

The Model Human Processor: An Engineering Model of Human Performance

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The Model Human Processor: A Model for Making Engineering Calculations of Human Performance

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ABSTRACT

It can be argued that one of the chief impediments to progress in human engineering is the lack of a model of the human information-processor posed in such a way as to enable approximate engineering calculations to be made of human performance. The Model Human Processor is an attempt at such a model. The use of the model is illustrated through sample computations.

Anyone who has had the task of trying to obtain from the literature psychological guidance for the design of an interactive computer system is aware of the great frustrations engendered by the jumble of empirical results and micro-theories, tightly bound to experimental paradigms, which he finds. It is not that psychology has no information to offer. Indeed, there has come to be established, especially in cognitive psychology, a robust set of verified facts about the working of the human mind. But these facts are difficult to retrieve and to apply in new circumstances. This is true partially because in psychology, unlike some other fields, there has been insufficient effort devoted to codifying and condensing the knowledge learned into simple forms, usable by workers with other specialties. This codification and simplification of established facts is important to the progress of science if the results from one specialty are to become the tools of another (Latour and Woolgar, 1979).

It is a great mistake to think that, by merely listing a miscellaneous collection of results, psychology is thereby rendered usable to support practical engineering projects. What is required is a more radical departure from what is usual in psychological research. The point of experimental manipulations is often to discriminate between competing theories no matter how small the discrimination. By contrast, in a psychology useful for engineering design, small differences are lost in the many approximations always necessary. What is important is the ability to do task analysis (determining the specific, rational means of accomplishing various goals), calculation (zero-parameter predictions of behavior capable of parametric variation), and approximation (simplification of the task and of psychological theory).

It is interesting that some of the most extensive efforts towards summary and codification of human performance knowledge, at least so far as data are concerned, have come not out of psychology itself, but from those allied disciplines which seek to make use of human performance knowledge for practical, engineering purposes: human factors and industrial engineering. Examples are the AIR Data Store (Munger, Smith, and Payne, 1962) and its descendants, the *Human Engineering Guide to Equipment Design* (Van Cott and Kinkade 1972), and the numerous "pre-determined time systems" (Maynard, 1971). While each of these is a useful step toward collecting data, there is a need for a simple, less atheoretical approach if the goals of task analysis, calculation, and approximation are to be satisfied.

In the remainder of this paper, I wish to suggest a way in which numerous results from cognitive psychology might be included in a single model, usable by computer system designers and others. Though limited, this model (which I shall christen the Model Human Processor) does make it possible to calculate predictions of user performance, albeit of an approximate kind. The purpose of the model is to provide a compact basis for applied analysis.

THE MODEL HUMAN PROCESSOR

The Model Human Processor can be described by (1) a set of processors, memories, and their interconnections (Figure 1) together with (2) a set of "principles of operation" (Figure 2). The principal properties of the processors and memories are summarized by a small set of parameters. A similar technique has proved successful for simplifying the analysis of electronic information-processing systems (see Siewiorek, Bell, and Newell,

1981). The memory parameters used in the model are are

μ , the storage capacity in items,
 δ , the decay time (half-life) of an item, and
 κ , the main code type (iconic, acoustic, visual, semantic).

The only processor parameter used is

τ , the cycle time.

The complete model is elaborated and argued in Card, Moran, and Newell (in preparation). Here, I wish only to give an illustration of how a single parameter τ from the model can be used to support system engineering analysis.

According to the Model Human Processor, the mind is comprised of three partially coupled processors, the Perceptual Processor, the Cognitive Processor, and the Motor Processor, each with a similar cycle time, derived from the literature.

$\tau_P = 100$ [50~200] msec

$\tau_C = 100$ [25~170] msec

$\tau_M = 100$ [70~360] msec

For some tasks (pressing a key in response to a light) the system must behave as a serial processor. For other tasks (typing, reading, and simultaneous translation) integrated, parallel operation of the three subsystems is possible, in the manner of three pipelined processors: information flows continuously from input to output, with a lag showing that all three processors are working simultaneously.

Suppose a stimulus impinges upon the retina of the eye at time $t = 0$. At the end of one Perceptual Processor cycle, $t = \tau_P$, the image is assumed to be available in the Visual Image Store and the human able to see it. Shortly thereafter, a recognized, symbolic, acoustically- (or visually-) coded representation of at least part of the Visual Image Store contents is assumed to be present in Working Memory. In truth, this description is an approximation since different information in the image becomes available at different times, much as a photograph develops, and a person can react before the image is fully developed or he can wait for a better image, depending on whether speed or accuracy is the more important. According to the model, perceptual events occurring within a single cycle are combined into a single percept.

Once in Working Memory, information is processed by the Cognitive Processor's *recognize-act* cycle, analogous to the fetch-execute cycle of standard computers. On each cycle, the contents of Working Memory initiate associatively-linked actions in Long-Term Memory ("recognize") which in turn modify the contents of Working Memory ("act"), setting the stage for the next cycle. Plans, procedures, and other forms of organized behavior can exist, but these are built up out of an organized set of recognize-act cycles.

Consequent to a decision to act by the Cognitive Processor, the action itself is controlled by the Motor Processor. Contrary to casual appearances, movement is not continuous, but consists of a series of discrete micromovements, each requiring one Motor Processor cycle of about $\tau_M = 100$ ms. The feedback loop from action to perception is sufficiently long (300~500 ms) that rapid behavioral acts such as typing and speaking must be executed in bursts of preprogrammed Motor Processor cycles.

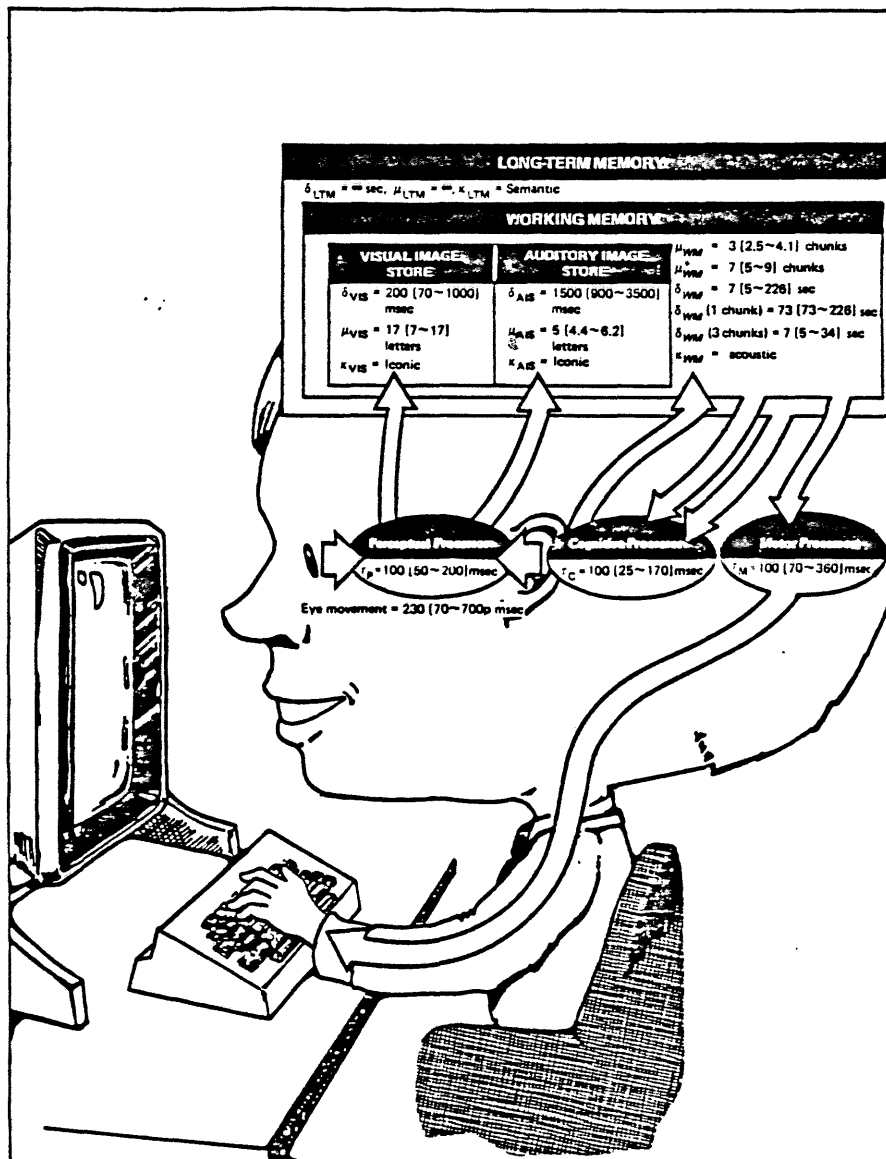


Figure 1. The Model Human Processor—Memories, Processors, and Basic Principle of Operation.

Sensory information flows into Working Memory through the Perceptual Processor; Motor programs are set in motion through activation of chunks in Working Memory. Working Memory consists of activated chunks in Long Term Memory. The Visual Image Store and Auditory Image Store can be thought of as special activations of the experiential and analogic properties of visual and auditory images. The basic Principle of Operation of the Model Human Processor is the Recognize-Act cycle of the Cognitive Processor.

On each cycle, the contents of Working Memory activate actions associatively linked to them in Long Term Memory, which, in turn, modify the contents of Working Memory.

- P1. Variable Perceptual Processor Rate Principle.** The Perceptual Processor cycle time τ_p varies inversely with stimulus intensity.
- P2. Encoding Specificity Principle.** Specific encoding operations performed on what is perceived determine what is stored, and what is stored determines what retrieval cues are effective in providing access to what is stored.
- P3. Discrimination Principle.** The difficulty of memory retrieval is determined by the candidates that exist in the memory, relative to the retrieval clues.
- P4. Variable Cognitive Processor Rate Principle.** The Cognitive Processor cycle time τ_c is shorter for greater task demands and increased information loads; it also diminishes with practice.
- P5. Fitts's Law.** The time T_{pos} to move the hand to a target of size S which lies a distance D away is given by $T_{pos} = I_M \log_2(2D/S)$, where $I_M = 100 \text{ ms/bit}$ [70~120 ms/bit].
- P6. Power Law of Practice.** The time T_n to perform a task on the n th trial follows a power law: $T_n = T_1 n^{-r}$, where $r = .4[.2 \sim .6]$.
- P7. The Uncertainty Principle.** Decision time T increases with uncertainty about the judgement or decision to be made: $T = I_C H$, where H is the information-theoretic entropy of the decision and $I_C = 150 \text{ ms/bit}$ [0~157 ms/bit]. For n equally probable alternatives (Hick's Law), $H = \log_2(n+1)$. For n alternatives with different probabilities of occurring p_i , $H = -\sum p_i \log_2 p_i$.
- P8. Rationality Principle.** A person acts so as to attain his goals through rational action, given the structure of the task and his inputs of information and bounded by limitations on his knowledge and processing ability:
Goals + Task + Operators + Inputs + Knowledge + Process-limits \rightarrow Behavior.
- P9. The Problem Space Principle.** The rational activity in which people engage to solve a problem can be described in terms of (1) a set of states of knowledge, (2) operators for changing one state into another, (3) constraints on operator movement, and (4) control knowledge for deciding which operator to apply next.

Figure 2. The Model Human Processor—Additional Principles of Operation

CALCULATING HUMAN PERFORMANCE

It is now illustrated how Model Human Processor might be used to calculate answers to problems of human performance. To address uncertainties in the parameters of the model, we define three model versions: one in which all the parameters listed are set to give the worst performance (*Slowman*), one in which they are set to give the best performance (*Fastman*), and one set for a typical performance (*Middleman*). Sensitivity analyses to see if the results of interest are affected by the true values of the parameters can be performed by making calculations for both *Slowman* and *Fastman*.

Example 1. Moving Picture Rates.

Compute the frame rate at which an animated image on a video display must be refreshed to give the illusion of movement.

Solution. Closely related images nearer together in time than τ_p , the cycle time of the Perceptual Processor, will be fused into a single image. The frame rate must therefore be such that:

$$\begin{aligned} \text{Frame rate} &> 1/\tau_p = 1/(100 \text{ msec/frame}) \\ &> 10 \text{ frames/sec.} \end{aligned}$$

In order to be certain that the animation will not break down, the frame rate should, of course, be faster than this number. How much faster? A reasonable upper bound for how fast the rate needs to be can be found by redoing the above calculation for the *Fastman* version of the model ($\tau_p = 50 \text{ msec}$):

$$\begin{aligned} \text{Max frame rate for fusion} &= 1/(50 \text{ msec/frame}) \\ &= 20 \text{ frame/sec.} \end{aligned}$$

This calculation is in general accord with the frame rates commonly employed for motion picture cameras (18 frames/sec for silent and 24 frames/sec for sound) and broadcast television (30 frames/sec).

The Model Human Processor also warns us of secondary phenomena which might affect these calculations. By the Variable Perceptual Processor Rate Principle, τ_p will be faster for the brighter screen of a cinema projector and slower for the fainter screen of a video display terminal.

Example 2. Perceptual Causality

In a graphic computer simulation of a pool game, there are many occasions upon which one ball appears to bump into another ball, causing the second one to move. What is the time available, after the collision, to compute the initial move of the second ball, before the illusion of causality breaks down?

Solution. The movements of the first and second balls must appear to be part of the same event and hence the collision will appear to cause the movement of the second ball, if the movement occurs within one cycle of $\tau_p = 100 \text{ msec}$. Since the illusion will break down in the neighborhood of 100 msec, the program should try to have the computation done well before this time. The designer can be sure the illusion will hold if designed for *Fastman*, with the computation done in $\tau_p(\text{Fastman}) = 50 \text{ msec}$. ■

These calculations are in accord with an analogous experiment conducted by Michotte (1946) in which subjects had to classify collisions between objects (immediate causality, delayed causality, or independent events) as a function of the delay before the movement of the second object. In the experiment, perception of immediate causality ended in the neighborhood of 100 msec and some degradation of immediate causality began for some subjects as early as 50 msec.

Example 3. Reading Rate

How fast can a person read text?

Solution. Assuming 230 msec/saccade (from Figure 2.1), a reading rate can be calculated (cf. Hochberg, 1976) from assumptions about how much the reader sees with each fixation. If he were to make one saccade/letter (5 letters/word), the reading rate would be:

$$\begin{aligned} (60 \text{ sec/min}) / (.230 \text{ sec/saccade} \times 5 \text{ saccade/word}) \\ = 52 \text{ words/min.} \end{aligned}$$

For one saccade/word, the rate would be:

$$\begin{aligned} (60 \text{ sec/min}) / (.230 \text{ sec/saccade} \times 1 \text{ saccade/word}) \\ = 261 \text{ words/min.} \end{aligned}$$

For one saccade/phrase (containing the number of characters/fixation found for good readers, 13 chars = 2.5 words), the rate would be:

$$(60 \text{ sec/min}) / (.230 \text{ sec/saccade} \times 1/2.5 \text{ saccade/word}) = 652 \text{ words/min.} \blacksquare$$

How much the reader takes in with each fixation is a function of the skill of the reader and the perceptual difficulty of the material. If the material is conceptually difficult, then the limiting factor for reading rate will not be in the eye-movement rate, but in the cognitive processing. The calculation implies that readers who claim to read much more than 600 words/min do not actually see each piece of the text. In other words, speed readers skim.

Example 4. Reaching to a button

Suppose a user needs to move his hand D cm to reach a button S cm wide on a calculator (He cannot reach it by touch). How long will the movement require?

The movement of the hand, as we have said, is not continuous, but consists of a series of micro-corrections each with a certain accuracy. To make a correction takes at minimum one cycle of the Perceptual Processor to observe the hand, one cycle of the Cognitive Processor to decide on the correction, and one cycle of the Motor Processor to perform the correction, or $\tau_P + \tau_C + \tau_M$. The time to move the hand to the target is then

the time to perform n of these corrections or $n(\tau_P + \tau_C + \tau_M)$. Since $\tau_P + \tau_C + \tau_M \approx 300$ msec, n is the number of roughly 300 msec intervals it takes to point to the target.

Let X_i be the distance remaining to the target after the i th corrective move and $X_0 (= D)$ be the starting point. Assume that the relative accuracy of movement is constant, that is, that $X_i/X_{i-1} = \alpha$, where $\alpha (< 1)$ is the constant error. On the first cycle the hand moves to

$$X_1 = \alpha X_0 = \alpha D.$$

On the second cycle, the hand moves to

$$X_2 = \alpha X_1 = \alpha(\alpha D) = \alpha^2 D.$$

On the n th cycle it moves to

$$X_n = \alpha^n D.$$

The hand stops moving when it is within the target area, that is when

$$\alpha^n D \leq \frac{1}{2} S.$$

Solving for n gives

$$n = -\log_2(2D/S) / \log_2 \alpha.$$

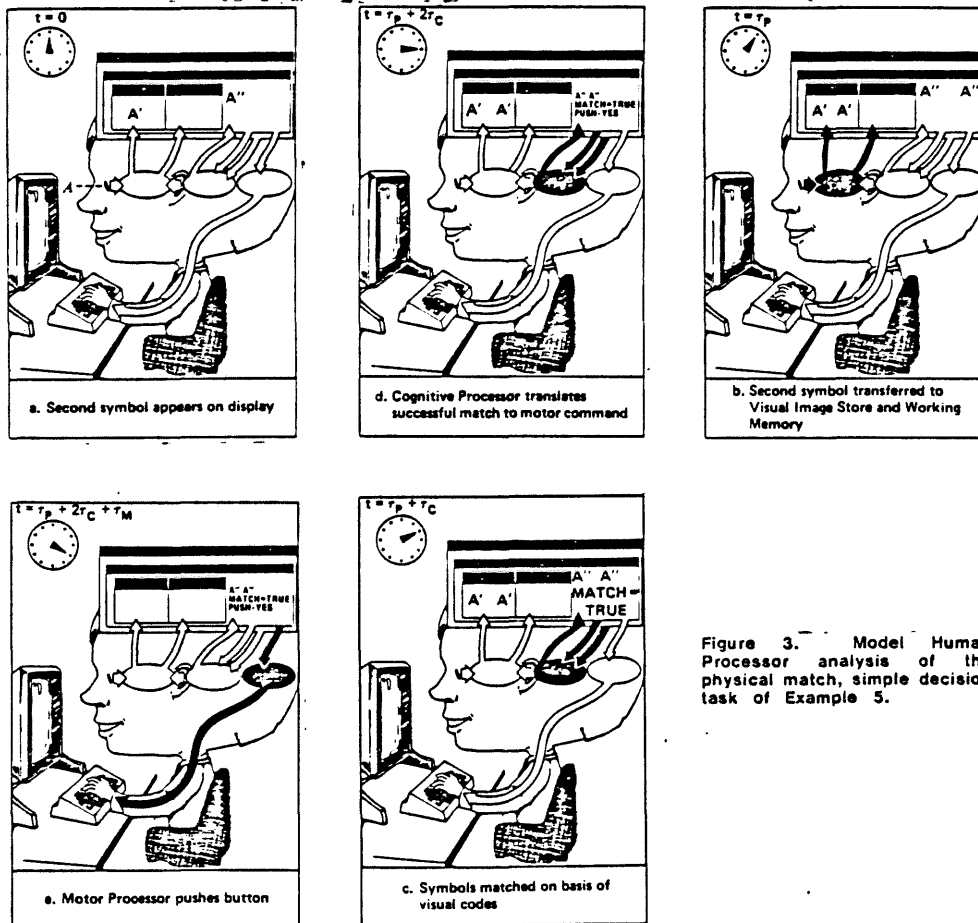


Figure 3. Model Human Processor analysis of the physical match, simple decision task of Example 5.

Hence the total movement time T_{pos} is given by

$$\begin{aligned} T_{pos} &= n(\tau_P + \tau_C + \tau_M) \\ T_{pos} &= I_M \log_2(2D/S) \\ \text{where } I_M &= -(\tau_P + \tau_C + \tau_M) / \log_2 \alpha. \end{aligned} \quad (1)$$

Equation 1 is called Fitts's Law (this derivation based on Keele, 1968). It says that the time to move the hand to a target depends only on the relative precision required, that is, the ratio between the target's distance and its size.

The constant α has been found to be about .07 (Vince, 1948), so I_M can be evaluated:

$$\begin{aligned} I_M &= -300 \text{ msec} / \log_2(.07) \text{ bits} \\ &= 78 \text{ msec/bit} \end{aligned}$$

Results from various experiments give values in the in the I_M = 70~120 msec/bit range.

Example 5. Simple Decision Times

The user is presented with two symbols, one at a time. If the second symbol is identical to the first, he is to push the key labeled Yes, otherwise he is to push No. What is the time between signal and response for the Yes case?

Solution. The first symbol is presented on the screen where it is observed by the user and processed by his Perceptual Processor giving rise to associated representations in the user's Visual Image Store and Working Memory. The second symbol is now flashed on the screen and is similarly processed (Figure 3a). Since we are interested in how long it takes to respond to the second symbol, we now start the clock at 0. The Perceptual Processor processes the second symbol to get an iconic representation in Visual Image Store and then a visual representation in Working Memory, requiring one cycle, τ_P (Figure 3b). If not too much time has passed since the first symbol was presented, its visual code is still in Working Memory and the Cognitive Processor can match the visual codes of the first and second symbols against each other to see if they are the same. This match requires one Cognitive Processor cycle, τ_C (Figure 3c). If they match, the Cognitive Processor decides to push the Yes button, requiring another cycle τ_C for the decision (Figure 3d). Finally, the Motor Processor processes the request to push the Yes button, requiring one Motor Processor cycle τ_M (Figure 3e). The total elapsed reaction time, according to the Model Human Processor, is

$$\begin{aligned} \text{Reaction time} &= \tau_P + 2\tau_C + \tau_M \\ &= 100 [50\sim200] + 2 \times (100 [25\sim170]) \\ &\quad + 100 [70\sim360] \text{ msec} \\ &= 400 [170\sim900] \text{ msec} . \end{aligned}$$

This analysis could be repeated for the case ("name match") where the user is to press Yes if the symbols were both the same letter, although one might be in upper case, the other in lower case. Here, an extra Cognitive Processor cycle is required to get the abstract code for the symbol (Computed reaction time = 500 [195~1070] msec). Likewise, if the user were to press Yes when the symbols were only of the same class ("class match"), say both letters, yet another Cognitive Processor cycle would be required. (Computed reaction time = 600 [220~1240] msec).

Experiments have been performed to collect empirical data on the questions presented in these examples. The finding is that name matches are about 70 msec slower than physical matches and that class matches are about 70 msec slower yet, a number in line with our 100 [25~170] msec value for τ_C .

The forgoing examples start from task analysis of a problem and proceed through approximation and calculation to make predictions of human performance of the sort that might be used in an engineering analysis of cognitive behavior. Although it is hoped that the Model Human Processor itself will be useful for

engineering, the real point is in the spirit of the enterprise: that knowledge in cognitive psychology and collateral sciences is sufficiently advanced to allow the analysis and improvement of common mental tasks. Of course, suggestions for improvement to the present model will occur all around. But then that is part of the idea and the challenge: to use the Model Human Processor as a framework into which new research results and insights can be fit in a way amenable to use in the cognitive engineering of practical mental tasks.

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