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Goal-Directed Man-Machine Systems and Human Information Processing Capacity*

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A goal-directed system is defined as a type of material system in which either the whole system or a part of it is directed towards an external goal. The paper includes the following points: (1) An analysis showing that the output in a goal-directed man-machine system is adjusted on the basis of information flowing through various loops some of which are open and some closed. This is in contrast to the conventional model of man-machine interaction where display information alone is considered sufficient for the adjustment of the system output and the system is regarded as a closed one. The characteristics of this more general model are illustrated schematically. (2) The sequential and priority aspects of visual information processing are treated in the light of this more general model. (3) The relationship between the amount of information carried by visual messages (patterns), decision time, and reaction time is described. (4) It is maintained that priority processing is caused by the energetic aspects of a message, primarily intensity and changes of intensity, and experimental evidence is provided in support of this view. Finally, (5) It is pointed out how the limitation of the visual information processing capacity as a result of sequential processing and priority processing bears on the problem of accident prevention.

In the field of human factors engineering the interaction between a human operator and a machine is studied in terms of the systems concept where man is considered as a component that functions as a serial connecting link between the display and the control mechanism. It can be seen in Fig. 1(A) that the output – x_d, x_0, x_c, x_m, – of one functional unit constitutes the input of the next unit in the series and consequently the system is considered to be a closed one. This would imply that the information necessary for the operator (man), in order for him to be able to make appropriate adjustments to the system output, is furnished exclusively by the display (x_d). However, the display cannot be the only source of information since, in addition to x_d, adjustment of the system also requires visual perception of the manoeuvring devices (the control mechanism) and in most cases tactile feedback information during the course of the manoeuvring too. Therefore the arrow x_c' in Fig. 1(B) was added to the conventional diagram Fig. 1 (A), to denote the inter-

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action between the units "man" and "control". The significance of this interaction will be discussed in a later section. The model of a man-machine system as represented in Fig. 1(A), where as far as man-machine interaction is concerned, the role of

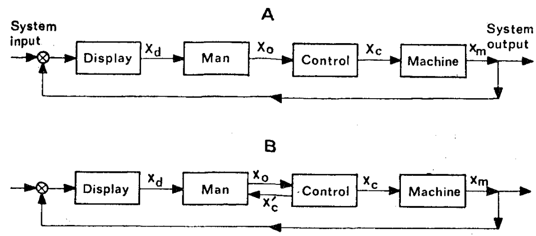

Fig. 1. (A), a diagram illustrating the closed system nature of man-machine systems. In this diagram, x_d denotes display output; x_0 operator output; x_c, control output; and x_m, machine or system output (from Morgan et al. 1963, p. 218). In (B) the interaction between man and control mechanisms is shown by arrows x_0 and x_c'.

display and control units is emphasized, is probably the main reason for the extensive and successful research which has been done in designing displays and control devices.

A GENERAL MODEL

The model in Fig. 1 might well represent a type of man-machine system in which internal (display) information alone is sufficient for the adjustment of the system output as for instance in the adjustment of a television set. This model does not, however, represent those systems in which the adjustment of the system output requires information both from inside and outside the system. A crane, a car, an

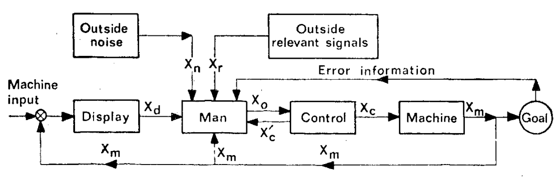

Fig. 2. A general model illustrating the information flows in goal-directed man-machine systems, where x_d, x_0, x_c, x_c', and x_m carry the same meaning as in Fig. 1. External information entering the system is denoted by x_r for relevant information and x_n for irrelevant information (noise). There are four closed loops and two open ones.

 aeroplane, are a few such examples. These can be called "goal directed systems", since either the whole system or a part of it (as with a crane) is directed toward a goal of some kind. The goal of a car at any given moment is a certain point on the road; that of an aeroplane when following clues from the ground is a certain direction in relation to these clues. A schematic model of such goal-directed systems is illustrated in Fig. 2. In contrast to the conventional model (Fig. 1(A)), where information flows through a single loop, several loops can be distinguished in the more general model (Fig. 2). These loops are as follows:

(*I*) *Closed-loop*: (Display → Man → Control → Machine → Display)
This loop is similar to and has the same function as that described in Fig. 1(A).

(*II*) *Closed-loop* (Man → Control → Machine → Goal → Man)
This loop carries error information, that is, the difference between the actual output and the desired output with respect to the goal itself. This kind of error, e.g. direction error in car driving, is not reflected on the display and has to be detected and estimated directly by the operator.

(*III*) *Closed-loop*: (Man → Control → Machine → Man)
This loop, which can be termed the "equilibratory" loop, affects the operator's state of equilibrium and can be described using force vectors. In this way he can obtain feedback information through the skin and kinesthetic senses and the semicircular canals. This effect can be strongly felt when the system output suddenly disturbs the equilibrium of forces, for example in high speed driving along a road with a sudden curve, or the abrupt fall or banking of a plane. This information either is not found or is only partly given on displays.

(*IV*) *Closed-loop*: (Man → Control → Man)
The totality of control devices which are manipulated by the operator are in themselves a kind of display, at least as far as their fixed positions and spatial relations are concerned. The operator needs to be able to perceive this with ease. Skill can only decrease the time required for the gain of perceptual information but it does not reduce the need for it. It is important to include this flow in a perceptual analysis because it certainly occupies part of the central information processing capacity, thereby interfering with the processing of information arriving from other flows.

Moreover, while manipulating control devices the operator should be aware of their status through tactile information: their resistance, position, etc. He cannot always wait to get this information through the system output. Skill again may decrease this activity but cannot reduce the need for it.

Therefore, arrow x'_c was added in Fig. 2 in order to represent this information flow.

(*V*) *Open-loop*: (Outside relevant signals → man)
It is called "open" because whilst the system output does not usually affect this

source of information, these signals might affect the output. The appearance of potential obstacles in the field of view of a moving system is an example of this case.

(*VI*) *Open-loop*: (Outside noise → Man)

This includes all the information not mentioned in I – V above, which arrives at but should be inhibited by the organism.

The differentiation of information flows as characterized above clearly shows that in a goal-directed man-machine system the adjustment of the system output is not based only on display information. In fact display actually loses its general significance in favour of other sources, particularly closed-loop (II). An operator is able to react to display indicators to the extent that he is free from dealing with outside information.

VISUAL INFORMATION PROCESSING IN GOAL-DIRECTED SYSTEMS

A human operator in most systems, and particularly in goal-directed man-machine systems, is primarily a visual information processor. The detection and transmission of information both from within and from without the system depends – as in the case of other information channels – on the capacity of the visual system. Any quantity of information in excess of this capacity cannot be received and processed by keeping the eye open, or by instructing the operator to be vigil or attentive. Training and skill can only help towards using the channel capacity in the most appropriate way without necessarily increasing it.

The amount of available information, both in the usual sense and technical sense of the word, is very large in the ordinary working conditions of a human being, especially when he has to deal with information from the environment of the system. Only a small fraction of all the existing information (visual patterns, messages) at a given moment of time forms the display and other pieces of information relevant to the system.

The nature of the visual source has been discussed elsewhere (Mashhour, 1967). It need only be remembered in this connection that all the patterns (visual messages) from the visual field reach the eye (input transducer) *simultaneously*. This is a critical characteristic of the visual messages, – due to the high velocity of light and ordinary observation distances – not only in view of the limited capacity of the visual system but also, and in particular, with regard to another important feature of this system called *sequential processing*. Sequential processing means that messages arriving at the gating mechanism (Fig. 3) and processed by the central information processing mechanism are not treated simultaneously but one at a time, i.e. in sequence.

The problem of sequential processing is very important in dealing with man-machine systems and we shall return to it shortly. Let us first illustrate the visual information flows involved in a goal-directed system. The diagram in Fig. 3 serves this purpose. For the sake of clarity some of the actual loops were not included but this will not affect the theoretical considerations and the conclusions that can be drawn. The small arrows at the eye represent information from outside the system which in Fig. 2 were designated "relevant" and "noise". The thick arrow represents the optic nerve carrying the information screened by the retina. This information arrives at the gating mechanism in the CNS. This hypothesized mechanism allows one message at a time to be transmitted to the central information processing and

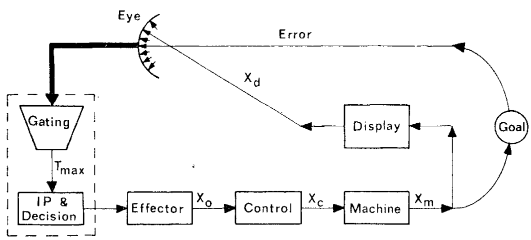

Fig. 3. A diagram of a goal-directed man-machine system showing information reaching operator's eyes simultaneously from different sources. Small arrows represent information both from outside and from control devices. For the sake of clarity the latter flows are not specified. T_{max} denotes the maximum rate of messages flowing sequentially to the central information processing and decision mechanisms (Ip & decision).

decision mechanism (IP & Decision). T_{max} denotes the capacity, i.e. the number of bits of information per unit of time, which can pass through the channel connecting "Gating" to "IP & Decision" mechanisms.

The sequential processing hypothesis was advanced by Broadbent (1958) and Welford (1967) who also provided experimental data in its support. However, the most convincing evidence is, in the present author's view, the results of Sziklai's experiment which will be described below.

SEQUENTIAL PROCESSING

Sziklai (1957) carried out an experiment to verify the supposition that the television signal is highly redundant and therefore very wasteful of channel capacity. Sziklai, as an engineer, was interested in TV-channel capacity rather than human channel capacity. His results, however, clearly confirm the sequential processing of the human visual system. He presented a number of images of ordinary objects simultaneously using various exposure times and found among other things (1) that the number of images perceived (identified) was a function of exposure time, (2) that the maximum rate of perception was between 30–50 bits/sec, which corresponds to 3–5 images per unit of time.

The following conclusions concerning the human being's visual information processing capacity can be drawn on the basis of Sziklai's findings:

(a) Of the total amount of information reaching the eye simultaneously only one message (object, pattern, signal, gestalt) can be processed at a time. The rate of information processing is limited to a maximum number, of messages per second, n_{max}, this corresponding to T_{max} bits/sec. This implies that all the messages arriving simultaneously at any given moment, including irrelevant ones (noise), are in a state of competition with one another. The problem of which message it is that is given priority processing will be discussed shortly.

(b) The number of messages transmitted n, is a linear function of time t, i.e. $n = kt$. Specifically, in Sziklai's case,

$$n = n_{max}t \;. \tag{1}$$

Since n and n_{max} are directly proportional to the respective amount of information transmitted in each case, T and T_{max}, it follows that

$$T = T_{max}t \;, \tag{2}$$

or

$$t = T/T_{max} \;. \tag{3}$$

Equation (3) which defines identification time, t, in terms of the amount of information rather than in terms of the number of objects (messages) identified, might turn out to be more useful in practice.

For instance, the identification of a road sign can take a longer time than was required for the identification of an object in Sziklai's case. The longer time needed to identify something that we might consider to be a single simple object may be necessary to identify sub-patterns, each of the sub-patterns being equivalent in complexity (information content) to one of the images (objects) used by Sziklai.

This is of considerable interest, for example in the design of signs and signals, as the visual channel might frequently be overloaded in goal-directed systems.

(c) Point (b) above has some bearing on the time required to form a decision (t_D), since decision time depends on the amount of information on which the decision is to be based. In the simplest case, that is, if the messages arrive at the central mechanism at the maximum rate T_{max}, then t_D should be the sum of a linear function of the amount of information T and a function of choice time, t_c (choice of the group of the effectors for taking action). Formally,

$$t_D = \frac{T}{T_{max}} + t_c \;. \tag{4}$$

 Thus, the reaction time RT would be

$$\text{RT} = \frac{T}{T_{max}} + t_c + t_m \,, \qquad (5)$$

(where t_m denotes the movement time.

In order to give an idea about the speed of action, or the number of control manoeuvres that an operator can make in one unit of time, it can be mentioned that in the simplest case, for example when reacting to a spot of light where the number of choices – consequently t_c in Equation (5) – is reduced to its minimum (i.e. to react or not to react), not more than 5 reactions per second can be made by the average subject (if RT $\approx$ 200 ms, see Figs. 4–5). Morgan et al. (1963, p. 231) report that the maximum rate of response by the operator is 2–3/sec regardless of how high the demand rate might be. It should be remembered that even this rate concerns the simplest of tracking tasks such as correction of error by a joystick.

In brief, the capacity of the central information processing machanism for the identification (perception) of objects and events is limited to a maximum level of T_{max} (50 bits/sec). This low capacity can easily be exhausted in goal-directed man-machine systems where the amount of information arriving simultaneously from different sources (see Fig. 2–3) lies far beyond this limit. This limitation in human information processing and consequently decision making, should characterize the direction of our research, particularly in the important field of accident prevention. As far as human capacity for information processing is concerned two closely related lines of research can be followed. One which is directed toward finding out how to minimize the number of messages coming simultaneously from different information sources (Fig. 2–3) and another which is directed toward measures which provide the relevant messages with those characteristics which will allow them to be processed prior to other messages.

PRIORITY PROCESSING

In addition to the mechanism involved in sequential processing there seems to exist a second mechanism, this one selecting the messages to be processed in sequence, the selection not being a random one. There are two cases, the organism is either searching for a particular message (object, pattern) or else the nature of a message itself is such that it is selected for being processed prior to the others. It is the latter case which is of interest here. The question is: what factors in a visual message are relevant to its undergoing priority processing?

This question can at least partly be answered by an examination of the physical aspects of visual patterns. They can be grouped into two categories: the geometric aspects and the energetic aspects. Geometric aspects are those whic are definable on a plane (or on the surface of the retina) and determine which particular receptoss are involved in the transmission of a message. The energetic aspects, on the other hand, determine the energy levels to which different receptors are activated. The energetic factors are primarily (1) intensity and (2) change in intensity (Mashhour, 1966). The latter includes both changes in intensity of a pattern arriving at the same group of receptors (e.g. the flickering of a pattern) and changes in intensity over different groups of receptors (e.g. rigid and non-rigid motions).

As to the remaining factors, i.e. contrast, colour, and size; contrast is included in the intensity factor since it determines the relative intensity, the energetic aspect of colour is its reflectance level which is also included in intensity, and size is proportional to the number of receptors involved and thereby to the total amount of energy forming the pattern arriving at the transducer. In this sense size can be considered as an energetic factor though experimental confirmation is needed. Following below is some experimental evidence in support of intensity and change as factors of priority processing.

INTENSITY

The best *indirect* evidence regarding the effect of intensity on priority processing is the variation of the time of reaction (transmission) with regard to different intensities of light, since changes in RT indicate how rapidly a pattern has been processed. There are abundant psychophysical experiments showing RT to be a decreasing function of intensity. This well established relationship is called Piéron's law (1914).

Sokolov (1963, p. 41) has found the same trend in his investigations concerning the effect of intensity on the strength of some physiological correlates called "the orientation reactions" and he calls the relation "the law of strength".

CHANGE

Taking RT as an index of priority processing, a series of experiments was performed which measured the RT of two groups of subjects ($N = 3$ and $N = 7$)

Table 1.

The means of the RT measurements in milliseconds for three individuals and a group of seven subjects

Subjects	Number of measurements	Rate of change, v, in min. arc/sec							
		9·5	19	32	52	77	126	186	297
A	80	580	—	491	—	399	—	355	—
B	80	714	—	468	—	374	—	330	—
C	80	461	—	355	—	321	—	288	—
Group	110	788	554	477	457	421	406	376	329

regarding the detection of change of position of visual stimuli (a small pattern (spot) of light, 0·5 mm. diameter) moving at various speeds. As in the case of intensity it was found that RT is a decreasing hyperbolic function of the rate of change (Mashhour, 1964). See Table 1, and Figures 4–5.

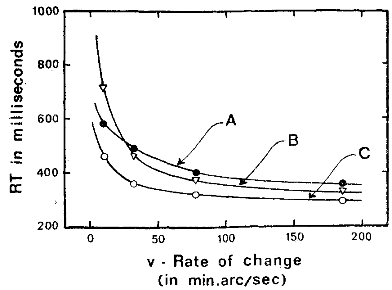

Fig. 4. Transmission (reaction) time as a function of the rate of change in a message position for three subjects. Each point is the average of 80 measurements.

The best direct evidence, however, would be gained by arranging an experimental situation similar to, but more comprehensive than, that used by Sziklai where the

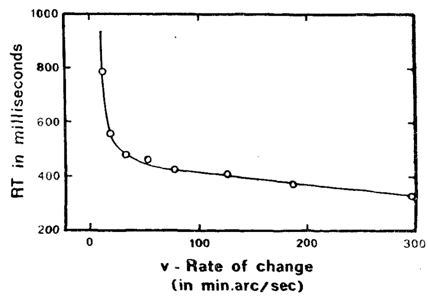

Fig. 5. Transmission (reaction) time as a function of the rate of change in a message position for a group of seven subjects. Each point is the average of 110 measurements.

effect on priority processing of the various energetic aspects mentioned above might be investigated more thoroughly on the basis of the direct reports of the subjects. An extensive experimental investigation covering this and other theoretical points discussed in this paper has been planned at our laboratories and the results will be published later.

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VÝTAH

Cílově řízené systémy člověk-stroj a kapacita lidského zpracování informace

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Cílově řízený systém je definován jako typ materiálního systému, ve kterém buď celý systém nebo jeho část je zaměřen k vnějšímu cíli. Zahrnuje následující body: 1. Analýzu, ukazující, že výstup v cílově řízeném systému člověk-stroj je upraven na základě informace protékající různými smyčkami, z nichž některé jsou otevřené a některé zavřené. To je v rozporu s konvenčním modelem interakce mezi člověkem a strojem, kde samotná zjevná informace je považována za dostatečnou pro nastavení výstupu systémů a systém je považován za otevřený. Charakteristiky tohoto obecnějšího modelu jsou ukázány schematicky. 2. O následných a prioritních aspektech vizuálního zpracování informace je pojednáno z hlediska tohoto obecnějšího modelu. 3. Je popsán vztah mezi množstvím informace obsažené ve vizuálních zprávách (obrazcích), rozhodovacím časem a dobou reakce. 4. Je ukázáno, že prioritní zpracování je zapříčiněno energetickými aspekty zprávy, především intenzitou a změnami intenzity a experimentální výsledky podporují tento názor. Konečně, 5. je určeno, jak omezení kapacity vizuálního zpracování informace, jako výsledek postupného a prioritního zpracování, ovlivňuje problém prevence nehod.

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