choice made next time (Figure 20). So, during learning, feedback is used both to revise the present action and to revise the choice of next action.

Choosing an action instruction on the basis of meta-knowledge is a similar process to choosing the working method used to maintain mental workload at an acceptable level. The choice of working method involves checking meta-knowledge about each method, to find which method has the properties best suited to the present situation.
A similar process is also involved when developing a new cognitive working method : a person develops a working method, hoping (on the basis of a combination of meta-knowledge and mental simulation) that it will give the required result, and then revises the method on the basis of feedback about the actual effectiveness of what they do.

Independent goals-means

In coping with mental workload, and in developing cognitive processes while learning, several working methods may be used for meeting the same function/ goal. Also the same behaviour may be used to meet several goals. So the link between goal and means must be flexible. The goal and means are independent in principle although, after learning, particular working methods may become closely linked to particular goals. In the section above on workload, the goal-means link was described as a point at which a decision between working methods is made on the basis of meta-knowledge.

It is generally the case (Sherrington, 1906) that behaviour at one level of organisation transfers information about the goal to be met, and constraints on how it should be met, to the lower levels of behaviour organisation by which the goal is met, but not detailed instructions about how to meet it. How to carry out the function is decided locally, in the context at the time. As behaviour is not dictated from above, but has local flexibility, human beings are not by nature well suited to following standardised procedures.

Changes in the mode of processing

Learning does not only lead to changes within a given mode of processing. A person may also change to a different mode of processing. If the task is consistent, then a person can learn to do the task in a more automatic way, that is by using a simpler mode of processing. Inversely, when there is no fully developed working method or knowledge for meeting a given goal/ function then it is necessary to devise one. So the possibility or need for developing a simpler or more complex mode of processing depends both on a person's experience with the task, and on the amount and types of regularity in the task. It may be possible, through learning, to change from any mode of processing to any other mode of processing, but two types of change are most typical : from more complex to simpler processing, or vice versa.

Someone may start a new task by developing a working method. But once they have had an opportunity to learn the regularities in the task, the processing may become simpler. If the task and environment are sufficiently stable, the person may learn that making a choice between methods to meet a goal, or to search for appropriate knowledge, are not necessary. In familiar stable situations, the working method may become so standardised that the person using it is not aware of goals or choices.

Alternatively, someone may start by learning parts of a task, and gradually become able to organise them together into a wider overview, or become able to choose behaviour which is compatible with several cognitive functions. These changes depend on changes in processing efficiency. When someone first does a complex task, they may start at the lowest levels of behaviour organisation, learning components of the task which will eventually be simple but which at first require all the person's problem solving, attention and other processing resources. As the processing for doing these sub-tasks becomes simpler with learning, this releases processing capacity. This capacity can then be used for taking in larger segments of the task at the same time, so the person can learn about larger regularities in the task.

In general any cognitive function, and any sub-goal involved in meeting it, may be met by any mode of processing, depending on the person's experience with the task, and the details of the circumstances at the moment. A task can become 'automated' or flexible at any level of behaviour organisation, depending on the repetitions or variety of situations experienced. So in some tasks a person may learn to do the perceptual-motor components automatically but have to rethink the task each time at a higher level, as in a professional person using an office computer. In other tasks, 'higher' levels of behaviour organisation such as planning may become automated while lower levels remain flexible, as in driving to work by the same route every day. It is not necessarily the case that 'higher' levels of behaviour organisation are only done by more complex modes of processing such as problem solving, or vice versa.

As any of the main cognitive functions in a task could become so standardised that they are done automatically or unconsciously, this is the origin of so-called 'short cuts' in processing. Inversely, at any moment, a change in the task situation, such as a fault, may mean that what could previously be done automatically now has no associated standard working method, so problem solving is needed to find one. At any time, or at any point in the task, there is the potential for a change in the mode of processing. So care is needed, if an interface design strategy is chosen of providing displays which support only one mode of processing.

3. Some training implications

Gagné (e.g. 1977) first suggested the concept that different modes of processing are best developed by different training methods. It is not appropriate to survey these methods here, but some general points link to the general themes of this chapter.

Simple processes

Training for simple processes needs to :
- maximise the similarity to the real task (the transfer validity) of discriminations, integrations and re-codings which are learned until they become automatic, by using high-fidelity simulation.
- minimise the need for changes in mode of processing during learning, by presenting the task in a way which needs little problem solving to understand.
- ensure that trainees retain a feeling of mastery, as part of their meta-knowledge about the task activities, by avoiding training methods in which errors are difficult to recover from, and by only increasing the difficulty of the task at a rate such that trainees continue to feel in control.

Complex processes

Tasks which involve building up an overview and using alternative strategies need more than simple repetition if they are to be learned with least effort. The status of errors is different in learning complex tasks. In training for simple discriminations, recodings, and motor tasks, the emphasis is on minimising the number of errors made, so that wrong responses do not get associated with the inputs. By contrast, when learning a complex task, an 'error' can have positive value as a source of information about the nature and limits of the task. So in learning complex tasks, the emphasis should be more on exploring the possibilities without negative consequences, in order to develop a variety of working methods and wide knowledge of the task alternatives. Flexibility might be encouraged by giving trainees :
- guided discovery exercises, in which the aim is to explore the task rather than to achieve given aims.
- recovery exercises in which people practise recovering from non-optimal actions.
- problem solving and planning exercises, with or without real time pressures.
- opportunities to share the discoveries made with other trainees.
- practise with considering alternative working methods, and with assessing the criteria for choosing between them.
- practise with thinking about alternative 'hypotheses' for the best explanation of events, or the best action.
- practise with multi-tasking.
- practise with using different methods for developing working methods, and with the case examples and recognition categories used.

A feature of cognitive skill is having a knowledge base which is closely linked to the cognitive processing which uses it, so that the knowledge is appropriately organised and easy to access. This suggests that knowledge is best learned as part of doing the task, not separately.

Training as part of system design
This chapter has mentioned several ways in which training needs interact with the solutions chosen for other aspects of the system design :
- the quality of interface or procedure design and the need for training may be inversely related.
- skills are lost if they are not maintained by practice, so the amount of continuing training needed may be related to the extent of automation.

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C. Difficulties and errors

Errors occur when people are operating at the limits of modes of processing. Errors result from misuse of normally effective processes. The concept of relating error types to modes of processing was first suggested by Rasmussen (1982), though the scheme suggested here is somewhat different.
There are several points, which the approach to complex tasks taken in this chapter suggests should be added to most error schemes.
Firstly, the notion of 'error' needs to be expanded. In some simple tasks such as recoding it is possible to be wrong. But in control tasks and in complex tasks it is useful to think in terms of difficulty, or lowered effectiveness, rather than focusing on being wrong. For example, Amalberti's novice pilots (Figure 28) were already qualified. They completed the task, they just did it less effectively than the more experienced pilots. So, as a basis for supporting people doing complex tasks, it is useful to look at factors which make the task more difficult, as well as factors which slow behaviour down or increase errors.

Secondly, many error schemes assume that task behaviour can be broken down into small independent units, each of which may be right or wrong. In Probabilistic Risk Assessment or Human Reliability Assessment techniques, behaviour is segmented into separate units. A probability of error is assigned to each unit, and the total probability of human error for the combined units is calculated by addition or multiplication. But this chapter has stressed that human behaviour in complex tasks does not consist of independent units. The components of complex behaviour are organised into an integrated interdependent structure. This means that, while PRA/HRA techniques are useful for practical purposes, any attempt to increase their fundamental validity while retaining an 'independent units' model of behaviour is doomed to failure (Hollnagel, 1993).

Thirdly, as the processes of building up and using an overview are often not included in models of human processing, the related errors are also often not discussed, so they will be the focus here. This section will briefly suggest some of the ways in which performance can be weaker (for examples, see Bainbridge, in press).

Discriminations
Decisions made under uncertainty cannot always be right, and are more likely to be wrong if the evidence on which they are based is ambiguous or incomplete. Incorrect expectations about probabilities, and incorrect biases about payoffs can also increase error rates. People make errors such as : misattributing risk, importance or urgency; ignoring a warning which is frequently a false alarm; or seeing what they expect to see. Some people when under stress refuse to make decisions involving uncertainty.

Re-codings
There are many sorts of error which can be attributed to mis-translations. Sometimes the person does not know the coding involved. People are more likely to make coding errors when they have to remember which specific code translation to use in which circumstances. Difficult codes are often ambiguous or inconsistent. The salience of some stimuli may give improper emphasis to them or to their most obvious meaning.

Sequences
The items which need to be retained in working memory during a sequence of behaviour may be forgotten within half a minute, if other task processing distracts or interrupts the rehearsal needed to remember the items.
In an overlearned sequence, monitoring/ supervision of parts of the activity may be omitted. This can lead to 'slips' in performance, or to rigid behaviour which causes difficulties when the environment changes and adaptive behaviour is needed.

Overview and behaviour organisation
There may be errors in organising the search for information. People may only attend to part of the task information, fail to keep up-to-date with changes in the environment, or look at details without taking an overall view. They may not get information which there is a cost on getting. They may only look for information which confirms their present interpretation of the situation ('confirmation bias'). In team work, people may assume without checking that another member of the team, particularly someone with higher status, has done something which needed doing.

There may also be errors in the allocation of time between tasks, which may lead to omissions or repetitions. People may react to events rather than anticipating events and how to deal with them. They may not apply available strategies in a systematic way. They may shift between sub-tasks, without relating them to the task as a whole ('thematic vagabonding', Doerner, 1987). They may break the task down into sub-problems in an inadequate way, or fail to devise intermediate sub-goals, or they may continue to do parts of the task which they know how to do ('encystment', Doerner *op cit*). Under high workloads, people may delay decisions in the hope that it will be possible to catch up later, or they may cycle through thinking about the task demands without taking any action.

The person’s overview influences their biases about what will happen, and what to do about it. If the overview is incorrect this can lead to inappropriate behaviour or expectations. People who have completed a sub-task, and so completed a part of their own overview, may fail to tell other members of the team about this. Once people have built up a complete and consistent overview, it may be difficult to change it when it turns out to be inadequate ('perceptual set'). The overview may also be lost completely if a person is interrupted.

Use of knowledge
People's knowledge of all types may be incomplete or wrong, so they make incorrect inferences or anticipations. There may be problems with assumed shared knowledge in a team, if team members change.

A person may have an incorrect or incomplete representation of the device they are using. For example, they may not know the correct causalities or interactions, or they may not be able to represent correctly the development of events over time. Or someone may use an inappropriate category in recognition primed decisions or in case based reasoning.

Knowledge about probabilities may be incorrect, or used wrongly. People may be under or over confident. They may have a 'halo effect', attributing the same probabilities to unrelated aspects. They may give inappropriate credence to information or instructions from people of higher status. Different social groups, for example unions, management, and the general public, may have different views on the risks and payoffs of particular scenarios.

This list of human weaknesses should not distract from two important points. One is that people can be good at detecting their errors and recovering from them, if they are given an interface and training which enable them to do this. So design to support recovery should be included in cognitive task analysis.

The second point is that care is needed with the attribution of responsibility for faults. Although it may be a given individual who makes an error, the responsibility for that error may be attributed elsewhere, to poor equipment design or poor system design (training, workload, allocation of function, teamwork, organisational culture).

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CONCLUSION

There are several integrative concepts in this chapter.

Cognitive goals : in complex tasks people use cognitive goals when implementing task goals. A person's cognitive goals are important in organising their behaviour, in directing attention to parts of the task, in choosing the best method for meeting a given task goal, and in developing new working methods. The cognitive goals might be met in different ways in different circumstances, so the goals and the processes for meeting them can be independent. For example, flying an aircraft involves predicting the weather, and this may be done in different ways before and during the flight.

Contextual overview : in complex tasks people build up an overview of understanding and planning, which then acts as the context for later activity. The overview provides data, expectations and values, and the criteria for deciding what would be the next best thing to do and how to do it.

Goal-means independence and meta-knowledge : Meta-knowledge is knowledge about knowledge, such as the likelihood of alternative explanations of what is happening, or the difficulty of carrying out a particular action. Alternative working methods have associated with them meta-knowledge about their properties. Decisions about how best to meet a particular aim are based on meta-knowledge, and are involved in :

- adapting behaviour to particular circumstances,
- the control of multi-tasking and mental workload,
- learning.

Modes of processing : As well as using different working methods, people may use different modes of processing, such as knowing the answer by association or thinking out a new working method. The mode of processing used varies from moment to moment, depending on the task and the person's experience.

Modelling human behaviour

Basing HF/E on an analysis of behaviour into small independent units fits well with a 'sequential stages' concept of the underlying structure of human behaviour. But a sequential stages model does not include many of the key features of complex tasks such as flying and air-traffic control. Complex behaviour is better described by a contextual model, in which processing builds up an overview which determines what processing is done next and how, which in turn updates the overview, and so on. In this mechanism for behaviour organisation, choices about what to do and how to do it depend on details of the immediate situation interacting with the individual's nature and previous experience.

The aspects missing from many sequential stages models are :

- the goal oriented nature of behaviour, and the independence of goals from the means by which they are met.
- the continuing overview.
- the flexible sequencing of cognitive activity, and the organisation of multi-tasking.
- the knowledge base, and the resulting predictions, anticipations and active search for information which are part of top-down processing ['top down' means starting from knowledge rather from environmental stimuli].

Some of these aspects require a fundamental change in the nature of the model used. The most important aspect to add is the overview, as cognitive processes in complex tasks are done within the context provided by this overview, and the sequence in which they are done is determined by what is in the overview.

A simple version of a contextual model has been suggested in Figure 22 and Figure 24. These figures can act as an aide-memoire about contextual processing, but any small diagram can only indicate some features of what could be involved. These simple figures do not make explicit important aspects such as:
- risky decision making and the effects of biases.
- goal orientation of behaviour.
- typical sequences of activity.
- different modes of processing, including devising new working methods.
- use of meta-knowledge.

Perhaps the most important disadvantage of the one page contextual model will be felt by people who are concerned with tasks which are entirely sequential, rather than cyclic as in flying or air-traffic control. But I would argue that, although dependencies may define the order in which some parts of a task are done, it could still be useful, when designing to support sequential tasks, to consider the task sequence as a frame for structuring the overt behaviour, while the underlying order of thinking about task aspects may be more varied (cp. Figure 28).

The difficulty of HF/E

Contextual processing underlies two types of difficulty for HF/E.

One group of issues is concerned with HF/E techniques. As indicated above, the overview suggests the need for several additions to HF/E techniques :
- consider the codings used in the task as a whole, rather than for isolated sub-tasks.
- orient cognitive task analysis towards the cognitive goals or functions to be met, as an intermediary between the task goals and the cognitive processing. (Analysing either goals or working methods alone is necessary but not sufficient.)
- design the interface, training, and allocation of function between people and machines, to support the person's development and use of the contextual overview, alternative strategies, and the processes involved in the development of new working methods.
- extend human error schemes to include difficulties with the overview and with the organisation of sequences of behaviour.

The second group of issues is concerned with a fundamental complexity problem in human behaviour and therefore in HF/E. Human behaviour is adapted to the particular circumstances in which it is done. This does not make it impossible to develop a general model of human behaviour, but it does make it impossible to predict human behaviour in detail. Predicting human behaviour is like weather prediction : it is not possible to be right, but it is possible to be useful. Any HF/E answer is always going to be context sensitive. The continuing complaints of HF/E practitioners, that researchers do not provide them with what they need, are a consequence of the fundamental nature of human behaviour. Specific tests of what happens in specific circumstances will always be necessary. What models of human behaviour can provide is, not the details, but the key issues to focus on when doing such tests or when developing and applying HF/E techniques.

References

Allport, D.A., Antonis, B., and Reynolds, P. (1972). On the division of attention : a disproof of the single channel hypothesis. Quarterly Journal of Experimental Psychology, 24, 225-235.
Amalberti, R., (1992). Modèles d'activité en conduite de processus rapides : implications pour l'assistance á la conduite. Unpublished PhD Thesis, University of Paris 8.
Atkinson, W.H., Crumley, L..M., and Willis, M.P. (1952). A study of the requirements for letters, numbers and markings to be used on trans-illuminated aircraft control panels. Part 5 : the comparative legibility of three fonts for numerals. Naval Air Material Center, Aeronautical Medical Equipment Laboratory, Report TED NAM EL-609, part 5.
Bailey, R.W. (1989). Human performance engineering : A guide for system designers (2nd ed.). London : Prentice Hall.
Bainbridge, L. (1974). Problems in the assessment of mental load. Le Travail Humain, 37, 279-302.
Bainbridge, L. (1978). Forgotten alternatives in skill and workload. Ergonomics, 21, 169 185.
Bainbridge, L. (1983). Ironies of automation. Automatica, 19. 775-779.
Bainbridge, L. (1988). Types of representation. In L.P. Goodstein, H.B. Anderson and S.E. Olsen (Eds.), Tasks, errors and mental models (pp. 70-91). London : Taylor and Francis Ltd.
Bainbridge, L. (1991). Multiplexed VDT display systems. In G.R.S. Weir and J.L. Alty (Eds.), Human-computer interaction and complex systems. (pp. 189-210). London : Academic Press.
Bainbridge, L. (1993a). Building up behavioural complexity from a cognitive processing element. Department of Psychology, University College London. pp.95.
Bainbridge, L. (1993b). Types of hierarchy imply types of model. Ergonomics, 36, 1399 1412.
Bainbridge, L. (1993c). Difficulties and errors in complex dynamic tasks. Unpublished report.
Barnard, P. (1987). Cognitive resources and the learning of human-computer dialogues. In J.M. Carroll (Ed.), Interfacing thought : Cognitive aspects of human-computer interaction. Cambridge, Mass : MIT Press.
Beishon, R.J. (1974). An analysis and simulation of an operator's behaviour in controlling continuous baking ovens. Reprinted in E. Edwards and F.P. Lees (Eds.), The human operator in process control. (pp. 79-90). London : Taylor and Francis Ltd.
Benson, J.M. (1990). The development of a model of multi-tasking behaviour. Unpublished PhD Thesis, Ergonomics Unit, University College London.
Bisseret, A. (1970). Mémoire opérationelle et structure du travail. Bulletin de Psychologie, XXIV, 280-294. English summary in Ergonomics, 1971, 14, 565-570.
Brennan, A.C.C. (1987). Cognitive support for process control : designing system representations. Unpublished Master's Thesis, Ergonomics Unit, University College London.
Briggs, G.E., and Rockway, M.R. (1966). Learning and performance as a function of the percentage of pursuit tracking component in a tracking display. Journal of Experimental Psychology, 71, 165-169.
Craik, F.I.M., and Lockhart, R.S. (1972). Levels of processing : a framework for memory research. Journal of Verbal Learning and Verbal Behaviour, 11, 671-684.
Crossman, E.R.F.W. (1959). A theory of the acquisition of speed-skill. Ergonomics, 2, 153 166.
Crossman, E.R.F.W. and Goodeve, P.J. (1963) Feedback control of hand-movement and Fitts' Law. Communication to the Experimental Psychology Society.
Davis, D.R. (1966). Railway signals passed at danger : the drivers, circumstances and psychological processes. Ergonomics, 9, 211-222.
Doerner, D. (1987). On the difficulties people have in dealing with complexity. In J. Rasmussen, K.D. Duncan and J. Leplat (Eds.), New technology and human error. (pp. 97-109). Chichester : Wiley.

Easterby, R.S. (1970). The perception of symbols for machine displays. Ergonomics, 13, 149-158.
Ellis, A.W. (1993). Reading, writing and dyslexia : A cognitive analysis. Hillsdale NJ: Lawrence Erlbaum Associates.
Eysenck, M.W. and Keane, M.T. (1990). Cognitive psychology : A student's handbook. Hove : Lawrence Erlbaum Associates.
Fitts, P.M. and Jones, R.E. (1947a). Analysis of factors contributing to 460 'pilot error' experiences in operating aircraft controls. Memorandum Report TSEAA-694-12, Aero Medical Laboratory, Air Materiel Command, Wright Patterson Air Force Base, Dayton, Ohio, July 1, 1947. Reprinted in H.W. Sinaiko (Ed.) (1961). Selected papers on human factors in the design and use of control systems (pp. 332-358). New York : Dover Publications Inc.
Fitts, P.M. and Jones, R.E. (1947b). Psychological aspects of instrument display. I : analysis of 270 'pilot error' experiences in reading and interpreting aircraft instruments. Memorandum Report TSEAA-694-12A, Aero Medical Laboratory, Air Materiel Command, Wright Patterson Air Force Base, Dayton, Ohio, October 1, 1947. Reprinted in H.W. Sinaiko (Ed.) (1961). Selected papers on human factors in the design and use of control systems (pp. 359-396). New York : Dover Publications Inc.
Fitts, P.M. (1954). The information capacity of the human motor system in controlling the amplitude of movement. Journal of Experimental Psychology, 47, 381-391.
Fitts, P.M., and Deininger, R.L. (1954). S-R compatibility : correspondence among paired elements within stimulus and response codes. Journal of Experimental Psychology, 48, 483 492.
Fleishman, E.A. (1975). Taxonomic problems in human performance research. In W.T. Singleton and P. Spurgeon (Eds.), Measurement of human resources (pp. 49-72). London : Taylor and Francis Ltd.
Folkhard, S. (1990). Circadian performance rhythms : some practical and theoretical implications. In D.E. Broadbent, J. Reason and A. Baddeley (Eds.) Human factors in hazardous situations. Oxford : Clarendon Press.
Gagné, R.M. (1977). The conditions of learning (3rd ed.). New York : Holt, Rinehart and Winston.
Gallaher, P.D., Hunt, R.A., and Williges, R.C. (1977). A regression approach to generate aircraft predictor information. Human Factors, 19, 549-555.
Gibson, J.J. (1950). The perception of the visual world. Boston, Mass : Houghton Mifflin.
Gray, J.A., and Wedderburn, A.A.I. (1960). Grouping strategies with simultaneous stimuli. Quarterly Journal of Experimental Psychology, 12, 180-184.
Green, R. (1990). Human error on the flight deck. In D.E. Broadbent, J. Reason and A. Baddeley (Eds.), Human factors in hazardous situations (pp. 55-63). Oxford : Clarendon Press.
Grether, W.F. (1949). The design of long-scale indicators for speed and accuracy of quantitative reading. Journal of applied Psychology, 33, 363-372.
Hayes-Roth, B., and Hayes-Roth, F. (1979). A cognitive model of planning. Cognitive Science, 3, 275-310.
Helson, H. (1964). Adaptation-level theory. New York : Harper and Row.
Hoc, J-M. (1988). Cognitive psychology of planning. London : Academic Press.
Hollnagel, E. (1993). Reliability of cognition : Foundations of human reliability analysis. London : Academic Press.
Howland, D., and Noble, M. (1955). The effect of physical constraints on a control on tracking performance. Journal of Experimental Psychology, 46, 353-360.
Hukki , K., and Norros, L. (1993). Diagnostic orientation in control of disturbance situations. Ergonomics, 35, 1317-1328.
Hunt, D.P., and Warrick, M.J. (1957). Accuracy of blind positioning of a rotary control. USAF WADC Technical Notes 52-106.
Johansson, G., Aronsson, G., and Lindström, B.G. (1978). Social psychological and neuroendocrine stress reactions in highly mechanised work. Ergonomics, 21, 583-599.

Kahneman, D., Slovic, P., and Tversky, A. (Eds.). (1982). Judgement under uncertainty : Heuristics and biases. New York : Cambridge University Press.
Klein, G.A. (1989). Recognition-primed decisions. In W.B. Rouse (Ed.), Advances in man machine systems research, Volume 5 (pp. 47-92). Greenwich, CT : JAI Press.
Leplat, J., and Bisseret, A. (1965). Analyse des processus de traitement de l'information chez le controleur de la navigation aérienne. Bulletin du CERP, XIV, 51-67. English translation in The Controller : IFACTCA Journal, 5, 13-22.
Lindsay, P.H., and Norman, D.A. (1972). Human information processing. New York : Academic Press.
Marshall, E.C., Scanlon, K.E., Shepherd, A., and Duncan, K.D. (1981). Panel diagnosis training for major hazard continuous process installations. The Chemical Engineer, 365, 66 69.
Miller, G.A. (1956) The magical number seven, plus or minus two : some limits on our capacity for processing information. Psychological Review, 63, 81-97.
Miller, G.A., Heise, G.A., and Lichten, W. (1951). The intelligibility of speech as a function of the context of the test materials. Journal of Experimental Psychology, 41, 329-335.
Moray, N.P. Hiskes, D., Lee, J. and Muir, B.M. (1995). Trust and human intervention in automated systems. In J-M. Hoc, P.C. Cacciabue and E. Hollnagel (Eds.), Expertise and technology : Cognition and human-computer cooperation (pp. 183-194). Hillsdale, NJ : Lawrence Erlbaum Associates.
Oborne, D. (1995). Ergonomics at work (3rd ed.). Chichester : Wiley.
Pheasant, S. (1991). Ergonomics : Work and health. London : Macmillan.
Posner, M.I., and Rossman, E. (1965). Effect of size and location of informational transforms upon short-term retention. Journal of Experimental Psychology, 70, 496-505.
Rabbitt, P.M.A., and Vyas, S.M. (1970) An elementary preliminary taxonomy for some errors in laboratory choice RT tasks. Acta Psychologica, 33, 56-76
Rasmussen, J. (1982). Human errors : a taxonomy for describing human malfunction in industrial installations. Journal of Occupational Accidents, 4, 311-335.
Reinartz, S.J. (1989). Analysis of team behaviour during simulated nuclear power plant incidents. In E.D. Megaw (Ed.), Contemporary ergonomics 1989 (pp. 188-193). London : Taylor and Francis Ltd.
Rouse, W.B. (1980). Systems engineering models of human-machine interaction. Amsterdam : North Holland.
Rumelhart, D.E. (1977). Towards an interactive model of reading. In S. Dornic (Ed.), Attention and performance VI. Hillsdale, NJ : Lawrence Erlbaum Associates.
Sage, A.P. (1981). Behavioural and organizational considerations in the design of information systems and processes for planning and decision support. IEEE Transactions on Systems, Man and Cybernetics, SMC-11, 640-678.
Samurçay, R. and Rogalski, J. (1988). Analysis of operator's cognitive activities in learning and using a method for decision making in public safety. In J. Patrick and K.D. Duncan (Eds.), Training, human decision making and control. Amsterdam : North-Holland.
Savin, H.B., and Perchonock, E. (1965). Grammatical structure and the immediate recall of English sentences. Journal of Verbal Learning and Verbal Behaviour, 4, 348-353.
Shaffer, L.H. (1973). Latency mechanisms in transcription. In S. Kornblum (Ed.), Attention and performance IV (pp. 435-446). London : Academic Press.
Sheridan, T.B., and Ferrell, W.R. (1974). Man-machine systems: Information, control and decision models of human performance. Cambridge, Mass : MIT Press.
Sherrington, C. (1906). The integrative action of the nervous system. Cambridge : Cambridge University Press (1947 ed.).
Smith, S.L., and Thomas, D.W. (1964). Color versus shape coding in information displays. Journal of Applied Psychology, 48, 137-146.

Sperandio, J.C. (1970). Charge de travail et mémorisation en contrôle d'approche. Rapport IRIA-CENA, CO 7009, R24.
Sperandio, J.C. (1972). Charge de travail et régulation des processus opératoires. Le Travail Humain, 35, 86 -98. English summary in Ergonomics, 1971, 14, 571-577
Teichner, W.H., and Krebs, M.J. (1974). Laws of visual choice reaction time. Psychological Review, 81, 75-98.
Wickens, C.D. (1984). Processing resources in attention. In R. Parasuraman and D.R. Davies (Eds.), Varieties of attention. London : Academic Press.
Wilson, J.R., and Corlett, E.N. (1995). Evaluation of human work : A practical ergonomics methodology (2nd ed.). London : Taylor and Francis.
Winograd, T. (1972). Understanding natural language. Edinburgh : Edinburgh University Press. Reprinted from Cognitive Psychology, 3, 1-195.
Yntema, D.B., and Mueser, G.E. (1962). Keeping track of variables that have few or many states. Journal of Experimental Psychology, 63, 391-395.