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A THEORY OF THE ACQUISITION OF SPEED-SKILL*

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Recent researches are cited which suggest that the acquisition of manual speed-skill proceeds by a certain type of selective action. A formal theoretical model is developed, and its predictions compared with the experimental results. Certain complications of the theory, and conclusions from it are outlined, and the nature of the selective mechanism is discussed. Some implications for training are indicated.

§ 1. INTRODUCTION

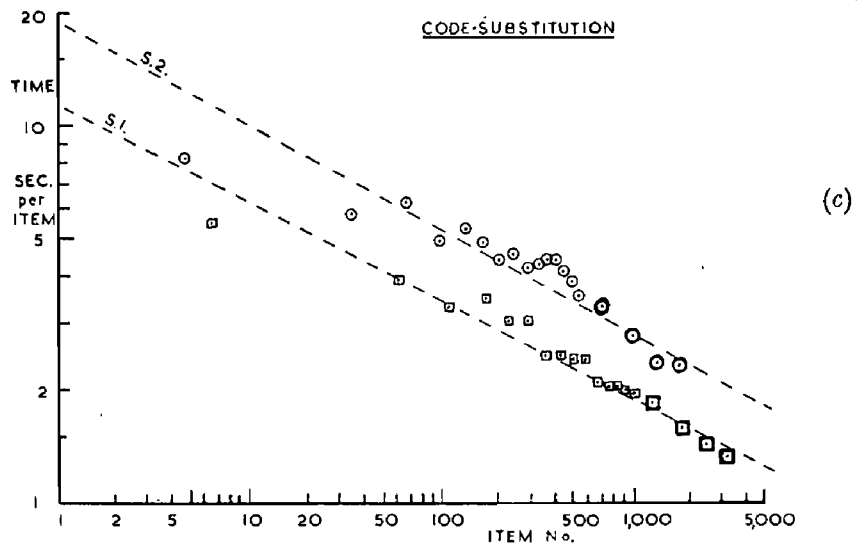
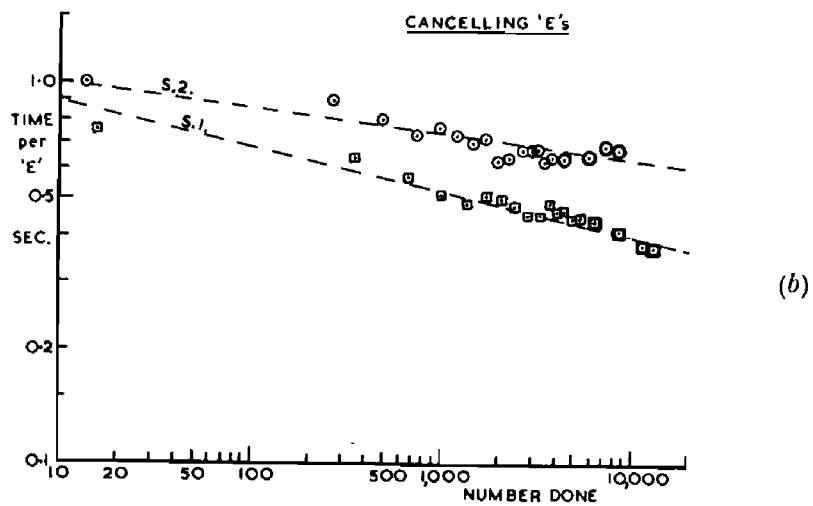
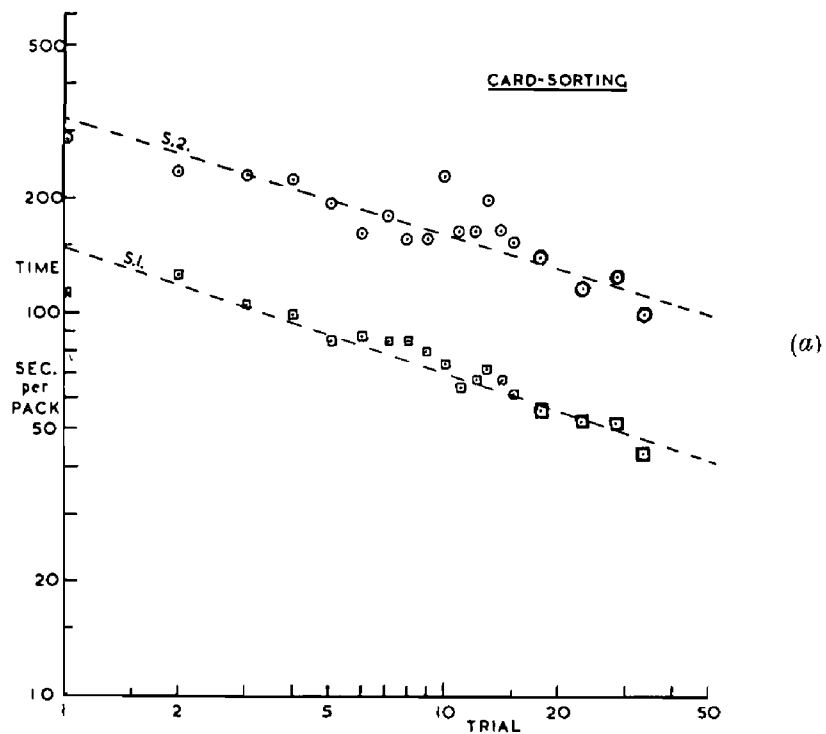
TRAINING is an art which can be successfully practised with little or no scientific backing, but as in other fields, really reliable and reproducible results flow only from a sound basic theory. Since training serves to facilitate the natural process of acquiring skill by practice, the most important theoretical question is: how and why does a learner acquire skill in ordinary practice?

This paper is concerned with manual speed-skills and dexterities, a class of skills which is both common and important in industry today. Its aim is to put forward a theory of their acquisition suggested to the writer by the results of some recent experimental work carried out by Seymour at Birmingham University, and by de Jong at the Berenschot Bureau, Amsterdam. The theory stems essentially from the trial-and-error view of learning put forward by Thorndike more than fifty years ago (Hilgard 1948). Though this view has since been elaborated by many students of animal learning, and concepts of drive, reward, habit-strength, etc. introduced, no serious attempt seems to have been made to build up a quantitative account of the acquisition of skill from it. The writer has taken up its basic premise that a learner faced by a new task tries out various methods, retains the more successful ones and rejects the less successful ones, and has constructed from it a formal theoretical model to explain the experimental findings. While the model is presented here in a skeleton form, it agrees quite satisfactorily with experiment, and interesting new questions are raised.

§ 2. SKILL AND LEARNING

Recent researches on manual skill have been largely concerned with the *general* features of skilled performance; the importance of perceptual and central organizing activities, the temporal interlacing of receptor and effector actions, and the role of feedback or knowledge-of-results have all been stressed. But when studying industrial operations the writer has been struck by the highly *specific* nature of most skills. The expert's ability seems to lie rather in knowing exactly the right method to use in each situation that arises in the task, than in having superior coordination, acuity or timing. He can select the right source of signals to attend to, choose the right course of action, make precisely the right movements, and check the results by the most reliable means. In other

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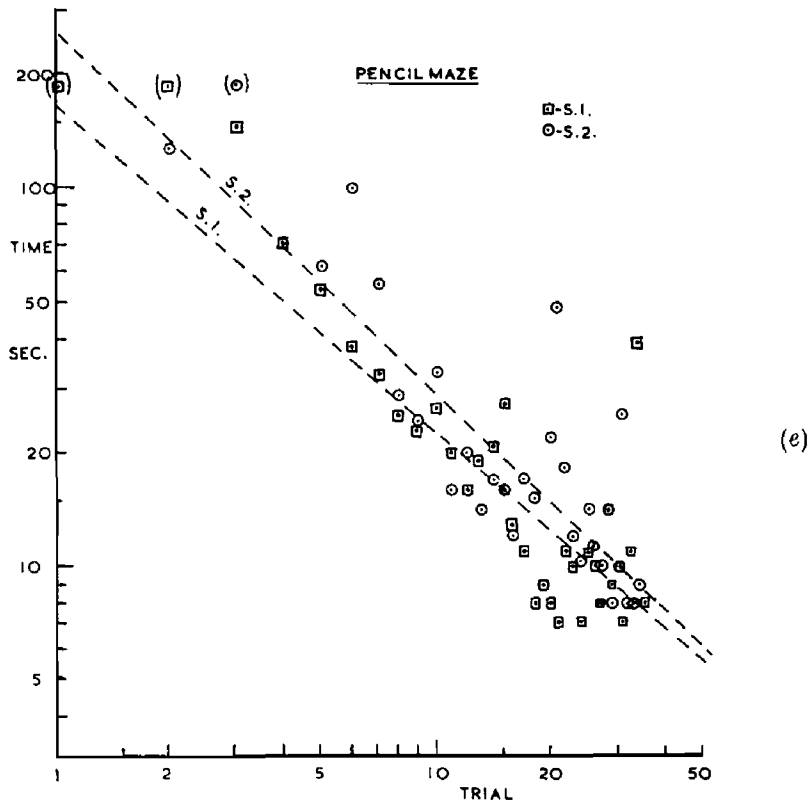
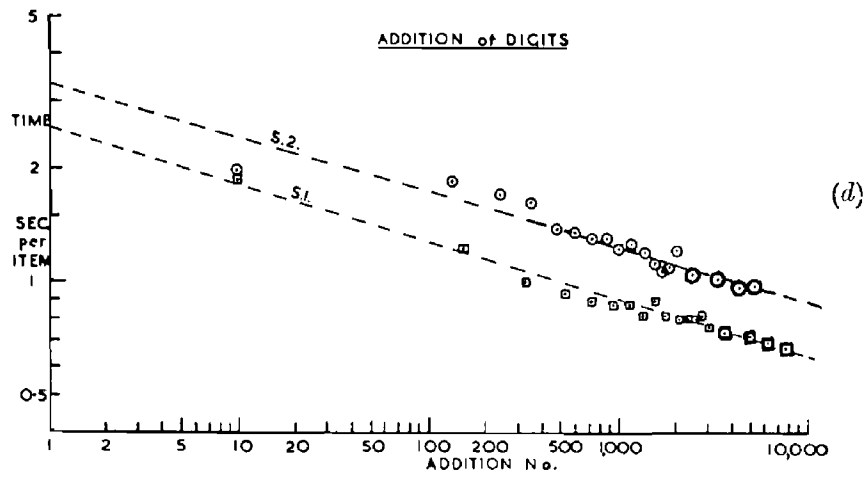


Figure 1. Learning curves on log-log scales for two subjects each on five tasks (data of Blackburn 1936).

words, his behaviour is closely 'adapted' to the situation in the same sense in which animals are said to become adapted to their environment by natural selection; he possesses only 'fit' behaviour-patterns.

For manual speed-skills, the operator's degree of adaptation is measured principally by his speed of performance, once success can be taken for granted. It increases gradually and continuously over long periods of practice, as many experimental learning curves have shown (Blackburn 1936). De Jong (1957) has recently put forward a rational equation which fits the results of several industrial studies. He finds that cycle-time plotted against cycle-number on log-log paper shows a linear decrease followed by an asymptotic approach to an 'incompressible' cycle-time; the relationship may be called 'de Jong's law'. De Jong has not provided statistical support for his argument, and some data are given here both to remedy the omission and by way of example.

2.1. *Practice and Speed in Five Simple Tasks*

Results given by Blackburn (1936) on card-sorting, cancelling *e*'s in nonsense French, adding digits, code-substitution, and maze-learning have been re-analysed. Figure 1 (*a* to *e*) shows the learning curves and Table 1 a statistical test of de Jong's law. The law clearly describes the data for the first four tasks well, but the fifth is doubtful.

2.2. *Long-period Improvement in Cigar-making*

A study was made of the speeds of production of several girls in the same shop, operating special-purpose cigar-making machines (Crossman 1956, Chapter 10). The job had a very short cycle, but considerable variation was experienced in the raw materials, and there was high 'perceptual load'. Figure 2 shows the weekly average cycle-time for operators of various lengths of service. Only after two years and about three million cycles does the curve depart appreciably from a straight line.

2.3. *Improvement of the Elements within a Motion-cycle*

Data provided by Seymour (1954) on learners operating a capstan-lathe have been re-plotted and are shown in Fig. 3. It is clear that the two elements obey de Jong's law as does the complete cycle.

The steady decrease in cycle-time shown by de Jong's law is accompanied by considerable variation from cycle to cycle. Studies of cycles and element times have shown quite clearly that the average does not decrease by a proportionate change in all times but by a change in frequency-distribution. Early in practice this is symmetrical; it becomes more and more skewed with practice, and finally J-shaped. Different elements show different initial distributions; very short ones (1-2 sec) tend to the rectangular or J-shaped, longer ones tend more and more to the Gaussian form. Figures 4 and 5 show typical results from an industrial assembly operation (15-20 sec cycle) and a laboratory assembly task (2 sec cycle). The scatter of element-times does not appear to be due to varying level of effort, and must presumably be attributed to variations of method. Unfortunately we have little direct evidence on the distribution of motion-patterns (but see de Montpellier 1935) and still less about that of perceptual activities. Lewis (1954) has, however, shown in car-driving that more skilled performers behave more consistently from occasion to occasion.

Table 1. A Statistical Test of de Jong's Law on Data given by Blackburn (1936) for Subjects Learning Five Simple Repetitive Tasks

Task	Subject	Regression coefficient <i>b</i>	Correlation coefficient <i>r</i>	Variance ratio <i>F</i>	Time for first trial	
					Predicted (sec)	Actual (sec)
Sorting 42 cards into individual compartments	1	-0.326	-0.95	1.40	149	111
	2	-0.300	-0.91	1.35	322	279
Cancelling e's in Nonsense French	1	-0.137	-0.94	4.67†	14.1	2 (estimated)
	2	-0.064	-0.76	2.68*	11.5	„
Substituting code symbols for letters	1	-0.261	-0.99	2.12	11.4	10 (estimated)
	2	-0.250	-0.95	2.65*	16.1	„
Adding pairs of digits	1	-0.147	-0.97	0.56	2.47	3 (estimated)
	2	-0.144	-0.94	2.52*	3.34	„
Tracing a pencil-maze blindfold	1	-0.949	-0.84	1.79	222	> 180
	2	-0.959	-0.88	1.05	266	> 180

* Significant at 5 per cent level.
 † Significant at 0.1 per cent level.

- Notes: (1) Each subject performed 35 periods of about 180 sec each, on successive days.
 (2) The logarithms (to base 10) of cycle-time have been correlated with the mean logarithm of the number of cycles performed up to and during each trial.
 (3) The significance of the departure from linearity has been tested by Analysis of Variance, grouping the last 5 blocks of 5 readings together in order to estimate error. In each case the variance ratio *F* is based on 13 and 20 degrees of freedom.
 (4) The times for the first trial are only known in two cases; in the others an estimate has been made.

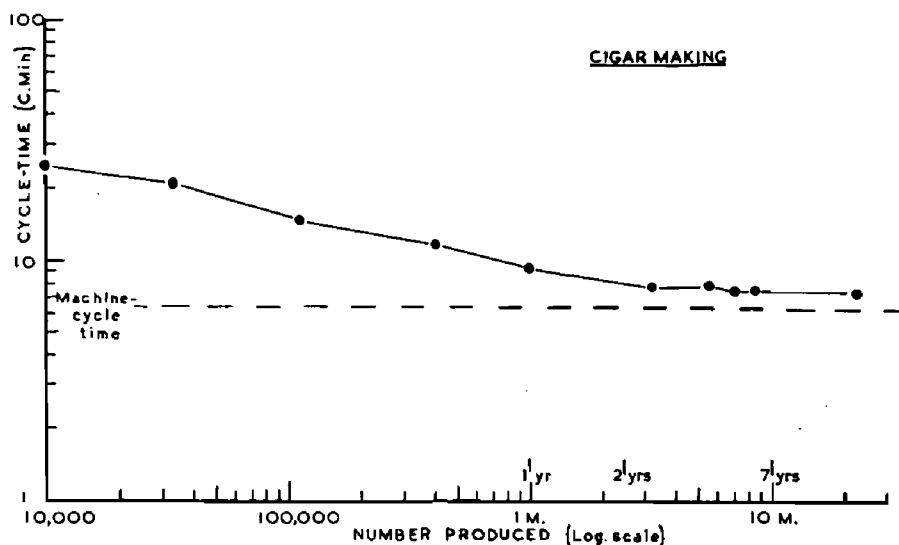


Figure 2. Practice and speed in cigar-making. Each point is the average cycle-time over one week's production for one operator. The ordinate is the total production by the operator since beginning work.

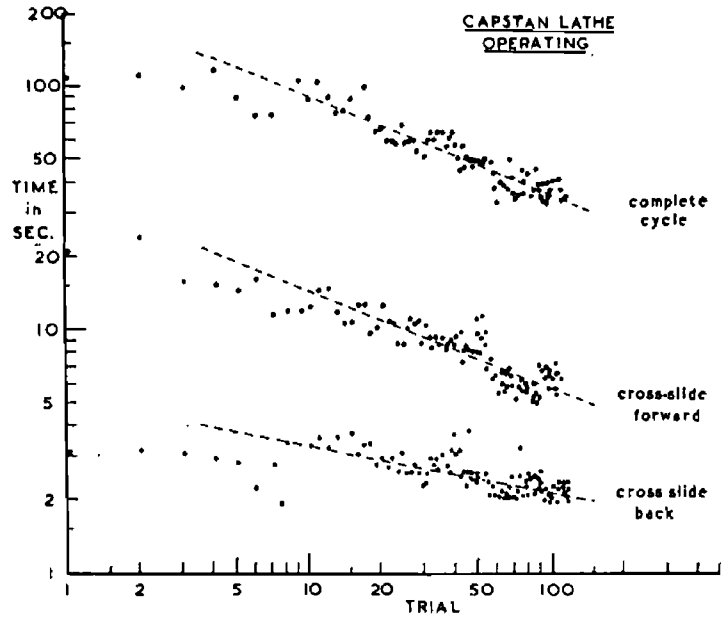


Figure 3. The effect of practice on element and cycle-times for a simulated capstan-lathe operation (data of Seymour 1954). The results of one subject are shown and each point represents one cycle of practice.

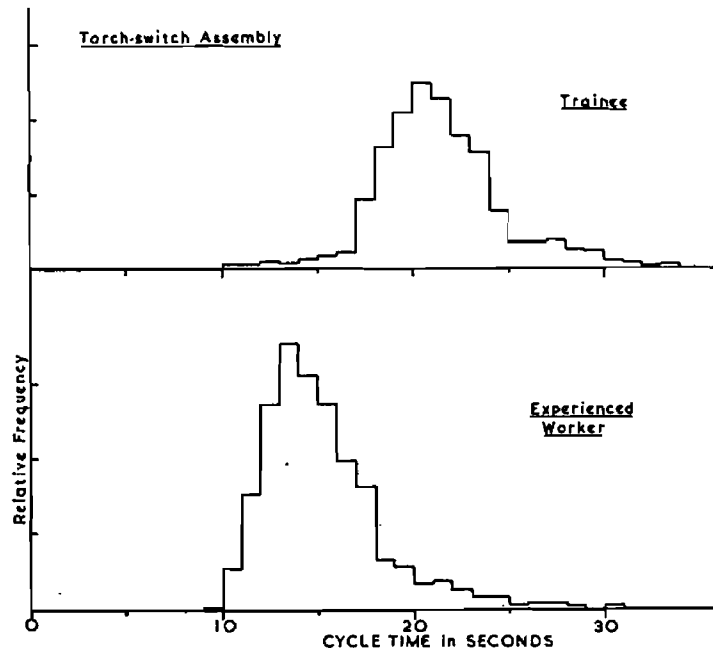


Figure 4. The distribution of cycle-times for a learner and an experienced worker at Torch-Switch Assembling (data of Dudley 1955).

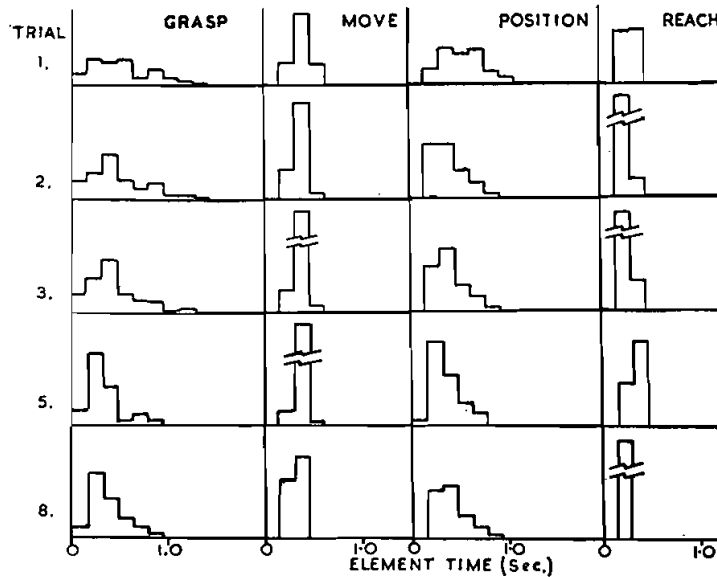


Figure 5. The distribution of element-times for a simple assembly operation (The Three-hole Connector). The four elements, reach, grasp, move, and position, are shown. Each histogram represents 100 cycles for one subject and there was no interpolated practice (data of Seymour 1956).

§ 3. A THEORY OF THE SELECTIVE PROCESS

These findings strongly suggest that practice exerts a selective effect on the operator's behaviour, favouring those patterns of action which are quickest at the expense of the others. In order to examine how this might work, a mathematical model of the selection process has been constructed, and will now be formally stated and discussed.

Let us consider an operator learning a repetitive task. For each trial or 'cycle' he will adopt some particular combination of sensory, perceptual, and motor activities, partly from deliberate choice, partly from habit, and partly by chance; these activities could, in principle at least, be completely described by an observer. In successive cycles he will use either the same or more or less different combinations. Let us call each such distinguishable action-pattern a 'Method' (M) and identify each by a subscript (e.g. M_1). The operator can be imagined to possess a repertoire or stock of r different methods, from which he picks one by chance for each cycle. The methods will each have a different 'habit-strength', availability or probability of use; let M_i occur with probability p_i where $\sum_{i=1}^r p_i = 1$. At the outset of practice the repertoire will normally include some wholly unsuccessful methods, but let us imagine that these have been eliminated, and that the repertoire includes only successful ones. From this point on, practice produces a steady decrease in the average cycle-time. At any one cycle, say the n th, the average cycle-time $T(n)$ is the time for all the Methods, M_i , weighted according to their probabilities p_i of occurring, i.e.

$$T(n) = \sum_{i=1}^r t_i \cdot p_i(n) \quad \dots \dots \dots (1)$$

where t_i = time taken by method M_i .

We assume that a selective effect takes place, increasing the availability of 'fit', i.e. quick methods, and reducing it for 'unfit', i.e. slow ones. To be precise, the speed of any method which happens to be used is measured in relation to the current average, and its probability of occurrence then changes in proportion to the result. Algebraically, let method M_i whenever it occurs have its future probability of being chosen increased by δp_i where

$$\delta p_i = -k(t_i - T(n)) \quad \dots \quad (2)$$

(where k is a small positive constant). Since M_i occurs on the average $p_i(n)$ times per cycle, the average change in its probability on one cycle is

$$p_i(n) \cdot \delta p_i = -k p_i(n) \cdot (t_i - T(n)) \quad \dots \quad (3)$$

and its probability for the next $(n+1)$ th cycle is,

$$p_i(n+1) = (p_i(n) + \delta p_i) = p_i(n)[1 - k(t_i - T(n))]. \quad \dots \quad (4)$$

The average cycle-time for the next or $(n+1)$ th cycle can now be calculated

$$T(n+1) = \sum_{i=1}^r p_i(n+1) \cdot t_i = T(n) - k \text{ (variance of the } t_i). \quad \dots \quad (5)$$

(It is a convenient property of expression (4) that the sum of the $p_i(n+1)$ remains unity, hence no 'normalizing factor' is needed.)

Ideally the next step would be to express $T(n)$ as an explicit function of n , and plot the resulting learning curve; this can be done but the expression is

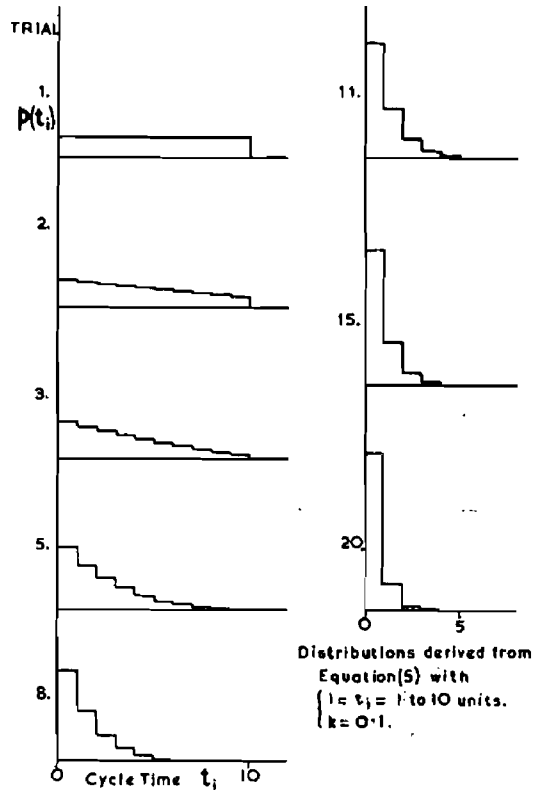


Figure 6. The distributions of cycle-times at successive cycles as predicted by the theoretical model (eqn. 5) for an imaginary task with 10 methods in the operators' repertoire ($k=0.1$).

complicated and involves high order moments of the initial distribution of the t_i . Instead, a learning curve has been computed numerically for an imaginary task where the learner starts with ten equiprobable methods, whose times are the integers 1 to 10, and practises with a selective constant $k=0.1$. The distributions for the first 20 cycles are given in Table 2, and plotted in Figs. 6, 7 and 8.

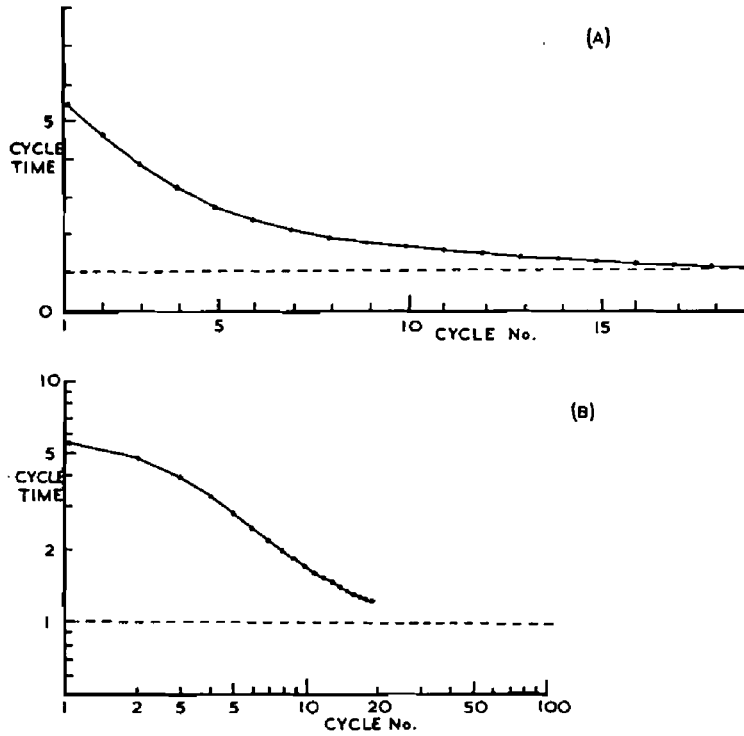


Figure 7. The learning-curve given by the theoretical model, plotted (A) on linear, (B) on double logarithmic coordinates.

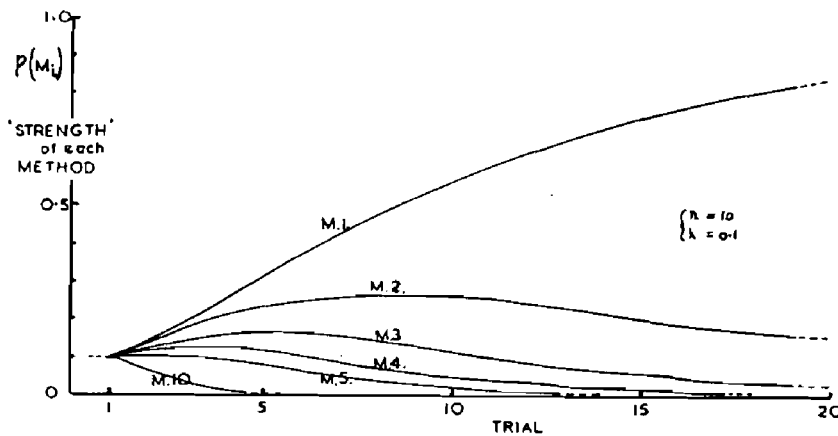


Figure 8. The change of availability of methods as practice proceeds according to the theoretical model eqn. 5.

Table 2. The Learning Performance of the Theoretical System

Time taken by method (units)	Probability of method							
	Cycle 1	2	3	5	8	11	15	20
1	0.1	0.145	0.198	0.315	0.476	0.607	0.733	0.839
2	„	0.135	0.171	0.230	0.264	0.253	0.205	0.140
3	„	0.125	0.146	0.164	0.140	0.097	0.050	0.020
4	„	0.115	0.123	0.114	0.069	0.030	0.101	0.002
5	„	0.105	0.102	0.075	0.031	0.010	0.002	—
6	„	0.095	0.082	0.047	0.013	0.003	—	—
7	„	0.085	0.065	0.028	0.005	—	—	—
8	„	0.075	0.050	0.016	0.002	—	—	—
9	„	0.065	0.037	0.008	—	—	—	—
10	0.1	0.055	0.026	0.003	—	—	—	—
Av. time	5.5	4.68	3.92	2.80	1.98	1.59	1.39	1.19

By comparing Fig. 1 with 7, and 5 with 6, the reader will see that the model does fit the experimental findings. There is only one clear discrepancy: the first few cycles of practice should be faster than de Jong's law suggests, and on this point there are indications (see e.g. Fig. 1) that the model gives a rather better fit to the experimental data than de Jong's formula. The theory could be tested more rigorously by applying it to the actual starting distribution for an element or cycle and testing the agreement between the predicted and actual learning-curves.

The curve of Fig. 8 shows that some individual methods may increase in strength at first, and only later decline towards zero; this recalls what does not seem to have been shown experimentally but can easily be seen in industrial practice, that certain methods may be learned at first, only to be discarded again as the average speed increases.

Several complications which arise in the real situation have been ignored, and a few of them will be briefly indicated:

1. It has been assumed that only one repertoire is being subjected to selection. In a real task there will be one for each different work-situation or sub-task that arises. Thus in reality several largely independent selection-processes must be going on at once.

2. Selection may act on elements rather than on the complete cycle. In order to find the distribution of cycle-times, one must then combine those of the element-times by *convolution*. The combined distribution may be quite unlike the separate ones (Fig. 9), and tends to be more and more Gaussian as the number combined increases (by the Central Limit theorem). The element-times for a long cycle must be highly skewed before the cycle-time is appreciably so.

3. The time for any one method may not be constant, but affected by chance variations in the work. This complicates but does not essentially change the picture.

4. The operator's repertoire may gain or lose methods during practice, by deliberate or chance invention, by instruction, or by forgetting. The rate of

learning is then affected in proportion as the variance of method-times is changed (eqn. 5), sometimes abruptly so.

5. The availability of methods may change for reasons other than selection. For instance, fatigue may be expected to reduce availability for any method which is used. The selection process would then be progressively distorted as any one practice period proceeds.

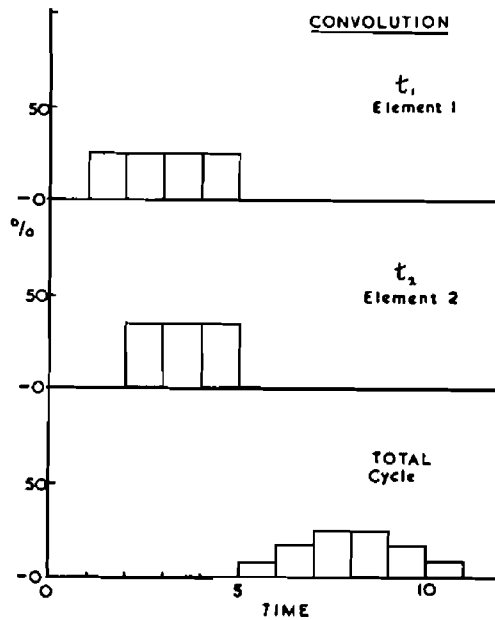


Figure 9. The frequency distributions of times for two elements combined by convolution to give the distribution of cycle-times.

Despite the complications, certain conclusions follow from the theory. First, the rate of learning for a sub-task will depend on the size of the learner's repertoire for it; on the variance within it, which in turn depends on the amount of previous selection; and on the selection pressure. Secondly, the overall learning period will increase steeply with the number of sub-tasks to be learned and with the initial variance of the repertoire for each; tasks whose sub-tasks are independent of each other will be more rapidly learned than those in which they interact. Third, transfer of skill from one task to another will take place where methods appropriate to one are also appropriate to the other, but the amount of transfer will depend on the *selectivity* that has been established rather than on the mere coincidence of methods.

The particular model given is only one out of a class of such models. The principle of selective processes in general can perhaps best be set out in a diagram (Fig. 10). The learner possesses a 'Pool of Methods', each with a certain strength, but no means of choosing particular ones; they differ in various respects, producing a variance in any given characteristic. The pool may have its variance increased or diminished as practice proceeds. The most important cause of reduction is selection in favour of methods more closely adapted to the work-situation. A parallel to this process is to be found in the genetical theory

of natural selection (Fisher 1930); here the genetic variance of a population is increased by mutation and reduced by natural selection. Unfortunately Fisher's mathematical treatment deals with two-factor (Mendelian) inheritance, and cannot be applied directly to this multifactor problem.

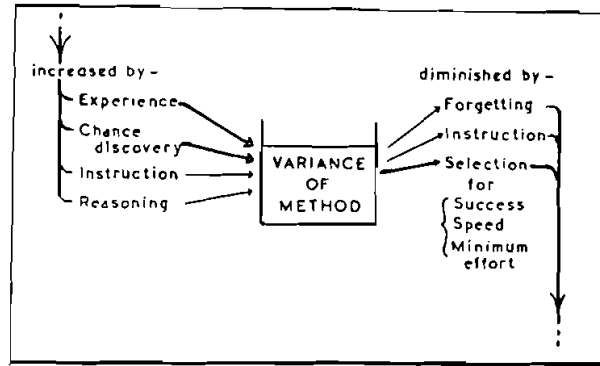


Figure 10. A diagrammatic representation of the selective process in the acquisition of skill.

§ 4. THE SELECTIVE MECHANISM

Although selection of methods for their relative speed has been postulated to account for the acquisition of speed-skill, it is not at all easy to see how the psychological and neural mechanisms could produce this result. At each trial the operator would have in some way to retain data about what method had been used, measure the time it took, and then alter its 'strength' in proportion. But judgment of short time-intervals is very inaccurate, and externally given knowledge-of-results such as the time taken for so many pieces, is not detailed enough to be effective. Instead of *time* the selective variable might well be *work* for if the operator exerts a constant level of effort, the work done to complete a cycle by any particular method would be proportional to its duration. If this were so, one would regard the gradual speed-up with practice as being secondary to the operator's pursuit of the minimum (physiological) 'cost' to himself, and the acquisition of speed-skill could be seen as an instance of the more general biological principle of 'Least Effort' (see e.g. Zipf 1949). Unfortunately there is even less indication that a mechanism exists for measuring physiological cost than one for measuring time.

A plausible case might be made for a mechanism based on the time-course of the decay of short-term memory. The method used for any given trial must necessarily be remembered to some extent, if any selective reinforcement is to take place at all, and it is obviously not permanently and perfectly remembered. If, as other experiments suggest, the memory of what has been done decays in a regular way with time, this might provide the necessary time-scale for the selective process. If the memory could be in some way 'fixed' by the successful completion of the element or cycle, then the sooner this happened, the more memory would remain to be fixed and the more chance there would be that the precise method would be recalled and repeated. Since most motion-elements seem to require a perceptual completion-signal of some kind, its arrival could cause the memory to be fixed.

§ 5. IMPLICATIONS FOR TRAINING

If the acquisition of speed-skill depends primarily on a selective process, it follows that training should aim at deliberately strengthening the selection-pressure, while taking steps to ensure that the best 'methods' are in the learner's repertoire to be selected. The trainer must first know what is to be selected, i.e. what methods (both perceptual and motor) give fast performance; secondly, he must ensure that the learner can do them; and thirdly he must set up conditions in which they are consistently more successful than all others.

Verbal or visual instruction and demonstration are of use for putting the best methods into the repertoire, but for selection systematic practice under pressure for speed is probably the only effective way. Breaking down the task into elements increases selective efficiency, but the trainer must ensure that by so doing he does not find wrong methods being selected, that is ones that are optimum in the isolated element but not in the complete task. Those elements which have most variation of method need most selection and should be isolated; they are usually the ones which are highly specific to the particular job and so have not been selected by previous practice. Training for transfer, except where there are many identical elements, should presumably be aimed at giving the learner a good power of selection.

§ 6. FURTHER RESEARCH

Studies of the distribution of methods rather than of times should show more clearly what is happening, and just how certain methods are selected; and tasks might be set up in which different sorts of selective pressure could be applied. Further mathematical analysis is also needed to make possible a proper comparison between theory and experiment.

On cite des recherches récentes qui donnent à croire que l'acquisition de l'habileté à vitesse manuelle a lieu par moyen d'un certain genre d'action sélective. Un modèle formel théorique est développé, et ses prédictions sont rapportées aux résultats des expériences. De certaines complexités de la théorie, et des conclusions qu'on peut en déduire, sont décrites, et l'essence du mécanisme de sélection est discutée. Quelques implications pour l'entraînement sont indiquées.

Es wird über neuere Forschungen berichtet, die annehmen lassen, dass die Erwerbung manueller Geschwindigkeits-Geschicklichkeit durch eine Art selektiver Handlung erfolgt. Dafür wurde ein theoretisches formales Modell entwickelt und die sich daraus ergebenden Voraussagen mit den experimentellen Resultaten verglichen. Gewisse Komplikationen der Theorie und Schlüsse, die sich daraus ziehen lassen, werden besprochen und die Natur des selektiven Mechanismus diskutiert. Einige Folgerungen, die sich daraus für das Anlernen ergeben, werden aufgezeigt.

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