FACTORS AFFECTING INDUSTRIAL LEARNING ON INTERRUPTED PRODUCTION SCHEDULES

by

ROGER WARREN DANIELS

B. S., University of Illinois, 1964

A MASTER'S THESIS

submitted in partial fulfillment of the

requirements for the degree

MASTER OF SCIENCE

Department of Industrial Engineering

KANSAS STATE UNIVERSITY
Manhattan, Kansas

1966

Approved by:

Major Professor

LD
2668
T4
1966
D35
c.2
Document

ACKNOWLEDGMENTS

I would like to acknowledge the constructive contributions and criticisms offered by the faculty and graduate students of Kansas State University, the consideration and assistance of industrial representatives such as Mr. T. K. Merrill, Mr. Marvin Wilson, and Mr. Verlis Miller, the forbearance and laboratory assistance of Mr. Doug Heath, and the heroic efforts of a very conscientious typist, Mrs. Peggy McCullick.

Most of all, however, I owe a great debt of gratitude to my major professor, Doctor Stephan A. Konz, for the opportunity to undertake such a work, for his gentle prodding and encouragement, for his technical advice and assistance in all phases of the work, and for his boundless and incessant patience. Thank goodness he had enough for both of us.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF ILLUSTRATIONS

FACTORS AFFECTING INDUSTRIAL LEARNING ON INTERRUPTED PRODUCTION SCHEDULES

1. INTRODUCTION

In retrospect, the Manufacturing Progress Function introduced by T. P. Wright (1) in 1936 represented the first industrial application of psychology's learning theory, initiated in 1885 by Ebbinghaus (2), to the man-machine system. Although, at the time, the "discoveries" of Wright were not directly associated with or developed from the work of Ebbinghaus and his successors, the associative link of application can be contrived.

Thenceforth, the applications of "learning curves" to the manufacturing situation have been numerous and varied. Blume and Norris (3) of North American Aviation employed simple examples to demonstrate the use of learning curves to determine subcontract lead time, labor loads, floor space requirements, assembly tool requirements, unit selling price, working capital requirements, subcontract cost control points, synthetic standards for small assemblies, and production schedules. Knowles and Bell (4) described the use of learning curves in cutting new employee training costs. Nissley (5) presented the use of learning curves in setting job shop standards. Ghormley (6) described applications of learning curves to evaluation of supervisors, to worker selection, and to evaluation of management policy changes. The literature is replete with descriptions and examples of learning curve applications.

Current manufacturing trends in industries such as electronics, military and space products, communications, and even some lines of consumer products have severely limited the use of learning curves and their concomitant applications. Foremost is the trend away from strict product standardization in those industries. Manufacturers now offer a wide variety of products, each having many options or "flavors". Furthermore, the rate of technological development in some industries is such that products can become obsolete before they leave the production floor. Thus, instead of building many hundreds of thousands of a few items in a product line, today's manufacturer is often faced with the problem of building but a few units of hundreds, or even thousands, of items comprising his product line.

For example, a customer who formerly ordered one thousand flight computers to be delivered over ten months at a rate of one hundred per month might today order one hundred of each of ten different flight computers to be delivered over ten months at a rate of ten of each type of computer per month. Formerly, at a rate of one hundred assemblies per month, the manufacturer could keep five people busy all month filling that order. Learning curves could be applied to each of the five workers, thereby taking advantage of the afore-mentioned applications.

Under the hypothetical example of the current situation (ten units per month of each of ten different flight computers), one worker would build ten units in the first half of the month. He would then have to work on a different assembly, perhaps even another type of flight computer, for the remainder of the month, as the prohibitive cost of excessive finished goods inventory would likely preclude the possibility of his building the ten month scheduled quantity of one hundred units on a continuous schedule over the first five months.

In short, the production employee no longer can build one item on a continuous basis. Instead, he must build two, three, or more different items on an alternating schedule. Thus, there could be a lapse of days, weeks, or even months between the time that an operator built his tenth unit of the C-3 flight computer and the time he built his eleventh unit of the same C-3 flight computer. Similar interrupted build schedules for a given operator on a given item or assembly occur in the rework and repair areas of even mass production manufacturers.

Can one still apply the learning curve to interrupted build schedules? What modifications must be made to the traditional learning curve model? What are the significant parameters reflected in those modifications? These are the questions to be investigated herein.

First, an investigation of the various Manufacturing Progress Functions and learning curves will be presented for the purpose of defining and describing the "traditional" learning model. That will be followed by a theoretical development of an "interrupted" learning model. Finally, a description of the experimental design and the laboratory study undertaken to test the parameters of the "interrupted" learning model and the results obtained will be presented.

2. THE "TRADITIONAL" LEARNING CURVE MODEL

2.1 Manufacturing Progress Curves

Dr. T. P. Wright, upon reviewing production costs for production runs of aircraft at the Curtiss-Wright Corporation, discovered that as more and more planes were built the average cost for a plane in a given production run was less than the average cost of the same model plane in prior production runs. The average cost for a plane in a production run was determined by dividing the total cost for a production run by the number of planes in the batch.

Conway and Schultz (7) listed eight during-production factors which could result in the cost reductions observed by Wright. These factors were:

1. Tooling--changes during production, methods of increasing capacity for increasing demand (replication or redesign of production processes).
2. Methods--changes during production, work simplification, operator-originated changes, process changes.
3. Design changes--the degree to which manufacturing and product designs are changed to allow minor savings, specification changes resulting from test and inspection experience.
4. Management--improved planning, scheduling and supervision to encourage progress, to increase effectiveness, and to diminish delays and idle time.
5. Volume changes--changes in rate or anticipated duration of production which affects other factors and decisions.
6. Quality improvements--the gradual reduction of rework and repair operations, the reduction of scrap losses.
7. Incentive pay plans--manner in which administered, the point in the production cycle at which they are installed.

8. Operator learning--degree to which operators decrease time utilized in execution of a specific task.

Doyle (8) broke the last factor, operator learning, into:

(a) The ability of workers to learn and improve their work through repetition, and

(b) The dimunition of conscious attention as a routine is learned.

Conway and Schultz felt that "contrary to the opinion of many such reporters it is believed that operator learning in the true sense of performance of a fixed task is of negligible importance in most manufacturing progress." On the other hand, Kottler (9) stated that "Most proponents of the learning curve theory agree that the first (another list) factor, worker learning, is the most important contributor to the following of a learning curve." Acknowledging the latter viewpoint, this paper will consider operator learning as a separate entity. The progress curve for an operator working on a fixed task will be called a "learning curve", whereas the progress curve for an entire manufacturing situation will be called a "Manufacturing Progress Curve", and will be subject to the afore-mentioned production parameters.

As Wright gathered more data on the cost reductions of planes as more and more planes were built, he began to see a regular pattern in the decline. Plotting the average cost of a batch of planes versus the cumulative number of that type of plane built, he arrived at a smooth exponential curve. Plotting the same data on log-log paper, Wright obtained a straight line. See Figure 1. He then suggested an equation of the form:

$$Y = AX^b \tag{1}$$

where X = number of aircraft built

Y = average cost of the X'th aircraft

A = cost for the first aircraft

b = a measure of the rate of reduction in cost.

Note that the exponent b, the rate of reduction in cost, is a constant. A characteristic of Manufacturing Progress Curves (and learning curves), depicted as straight lines on log-log paper, is that as the quantity is doubled, the cost is reduced by a constant percentage, z. Thus, an 80% (z = 80%) curve means that the cumulative average cost for the first four planes would be eighty per cent of the cumulative average cost of the first two planes. Assuming that the first airplane cost $100,000 and that an 80% Manufacturing Progress Curve was applicable to the situation, the cumulative average cost for succeeding planes is shown in Table 1.

The percentage of reduction between doubled quantities, z, is related to the exponent, b, of equation 1 by the following equation from Raborg (10):

$$b = -3.32 \log \left(\frac{100\%}{z}\right) \tag{2}$$

Table 2, from Janzen (11), contains values of b for various common values of z.

The next step in the development of the Manufacturing Progress Curve was to devise a curve showing the unit cost for any particular unit. Since historical unit cost data was either not available or difficult to obtain because long, costly stopwatch

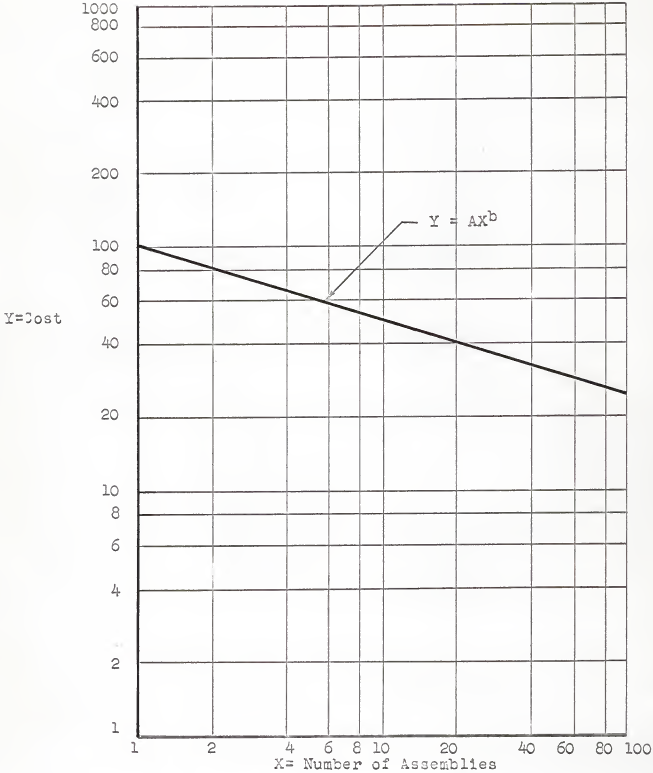


Fig. 1--Wright's Manufacturing Progress Curve.

TABLE 1

CUMULATIVE AVERAGE COSTS OF AIRPLANES ASSUMING AN 80% CUMULATIVE MANUFACTURING PROGRESS CURVE

Number of Planes	Cumulative Average Cost
1	$100,000
2	80,000
4	64,000
8	51,200
16	40,960
32	32,768

TABLE 2

VALUES OF THE RATE OF REDUCTION EXPONENT, b, FOR COMMON PERCENTAGE OF REDUCTION, z, VALUES

z	b	1+ b
70%	-.514	.486
72%	-.474	.526
74%	-.434	.546
76%	-.396	.604
78%	-.358	.642
80%	-.322	.678
81%	-.304	.696
82%	-.286	.714
83%	-.269	.731
84%	-.252	.748
85%	-.234	.766
86%	-.218	.782
87%	-.201	.799
88%	-.184	.816
89%	-.168	.832
90%	-.152	.848
91%	-.136	.864
92%	-.120	.880
93%	-.105	.895
94%	-.089	.911
95%	-.074	.926
96%	-.059	.941

study was required, the unit cost curve was developed from the cumulative average cost curve.

The unit cost and the cumulative average cost for the very first unit built would be the same--$100,000, for example. If the second unit cost $60,000, then the average cost for the first two units would be $80,000. Thus, the cumulative average curve would be eighty per cent. In like manner, the rest of the unit cost points could be determined. For a complete mathematical and graphical development of the various cost curves, see Berghell (12).

A unit cost curve, along with a cumulative average cost curve, is shown in Figure 2. Note that, except for the first few units, the unit cost curve is essentially a straight line which is parallel to the cumulative average cost curve. The vertical distance between the parallel portions of the two curves is such that, at any point on the independent axis, the value of the unit cost curve is equal to $(1 + b)$ times the value of the cumulative average cost curve, where b is the exponent in the mathematical models. Refer to Table 2.

Although mathematically the unit cost curve should never parallel exactly the cumulative average cost curve, most investigators (12) admit that the deviation from parallelism becomes insignificant after twenty units. Furthermore, many users (3) (13) assume a parallel relationship from unit three to infinity and a converging straight-line relationship from unit three back to unit one.

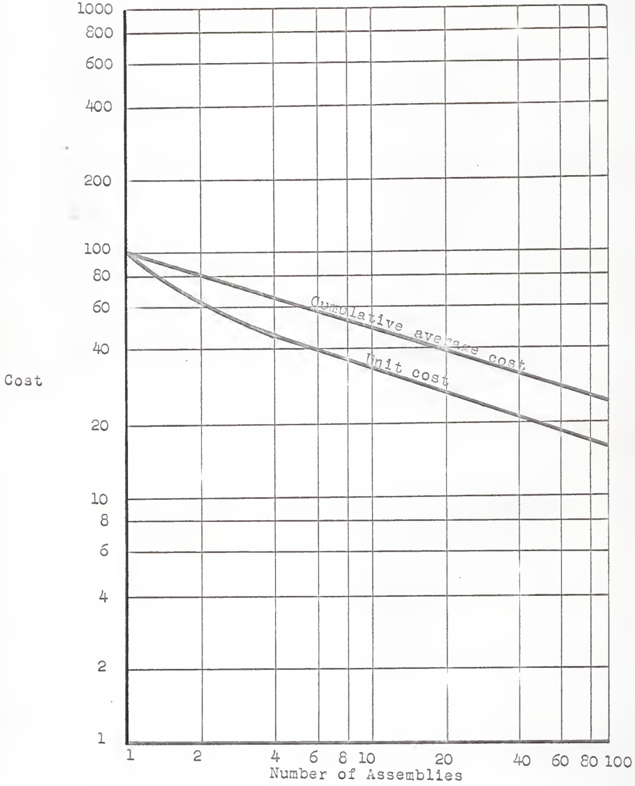


Fig. 2--Cumulative average cost and unit cost Manufacturing Progress Curves.

Initially, the aircraft industry found that costs for many of its planes followed the 80% cumulative average cost Manufacturing Progress Curve. Thus, the 80% curve was adopted throughout the industry and was referred to as the "Curtiss 80% Curve" (13).

In 1951, Conway and Schultz questioned the existence of a "universal 80% curve". Andress (14) and Jordan (15) pointed out the fact that a 100% automated job could not improve at an 80% rate since the big factor in manufacturing progress, namely operator learning, is not available. Jordan suggested the following criteria for selecting the applicable percent improvement curve:

75% manual, 25% machine task---------use an 80% curve

50% manual, 50% machine task---------use an 85% curve

25% manual, 75% machine task---------use a 90% curve

In 1963, Zimmerman (16) described the following factors of slope determination:

1. The degree of machine and process control of operations
2. Complexity of manufacture
3. Accessibility
4. Effective units of learning
5. Rate or production schedule

Numerous subsequent studies have centered around determining the slopes for various tasks and processes.

With this background in Manufacturing Progress Curves, the ensuing section will discuss in greater depth one of the most important constituents of the Manufacturing Progress Curve, the (operator) learning curve.

2.2 The Learning Curve

As described earlier, the learning curve is the improvement shown by a given operator on a fixed task in which the method and required work content are held relatively constant. Improvement is realized from faster movements, tool and workplace familiarity, repetition, elimination of fumbles, reduced information gathering and decision time, and the reduced need for diligent attention. Unlike the Manufacturing Progress Curve, the learning curve does have a limiting value beyond which the operator theoretically can not improve.

The axes for the learning curve and the Manufacturing Progress Curve are the same: number of units produced on the independent axis and cost on the dependent axis. However, where cost is usually measured in dollars for the Manufacturing Progress Curve, it is often measured in units of time for the learning curve.

The models developed for the Manufacturing Progress Curve are equally applicable to learning curves. Many studies of learning curves involve timing operators on a unit to unit basis. Thus, a unit learning curve is used more frequently than a cumulative average learning curve.

To avoid the mathematical complications of the non-linear (on log-log coordinates) model developed for the unit Manufacturing Progress Curve, many researchers assume a linear logarithmic unit learning curve. As pointed out by Torgerson (17), neither model can be substantiated on the basis of logic. The only supporting evidence for either model is empirical. To date, this empirical evidence is far from sufficient to prove one model better than the other over the first few cycles where the models differ. The straight-line cumulative average cost model was proposed because, as mentioned previously, the data available to Dr. Wright was cumulative in nature. Had unit cost data been available, it is quite likely that the unit cost curve would have been linear instead of the cumulative average cost curve being so. Torgerson went on to state "The only remaining basis for selecting one model over the other must be due to the preference of the personnel using the model and the use to which the model will be put."

Psychologists and industrial investigators have proposed several additional learning curve models, some of which do not seem too applicable to the industrial situation. They will be presented briefly in the following paragraphs. Graphical representations of those models, along with the straight line unit model and T. P. Wright's unit model, are shown in Figure 3.

Psychologists have described an "S" shaped curve composed of three stages. The first stage, the acquisition stage, proceeds at a high initial rate associated with the cognitive aspects of the task (18).

The second stage, the plateau, is one in which the operator improves very little or not at all. There is considerable controversy over whether or not plateaux are a legitimate learning curve characteristic or merely the result of subjective factors. If plateaux do exist, Cox (18), Bryan and Harter (19), and Batson (20) agree that they are a result of consolidation of lower level

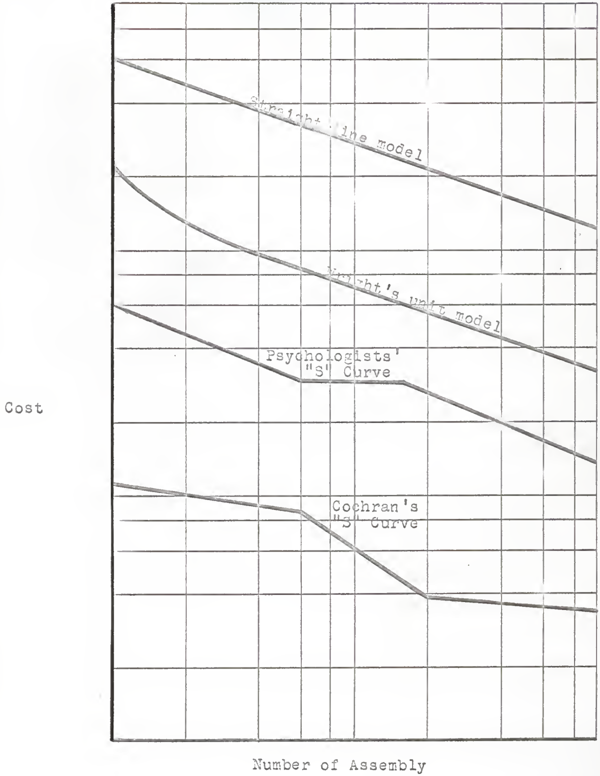


Fig. 3--Examples of various forms of unit cost learning curves.

learning achievements prior to shifting into a progressively higher level learning requirement.

The final stage is another period of rapidly progressing learning, due to the realization of higher level learning achievements and improvements in motor skill.

An interesting contrast is the "S" curve described by Cochran (21). This "S" curve has a slow initial stage, an accelerated second stage, and a slow final stage. This is just opposite from the psychologists' "S" curve. In all fairness, however, Cochran's "S" curve is more directly related to the Manufacturing Progress Curve than to operator learning.

There are several other adaptations of the Manufacturing Progress Curve, such as the Stanford "B" Curve, the Rand Modified Progress Curve, and the Boeing Modified Progress Curve. A brief description of these curves is included in Torgerson (17) and Zimmerman (16).

Extensive experimentation in the area of operator learning curves has been conducted in the psychological and industrial applications fields, although a preponderance of work done to date has been very specialized and quite removed from the realities of the industrial situation. Although summaries of the many investigations conducted will not be included herein, the interested reader is referred to Konz (22) for an extensive description of work conducted in the industrial field. In addition to the several periodicals and journals which report on the field of applied psychology, several texts describe learning curve research in the psychological sphere, of which Bugelski (23), Hilgard (24), and Finlay, Sartan, and Tate (25) are recommended.

2.3 Selection of a Traditional Improvement Model

Having now examined the development of several Manufacturing Progress Curves and learning curve models, it is necessary to select one model from which to develop, and against which to compare, an "interrupted production" progress model. The basic model to be selected will hereafter be referred to as the "traditional" model.

The traditional model selected by this investigator has four major characteristics. First, it is a learning curve rather than a Manufacturing Progress Curve. Second, it is a simple exponential curve throughout. That is, it is linear when plotted on logarithmic coordinates. Third, it is a unit cost curve, rather than a cumulative average cost curve. Finally, cost is defined in terms of time, instead of in monetary terms. An example of the traditional model is shown in Figure 4.

The learning curve was selected over the Manufacturing Progress Curve for its relative ease of experimental control. Improvement realized with the learning curve results from the attainment of higher levels of mental and physiological proficiency by the operator. In addition to the development of operator proficiency, Manufacturing Progress Curves reflect changes in the task and work environments, such as new methods, new tools, and the other factors mentioned previously. Any such changes in the task or work environment occurring immediately before, during, or immediately after an interruption or break in the production schedule would likely compound, confuse, or conceal the effect of the interruption. How does an experimenter control the

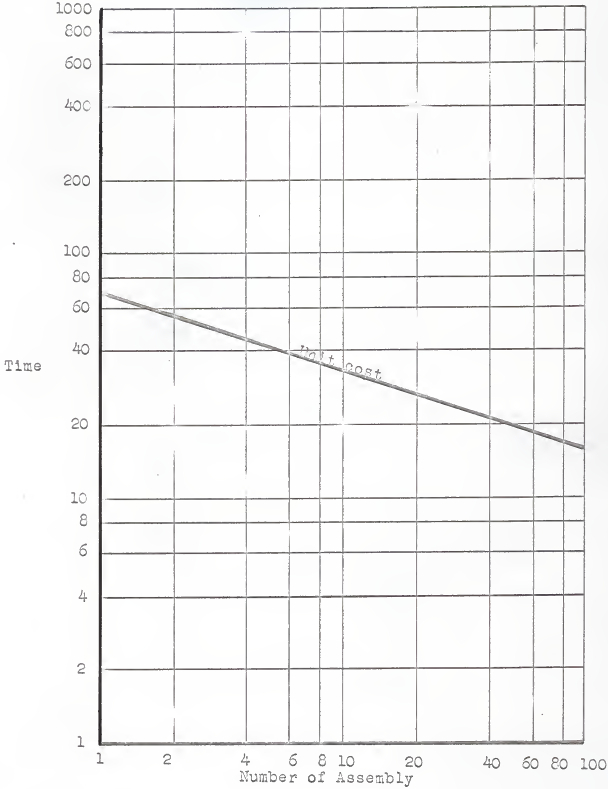


Fig. 4--The traditional learning curve model selected.

unpredictable, perhaps fortuitous, tooling changes, design changes, methods changes, or other such changes? This experimenter has controlled such changes by eliminating them altogether. The experimental design is one in which the method and required work content are held constant for a given operator--the conditions applicable to the learning curve.

The simple exponential model was selected over Wright's unit cost curve, the "S" curves described by Cox and Cochran, or the other modified Manufacturing Progress Curves for its mathematical and graphical simplicity and its basic acceptance among experimenters. Use of a modified Manufacturing Progress Curve would be hard to justify, since a learning curve model had been positively confirmed in industrial applications. Furthermore, the "S" curves described by Cox are, in a sense, just opposite the "S" curve described by Cochran. Wright's unit cost curve is very similar to the simple exponential model, the only significant difference occurring over the first three units. Any conflict between this model and the model selected would be of little consequence if the critical events designed into the study occurred after the third unit of production, as was provided in the experimental design presented later in the work.

A unit cost curve, rather than a cumulative cost curve, was selected because data could be more precisely collected and analyzed on a unit by unit basis than on a cumulative units basis. The justification for using a straight line logarithmic model in conjunction with a unit cost curve, instead of with a cumulative average cost curve per T. P. Wright, is based on the belief that

Wright's straight line logarithmic cumulative average cost curve was based on simplicity and expediency, rather than on the results of irrefutable, controlled experimentation. Thus, taking advantage of the investigator's prerogative by Torgerson, this experimenter selected the linear logarithmic unit cost curve.

Since the task and methods were relatively fixed, the major cost variable was operator labor costs which, in turn, is a direct and simple function of time taken by the operator to perform the task. Thus, time was selected as the measure of cost. Time is relatively easy to control and observe accurately.

3. DEVELOPMENT OF THE INTERRUPTED LEARNING MODEL

Using the traditional learning curve model described in the previous section as a base, this investigator developed a theoretical "interrupted" learning curve model for tasks in which assembly periods on two successive units might be separated by a break or interruption of several days or weeks. Throughout the ensuing development of the interrupted learning model reference will be made to the graphic representation of the interrupted learning curve model shown in Figure 5. Necessary definitions will be indented and numbered in the body of the text as they are required.

3.1 The First Hypothesis

Hypothesis I: An interruption in production will result in the succeeding unit requiring more time than it would have required had there been no interruption.

1. interruption--a break of two or more days in the production of a given assembly by a given operator.
2. work interruption--an interruption during which the operator works on other assemblies.
3. non-work interruption--an interruption during which the operator does not work on any assemblies. This includes weekends, vacations, and other absences from work.

In short, the first hypothesis suggests that interruptions hinder progress and are therefore harmful and costly. The reasoning behind this statement is based on the assumed inability of an operator to completely return, following an interruption, to the mental and physiological skill levels attained through experience on prior assemblies. During the interruption the

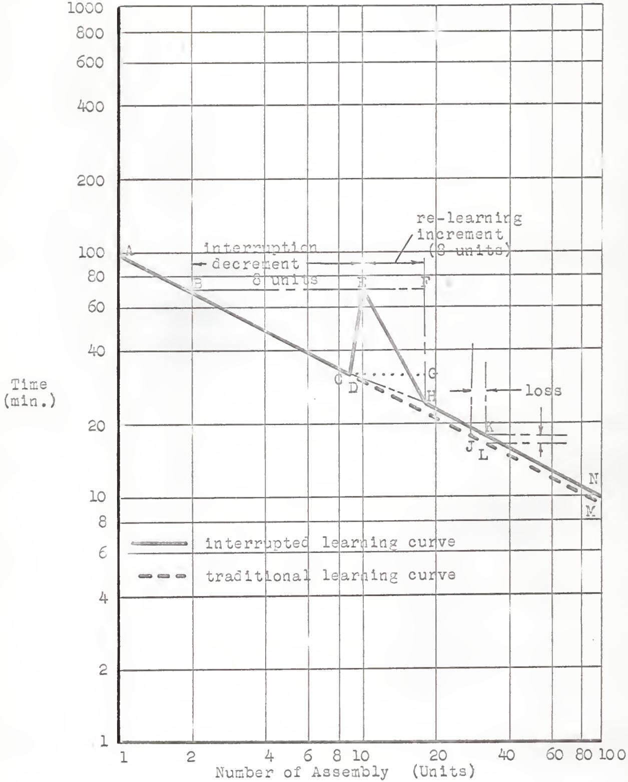


Fig. 5--The unit cost interrupted learning model.

operator will forget memorized instructions or portions thereof. He will also lose some of the dexterity gained through actual familiarity and manipulative practice with the tools, fixtures, piece parts, and other objects of the work station and task.

By studying long cycle tasks having a standard time of fifteen minutes or longer, and by defining interruptions in terms of days and weeks, it was anticipated that the detrimental effects mentioned above would greatly predominate over possible minor advantageous effects such as relief of boredom and fatigue.

On Figure 5, the straight line A-M depicts a traditional 70% unit learning curve. If an operator built nine assemblies, his learning curve for those first nine units would be that shown by the straight line A-C. If he continued and built the tenth unit, his time for the tenth unit could be determined by extending the straight line A-C to point D, yielding an anticipated time of about thirty minutes for unit ten. On the other hand, if the operator were interrupted after completing the ninth unit, according to Hypothesis I the anticipated time for unit ten, point E, would be greater than thirty minutes. Thus, the interrupted learning model for the first ten units built by this operator, assuming an interruption after the ninth unit, would take the form of straight lines A-C and C-E.

The height of point E above point D is hypothesized to be dependent upon such things as the length of interruption, the number of units built prior to the interruption, the complexity of the task, and the activity of the operator during the interruption. Such factors are the bases for the four hypotheses which follow.

3.2 The Second Hypothesis

Hypothesis II: The magnitude of the interruption decrement is dependent upon the length of interruption.

4. interruption decrement--the loss resulting from an interruption. Note that on Figure 5 the interruption decrement can be measured in number of assemblies (E-A) or in time (E-D).

This hypothesis is based on the belief that the longer the interruption the greater the interruption decrement, since the interruption decrement is largely due to the loss of retention, or forgetting.

3.3 The Third Hypothesis

Hypothesis III: The magnitude of the interruption decrement is dependent upon the "effective units of experience" prior to the interruption.

5. effective units of experience--the number of units actually built by an operator minus that operator's interruption decrement in terms of units. The effective units of experience at a point is the intersection of the traditional learning curve with a horizontal projection from that point on the interrupted learning curve. Thus, at point E in Figure 5, the effective units of experience would be two.

This third hypothesis is based on the belief, supported by Hancock's investigations (26), that interruptions will have a greater detrimental effect in the early stages of learning than after hundreds or thousands of units of experience. The use of "effective units of experience" provides a logical means of working with multiple interruptions over an operator's history on a particular assembly.

3.4 The Fourth Hypothesis

Hypothesis IV: The magnitude of the interruption decrement is dependent upon the information content of the task.

This hypothesis is one of two attempts to incorporate the concept of task complexity via a definite, definable measure of complexity. Attempts to develop an absolute universal procedure for the measurement of task complexity have met with little success because, this investigator feels, an important, yet unrecognized, variable is the use for which "complexity" is to be measured. Measures of complexity obtained for the purpose of pricing design modifications, for example, would likely have little meaning if used to predict how much information an operator would forget over a two-week vacation.

As mentioned previously, the interruption decrement reflects a mental loss of information and a physical or tactual loss of familiarity with objects related to the task. Of these two losses, the mental loss is applicable to each task, but the physical loss likely diminishes with the overall experience of the operator. Soldering irons, hog-nosed pliers, resistors, and many other items are common to numerous electronic assembly tasks. Thus, if an operator is shifted to another job during a work interruption, he will likely retain much of his tactual proficiency.

Therefore, the mental loss of information is likely the major component of an interruption decrement. Janzen (11) (27) separated read time (input-output time) from motion element time (processing time) and found that "the reduction of read time was the major factor in cycle improvement," and that it "tends to overshadow the improvement of motion elements." Correspondingly, the more information contained in a given task, the greater the opportunity for, and possibility of, forgetting during an interruption. One method for measuring the information content of a task is by the use of information theory as adapted for work analysis by Ross (28) and Fitts and Peterson (29), with a subsequent application by Hart (30).

Information theory applied to work analysis is a statistical concept based on the probabilities of occurrence of various stimuli confronting the operator. Included therein are the number of alternative actions available to the operator, the difficulty of discriminating between perceptions, subjective factors related to the operator, and environmental noise factors. Although at the present time the application of information theory to work analysis is somewhat complex and subjective, it is included as part of the interrupted learning model until a simpler, more objective measure of complexity is developed.

3.5 The Fifth Hypothesis

Hypothesis V: The magnitude of the interruption decrement is dependent upon the ratio of input-output time versus processing time.

6. input-output time--the time spent by an operator in perceiving, receiving, analyzing, and comprehending an instruction prior to initiation of action.
7. processing time--the time spent by an operator carrying out an instruction once it has been comprehended and a course of action has been chosen.

This hypothesis is an alternative attempt to include task complexity in the interrupted learning model. It is based on the same premise as was the previous hypothesis; that mental loss of information is likely the major component of an interruption decrement. Therefore, the higher the ratio of input-output time to processing time, the larger the interruption decrement.

This measure of complexity in the learning situation is included for its relative simplicity of application. The input-output/processing ratio can be determined by careful time study. It is likely, however, that this ratio will decrease as the operator builds more and more units, approaching zero as the operator memorizes the task and approaches a predetermined time standard. It is thereby essential to describe a point in the production schedule at which this ratio should be determined. Since the third hypothesis accounts for operator experience, this investigator has chosen to measure the input-output/processing ratio for skilled operators on their first unit of an assembly with which they have had no prior experience. Recognizing the degree of variability often accompanying performance on the first cycle, this investigator suggests taking the arithmetic mean of the ratios obtained over the first three cycles to smooth early fluctuations.

Note that this criterion of complexity is also somewhat subjective in that it has been defined for individual operators rather than for a population of operators or for a specific task. Until the impact of this complexity factor on the interruption decrement and the variability among individual operators' input-output/processing ratios are quantified, one can not determine whether universal ratios can be applied to the interrupted learning model, or if subjective individual ratios must be used to attain desired accuracy.

Although many other measures of complexity have been mentioned in the literature, the two studied in the preceeding hypotheses were selected for their direct relation to task information content. No suggestion of the cycle time of the particular task as a variable has been, or will be, made herein, either as a measure of complexity or as a separate variable influencing the magnitude of the interruption decrement. By measuring the interruption decrement in units lost, rather than in time, all assemblies can be reduced to a common denominator regardless of the cycle length. That is, an eight unit interruption decrement on a thirty hour job represents the same portion of the total job experience as does an eight unit interruption decrement on a thirty minute job, although the interruption decrements in terms of time might be forty hours and forty minutes respectively. Interruption decrements will therefore be measured in units lost rather than in terms of time.

3.6 The Sixth Hypothesis

Hypothesis VI: A non-work interruption is not the same as a work interruption.

Whether an operator goes on vacation for two weeks or just works on other assemblies for the two weeks could affect the magnitude of the interruption decrement and influence performance following a break. It is hard to predict which type of interruption will have a more deleterious effect. There are many complex and opposing factors included, such as fatigue and boredom relief, positive or negative transfer of training, the number of different jobs taken during a work break, personnel and personal problems of job rotation, and the similarity between the object task and the tasks performed during the interruption. It is hoped that the interrupted learning curve model can be kept simple by introducing different constants (in terms of units lost) for work and non-work interruptions, rather than attempting to isolate, study, and quantify each of the complex interactions mentioned above.

Having now described the important parameters necessary to determine the height of point E in Figure 5 following an interruption, it is necessary to define the shape of the interrupted learning curve model for succeeding units. Upon return from an interruption, the operator will, in the process of assembling units, recall or remember forgotten information and simultaneously assimilate some new information. This defines:

8. re-learning increment--the number of units following an interruption during which recall and new learning proceed simultaneously.

3.7 The Seventh Hypothesis

Hypothesis VII: Units built during the re-learning increment are built at a faster rate than are units built on a non-interrupted basis using the traditional learning curve model.

Referring again to Figure 5, this hypothesis assumes a straight line from point E to some point H, as yet undefined, such that the slope of line E-H is greater than the slope of line A-M, the traditional learning rate. This hypothesis is based on the proven premise that recall proceeds much faster than new learning. Hancock reported that "the rate of improvement to the performance level before he (operator) stopped was quite rapid". Non-industrial studies conducted in the field of psychology further support this premise.

Note that F-H, the vertical component of line E-H, is composed of two segments, F-G and G-H. Segment F-G is the vertical component of line C-E and represents the amount of information forgotten during the interruption and subsequently recalled during the re-learning increment. Segment G-H represents the amount of new information learned during the re-learning increment. The line C-H represents the rate of new learning during the re-learning increment. This rate of new learning during the re-learning increment is slower than the rate of learning on the traditional learning curve model, line A-M, because some of the operator's attention and learning abilities are devoted to recall. It is hypothesized that new learning and recall proceed simultaneously along line E-H since there is no reason to believe otherwise.

3.8 The Eighth Hypothesis

Hypothesis VIII: The re-learning increment (units) is equal to the interruption decrement (units).

This hypothesis states that an operator who had an interruption decrement of "n" units, or who essentially forgot "n" units of experience, would completely and simultaneously recall all of the forgotten information and learn additional new information within "n" additional uninterrupted assemblies. The intent here is to define the end point of the re-learning increment.

Two opposing effects are balanced in this hypothesis. As stated earlier, recall proceeds at a faster rate than does initial learning. Therefore, if eight units of experience were lost in the interruption decrement, one would expect to recall all of that same information in less than eight additional uninterrupted units, perhaps in six or four units time. However, the operator does not devote full attention and learning ability solely to recall. New learning occurs also. Therefore, if only a portion of the operator's ability is devoted to recall, the re-learning increment would stretch out to perhaps eight or ten units. Since no work has been done in this field, this model assumes a convenient balance such that the re-learning increment is equal to the interruption decrement when both are measured in terms of units or number of assemblies.

By working with "effective units of experience" as defined previously, one can study the effects of an interruption occurring even within a re-learning increment.

3.9 The Ninth Hypothesis

Hypothesis IX: After the re-learning increment, learning proceeds at a rate equal to the rate for the non-interrupted traditional learning curve model.

In Figure 5 this means that the line H-N is parallel to line A-M. Since, by definition of the re-learning increment, all recall has been completed prior to point H, all operator learning after point H is new learning. Clearly then, the situation is the same as for traditional learning and the resultant model should take the same form as the traditional learning model until another interruption occurs.

3.10 The Tenth Hypothesis

Hypothesis X: There is a non-recoverable loss due to interruption.

This means that the harmful effect of an interruption is never completely overcome, even after complete recall during the re-learning increment. Once an interruption has occurred, an operator's effective units of experience will always be less than his actual units of experience. Figure 5 depicts two methods of measuring the non-recoverable loss due to interruption. The horizontal distance between points J and K measure the loss in units of production, while the vertical distance between points K and L measure the same loss in terms of assembly time on a particular unit.

The non-recoverable loss stems from the reduced rate of new learning that takes place during the re-learning increment, depicted by the slope of the line C-H. The interrupted operator must recall and learn new information, whereas the uninterrupted operator on the traditional model would devote full capabilities to new learning. Thus, at any subsequent assembly number, the uninterrupted operator could assemble that unit faster than could an interrupted operator.

3.11 Summary of Hypotheses

The ten preceeding hypotheses have completely defined the theoretical interrupted learning curve shown in Figure 5 as the straight lines A-C, C-E, E-H, and H-N. Point A is the initial point of the traditional learning curve. Point C is the first point on a traditional learning curve at which an interruption occurs. Point E is one unit to the right of point C and above (by Hypothesis I) the traditional learning curve. The distance of point E above the line is established by Hypotheses II, III, IV, V, and VI. Point H is located by drawing a straight line parallel to line A-M (by Hypothesis IX) and above line A-M by an amount equal to the non-recoverable loss (Hypothesis X). Point H is located where that line intersects the vertical line which is a number of units (equal to the interruption decrement by Hypothesis VIII) to the right of point E.

Having thus described and developed the interrupted learning curve model, the following section will outline the procedure for investigating the hypotheses presented in an industrial situation and the modifications made to that experimental procedure for the laboratory study that was conducted.

4. THE EXPERIMENTAL DESIGN

The first part of this section outlines the actual experimental design developed to test the hypotheses of the interrupted learning model in the plant of an electronics manufacturer. Although abrogation of that company's permission to conduct the experiment at their facility resulted in a laboratory investigation on a more limited scale, as described in the latter portion of this section, a discussion of the development of the original industrial experimental design is included to amplify the interrupted learning curve model and to demonstrate the application of this model to the industrial situation.

4.1 The Industrial Experimental Design

4.1.1 The task. Since the model to be tested was a learning curve model and not a Manufacturing Progress Curve Model, it was important to select an assembly which had been built frequently for at least a year and that the design, tools, and methods were relatively set and stable. In addition, it was desired that the task have a long cycle, one having a standard time of two hours or more. The longer the task, the greater the interruption effects should be in comparison with external effects. For example, a 12 percent non-recoverable loss due to interruption on an eight hour standard assembly would be one hour, whereas the same loss on an eight minute standard assembly would be one minute.

A one minute loss would be hard to separate or distinguish from the fluctuations resulting from other factors such as employee attitude that day, boredom, fatigue, timing inaccuracies, temporary parts shortages, and many other "noise" factors which could affect performance one way or another by several minutes or more on each cycle. On the other hand, a one-hour loss would predominate over the above noise and would be readily distinguishable. Thus, the longer the cycle, the longer the breaks, and the larger the sample size, the greater the possibility of distinguishing the effects sought from the noise.

As the cycle time gets longer, the breaks longer, and the subjects more numerous, the experimental cost increases. Thus, it was desirable to select a task which was long enough to yield the gross effects sought, but not any longer than necessary. A task having a standard time of three to five hours was deemed satisfactory.

To investigate the fourth and fifth hypotheses, related to task complexity, several different tasks, all of which met all other task criteria, would have to be studied.

Finally, one would have to find tasks having a high monthly production requirement. It would be very difficult to study eight operators working on a given unit if only ten units could be built in a month. If fifty units per month were required, however, it is more likely that they would be built by a few operators on a continuous basis than by many operators all on a part-time basis.

In the company for which the study was designed, it was impossible to find four or five stabilized assembly tasks having around four-hour standard times which would be built in large quantities. There was, however, one job having a twenty-two hour standard time for which the schedule called for around one hundred completed units per month. This particular unit had been in production intermittently for three years with over two thousand units built previously. Design and procedures were quite stable.

The twenty-two hour standard cycle time was much too long, however. Therefore, the assembly operation was divided by the experimenter into five four-hour standard tasks and a final two-hour standard task. All of the requirements were met. There were five different stable tasks each requiring four hours standard time and all having high production requirements.

4.1.2 Subjects. To focus more on the mental learning and information assimilation aspects of the learning process and to eliminate some of the individual manipulative skill differences between new and experienced operators, the investigator chose to select only subjects from among those who had a year or more of experience in the plant as assembly operators and who had reached standard on at least two previous assignments. Whereas most of the electronic assemblers were women, the subjects selected were all to be women.

All subjects selected were not to have had any experience on or association with the unit selected for the task. To minimize manning problems on other assemblies and to placate the foremen, they would be permitted to specify the operators to be taken from their groups for the experiment, provided those subjects met the control requirements of the experiment. It would be understood, however, that once an operator started the experiment, she could not be temporarily removed or replaced. Thus, pregnant operators and others who might conceivably be leaving the company for a long period during the course of the study would not be accepted as subjects.

Desired personal and historical data for each subject included age, educational training, amount of formal job training, number of years with the company, number of years in the Instruments Department of the company, and the names of the units built by the operator for two years prior to the initiation of the project, to the extent that such data was available.

4.1.3 Job breakdown. As mentioned previously, the twenty-two hour standard cycle time was broken down into five cycles of four hours per cycle and a final two-hour cycle. Thus, it would have taken about 5½ operators to make one complete unit. The subjects would be classified as members of one of nine teams, where a team is composed of one operator for each of the five four-hour cycles.

Operators on the final two-hour cycle would not be part of any team, but would alternate between teams as needed to finish the units. The total number of subjects would be the forty-five operators on the nine five-man teams plus the three operators who would work on the two-hour jobs, or a total of forty-eight subjects.

4.1.4 Interruption and production schedules. To study the effects of interruptions and the lengths of interruption on operator progress, four interruptions of various duration (1, 2, 3, and 4 weeks) would be scheduled for each team. These four durations were selected because it was felt that they were long enough for any effects to predominate over random noise in the experimental situation. Furthermore, longer breaks were not scheduled because it would be more costly and not as realistic as the above breaks, since production at the concerned company was scheduled over four-week production periods.

In accordance with the sixth hypothesis concerning work and non-work interruptions, all interruptions of one day or longer were to be recorded. Included therein would be weekends, holidays, vacations, and sick leaves.

As a control between teams, each team was to build the same number of units between interruptions. Otherwise, if the second hypothesis concerned with the influence of the number of units built prior to a break on that break were true, the effects of breaks of equal duration taken by two teams would be hard to compare. A production and break schedule for each of the eight experimental teams is shown in Table 3.

Each team would build fifty units. Beyond fifty units of experience, an interruption decrement of even eight units would show as a very small inflection on the learning curve. Therefore, the interruptions were all worked into the first fifty cycles so that more data could be obtained in the early learning stages where interruption effects are likely to be most critical.

While there are twenty-four different ways in which the four interruptions or breaks can be ordered, it was not possible to incorporate all twenty-four arrangements into the experimental design. Therefore, eight different arrangements were selected, one for each team, such that each of the breaks occurred twice as

TABLE 3

PRODUCTION AND INTERRUPTION SCHEDULE

Team	Build (units)	Break (weeks)	Build (units)	Break (weeks)	Build (units)	Break (weeks)	Build (units)	Break (weeks)	Build (units)
A	8	4	12	2	12	1	12	3	6
B	8	2	12	1	12	3	12	4	6
C	8	1	12	3	12	4	12	2	6
D	8	3	12	4	12	2	12	1	6
E	8	3	12	1	12	2	12	4	6
F	8	1	12	2	12	4	12	3	6
G	8	2	12	4	12	3	12	1	6
H	8	4	12	3	12	1	12	2	6

the first, second, third, or fourth break. Furthermore, an interruption of given duration directly preceeded another interruption of a different duration in no more than four of the eight teams' schedules. For example, for no more than four teams does a three-hour break follow a build period preceeded by a one-hour break.

4.1.5 Collecting data. Although it would be very desirable to time-study each operator on each unit built, manpower required to time-study forty-five operators for fifty cycles each on a task requiring an average of ten hours per cycle would approach 25,000 man-hours and be prohibitively expensive. Therefore, a procedure was developed in which operators were to be responsible for recording their own data.

At the beginning of each calendar week, a weekly data sheet similar to the one in Figure 6 would be distributed to each operator in the study. On this data sheet they would record the time when they start building a unit, the time they completed a unit, and any breaks of five minutes or more which occurred while they are working. These breaks would include rest breaks, interruptions by supervisors or engineers, and other such interruptions which prevent them from continuously working on a cycle. Coffee breaks and lunch breaks would be placed on the data sheet in advance by the investigator.

To obtain maximum cooperation with the operators, they would be allowed to select and use a pseudonym in place of their own name on the data sheet as long as they retain the same pseudonym. Furthermore, no operator would be required to record reasons for any interruption or break which might occur. Likewise, they also would not have to explain or account for the number or duration of any breaks which might develop. To further assure anonymity, all data sheets would be collected at the end of the week by the various foremen, who would in turn give them to the experimenter.

The sample data sheet of Figure 6 shows how the data should be recorded. When a unit is started or finished, the actual time should be recorded in hours and minutes. If a break occurs within one of the fifteen minute intervals on the data sheet, the operator should just record the minutes at which the interruption began and ended in the appropriate interval. On the sample data sheet this is shown for the break from 10:05 to 10:10 on Monday.

4.1.6 Disguising the project. Since operator cooperation in recording data is one of the most critical aspects of this project, it is best to design the study to assure maximum cooperation. This would be accomplished in part by guaranteeing anonymity for the operators.

Nevertheless, since this study is related to learning curves, performance, and ultimately to standards, it is quite possible that the operators might attempt to bias the data in their favor, as is sometimes the case in time-study. Therefore, this project would be disguised as a cost analysis study for the purpose of evaluating the propriety and effectiveness of the current bidding model. In other words, are the prices being quoted representative of the actual costs incurred in building a given unit? It is less likely that any employees would be able to draw any personal connection between this disguised purpose and their own security.

Cost Analysis Data Sheet

Unit Type__________Prior Build__________Operator________________

Tooling Costs__________Setup Time__________Eng'g Costs__________

Time	Monday		Tues.		Wed.		Thurs.		Fri.		Sat.	
7:30-7:45	S	32										
7:45-8:00												
8:00-8:15												
8:15-8:30												
8:30-8:45												
8:45-9:00												
9:00-9:15												
9:15-9:30	F-S	17										
9:30-9:45												
9:45-10:00												
10:00-10:15	X	5-10										
10:15-10:30												
10:30-10:45												
10:45-11:00												
11:00-11:15	F	13										
11:15-11:30	L											
11:30-11:45	L											
11:45-12:00												
12:00-12:15												
12:15-12:30												
12:30-12:45												
12:45-1:00												
1:00-1:15												
1:15-1:30												
1:30-1:45												
1:45-2:00												
2:00-2:15												
2:15-2:30												
2:30-2:45												
2:45-3:00												
3:00-3:15	X	7										
3:15-3:30		19										
3:30-3:45												
3:45-4:00												
4:00-4:15												
4:15-4:30												

X = break   C = coffee   L = lunch   S = start new unit

F = finish a unit   F-S = finish one unit and start on a new unit

Fig. 6--Sample industrial data sheet.

Often the realization that the study has been disguised can generate repercussions far more serious than original bias which might have occurred had the purpose not been disguised. Thus, it is advisable to not disclose the true intent of the study any further down the line or to any more people than absolutely necessary to obtain approval of the project.

A quick look at the proposed sample data sheet in Figure 6 will reveal one method used to disguise the purpose of this study. Note the title and the lines referring to tooling, setup, and engineering costs. These lines would not be used at all, but were included to lend credence to the ostensible purpose of the study.

4.1.7 Other procedures.

a. MTM standards would be used to determine the standard times of the various tasks.

b. A limited amount of time-study would be performed to determine the amount of input-output time and processing time involved in each cycle.

c. Work sampling would be conducted on a limited basis throughout the project to see that operators did record breaks as they occur. The work sampling would record whether an operator was working or taking a break. No reasons for breaks would ever be recorded or demanded.

d. Any engineering changes or workplace methods changes would be recorded along with the effects of those changes on standards and on actual performance.

e. Setup would be done by utility operators, as would all re-work. To cut high setup costs arising from the interrupted schedules which would be used, it is recommended that work stations for seven teams be continually maintained. Only seven team stations would be required, as there are always at least two teams on a break.

f. Absence records for each of the operators would be kept (again by pseudonym if preferred) in order to observe any non-work interruptions.

g. Since it is quite important that only scheduled interruptions occur, heavy emphasis would be placed upon expediting to eliminate all avoidable parts shortages.

h. Each of the five tasks would be analyzed for information content applying information theory as described by Ross (27).

4.2 The Laboratory Experimental Design

Recision of permission to conduct the aforementioned study in the plant of an electronics manufacturer, and subsequent inability to gather sufficient quantities of controlled data from other industrial sources necessitated the laboratory study to be presented herein. Limited supplies of both time and money constrained the scope of the study. The cycle time of the task had to be reduced from four hours to around ten minutes. Likewise, breaks of from one to four weeks were not used, as the industrial design prescribed breaks totaling ten weeks. To keep costs down, either the number of operators studied or the amount of time that each operator worked had to be reduced. This investigator elected the latter.

Furthermore, the scope of the industrial study was entirely too large for incorporation into a laboratory experiment. The extensive labor costs arising in the industrial study are offset by the sale of marketable products built during the study. Laboratory experiments, on the other hand, often use tasks from which no marketable products emerge. With no sales income to offset labor costs, the laboratory experiment becomes very expensive very quickly. Hypotheses IV and V, related to task complexity, would require the study of two or more different tasks. To provide work interruptions essential to the investigation of Hypothesis VI, one would have to provide additional tasks. For a fixed experimental budget, as the number of tasks is increased, the number of operators to be studied on a task must correspondingly decrease. Preferring to study as many operators as possible on a given task in hopes of preserving statistical significance, this investigator studied just one task and thereby did not include Hypotheses IV, V, and VI in the laboratory experimental design.

4.2.1 <u>The task</u>. The task selected for this experiment had to meet several criteria. First, it had to be a task which required about ten minutes time for an experienced operator. Second, it couldn't require an elaborate work station, facilities, tools, or fixtures. Third, the task had to use very inexpensive piece parts or parts which could be used repeatedly. Fourth, since parts were to be re-used on succeeding assemblies, the task had to be designed for rapid disassembly. Fifth, in order to focus on the mental aspects of learning, the task had to involve a minimum of manual skill. It was further hoped that by compressing much information into a short cycle task, the effects of interruptions might be the same as for longer cycle tasks having the same information content; the difference in the cycle times being due to the differences in the manual motion requirements of the two tasks. Sixth, to avoid Manufacturing Progress Function forms of improvement, the task had to be one in which the subjects would be familiar with the tools and components used. Finally, for expediency, it was desirable that the task be one which lent itself to relatively simple work analysis and information content determination.

In line with these criteria, the task designed was one in which the subjects selected a specified washer from a parts board and properly positioned that washer over a prescribed peg on a pegboard. After all the washers were positioned, the subjects completed the task by dumping the washers from the pegboard onto the workbench and replacing the washers in their proper positions on the parts board. Figure 7 shows a typical work station, while Figure 8 depicts a subject at work during the assembly portion of the task. A mirror-image arrangement of the work station was provided for left-handed subjects.

There were four major components of the work station, as shown in the schematic of Figure 9. These were the pegboard, the parts board, the instruction sheets, and the stopwatch. The pegboard contained sixteen upright wooden pegs arranged in a four by four matrix as shown in Figure 10. Each peg was identified by a letter (row) and a number (column). Plastic tape was used to label the rows with the letter D for the row nearest the subject and C, B, and A for respectively farther rows. Columns were labeled with the numerals 1, 2, 3, and 4 from left to right, respectively.

The parts board had similar, but unlabeled, pegs arranged in a rectangular four row by eight column pattern (see Figure 11). A different type of washer was in each row: 3/8 inch brass on top, 3/4 inch rubber in the second, 3/8 inch steel in the third, and 3/8 inch steel lock washers on the bottom row. Those washers were painted different colors on each side, with one color combination for each of the eight columns. The circumferential edge of the brass washer was unpainted and polished to reveal the brass material. Paint overlapped the edges of the other types of washers.

All washers--brass, rubber, steel, and lock--on the four pegs in the far left column were painted light blue on the side facing the subject and white on the reverse side. Likewise, the ensuing seven rows from left to right were green and white, black and white, orange and white, red and white, light blue and red, green and red, and black and red. Thus, the washers in the lower left corner of the parts board were lock washers painted black on the front side and red on the reverse side. Five washers were provided at each peg.

Each subject installed ninety-six washers on the pegboard using the instructions included in Appendix A. Note that each instruction conveys four items of information: the colors of the washer, the material or type of washer, the location of the object peg on the pegboard, and the orientation of the washer on

Fig. 7--Close-up of work station.

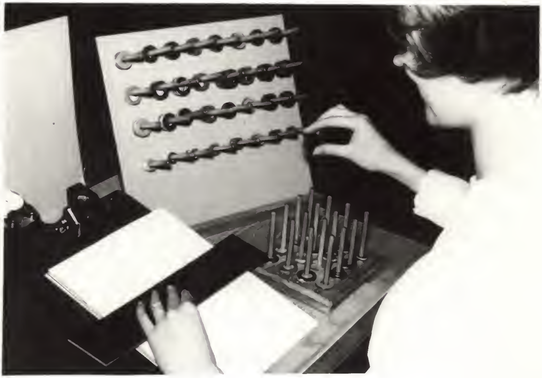


Fig. 8--Subject at work.

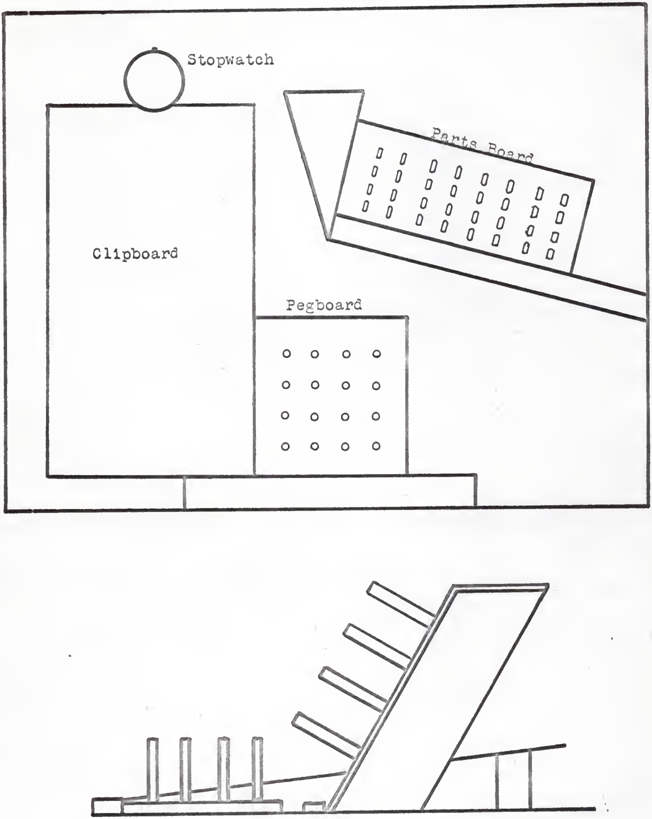


Fig. 9--Work station layout.

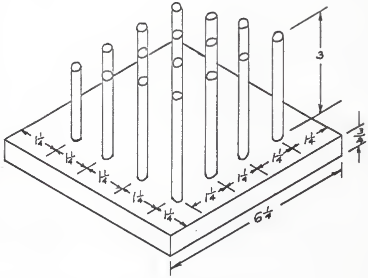
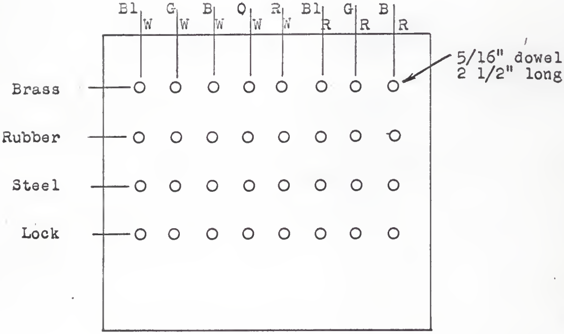


Fig. 10--The pegboard



Bl = Blue W = White G = Green B = Black
O = Orange R = Red

Fig. 11--The parts board.

that peg. Each instruction was composed by sequentially drawing, without replacement, a washer from the thirty-two possible color-type combinations on the parts board and a pegboard location designation from the sixteen possible pegboard locations. The orientation designation was selected by drawing with replacement from a sample of two--front side up or reverse side up.

The pegboard was assembled in layers; that is, each peg on the pegboard received one washer before any peg received its second washer, thereby beginning the second layer. At the end of the assembly portion of the task, each peg on the pegboard contained six washers. Similarly, a second washer was not removed from any location on the parts board until one washer had been removed from each location on the parts board. At the end of the assembly portion of the task, two washers remained at each location on the parts board as a guide for replacement of all washers on the parts board during the disassembly portion of the cycle.

The four numbered instruction sheets were enclosed in protective acetate covers. They rested loosely on a slightly inclined time-study clipboard as shown in Figure 7. The subjects were permitted to refer to the instruction sheets at all times and were provided with a black formica straight-edge to use as a guide. A decimal-minute stopwatch was clamped into position on the time-study board.

Four identical work stations were positioned on a long wooden table as shown in Figure 12. The table was raised with a brick under each end and the chairs were placed on wooden platforms which could be raised or lowered depending upon the height

Fig. 12--Four-station work area.

of the subject. Short subjects were seated as high as possible to minimize fatigue due to continuous long reaches to the more distant locations on the parts board.

The complete task, including assembly and disassembly, was measured using Methods Time Measurement (MTM) pre-determined time values (31). MTM analysis revealed a base time of 5.12 minutes. A sample elemental breakdown of several instructions and a summary calculation sheet are included in Appendix B.

Although Hypothesis IV, related to information content, was not investigated in the laboratory experiment, the one task utilized throughout the experiment was analyzed for information content to demonstrate an application of information theory to work analysis and to provide a base of reference for future investigators in the area of interrupted learning. The task was measured in terms of Ross's two prime information measures: (a) the total number or range and probability of occurrence, and (b) psychomotor performance. Other measures such as stimulus-response compatibility, timing of stimuli, and redundancy of stimuli were not analyzed because the state of the art has not yet provided adequate definition and measurement techniques and/or because those other factors were not significantly applicable to this task. The information content analysis summarized in Appendix C yielded an information content of 3416 bits for this task.

4.2.2 Build and interruption schedules. The schedules used in the laboratory experiment differed in two ways from those of the industrial experimental design. First, the interruptions were reduced from one, two, three, and four weeks to one-half, two, four, and sixteen hours. Those breaks varied in range by a ratio of thirty-two to one, they were well suited to exponential or logarithmic analysis, and they provided workable schedules for subjects in that the sixteen hour break could be used to permit the subject to go home overnight without adversely affecting the experimental design.

Secondly, instead of using eight of the twenty-four possible sequences of breaks, only four sequences were used. This doubled the number of subjects in a particular sequence. The work schedules are shown in Table 4. Note that Group A took two sixteen hour breaks and no four hour break. This was necessary, since an operator would have had to work on four three-hour work periods separated by breaks of two, one-half, and four hours all in the same day. Eighteen hours is too long a day for all experimenters and for most subjects. The schedule for group A covered three consecutive days, while the schedules for the other groups covered two consecutive days.

Due to shortages of time and subjects, the experiment was conducted seven days per week. The experimenter tried to load the four work stations as much as possible, but there were times when a subject was working alone on the task.

The two control subjects worked continuously without interruption except for a half hour for lunch and a thirteen hour overnight break.

TABLE 4

BUILD AND BREAK SCHEDULES

Team	Build (units)	Break (hours)	Build (units)	Break (hours)	Build (units)	Break (hours)	Build (units)	Break (hours)	Build (units)
A	8	16	12	2	12	½	12	16	6
B	8	2	12	½	12	16	12	4	6
C	8	½	12	4	12	16	12	2	6
D	8	4	12	16	12	2	12	½	6

TABLE 5

ASSIGNMENT OF OPERATORS TO GROUPS

<u>Group</u>	<u>Subject</u> <u>Numbers</u>
A	13, 18, 19, 20, 22, 24, 27
B	4, 6, 15, 16, 25, 28*
C	3, 7, 9, 14, 17, 21
D	5, 10, 11, 12, 23, 26
Control	1, 2

*<u>Note</u>: Subject number 8 did not show up for work and was replaced by subject number 28.

4.2.3 Subjects. Since each schedule required two consecutive days of work, students could serve as subjects only on the weekends. The small pool of labor in the community was barely able to provide the twenty-six subjects required for the experiment. The short tenure of work and minimum pay scale was not attractive. The evening hours and irregular allotments for meals necessitated by the schedules were not appealing to married students' wives, particularly those with young children. Thus, it was not possible to draw the number of subjects required from a restricted population. The experimenter had to hire whoever was willing to work. The only restrictions placed on subjects were an age range of sixteen to thirty-five years, fluent in English, not color-blind, and physically able to perform the task.

Two subjects served as control subjects for the purpose of determining the slope of the traditional learning curve. They built for 4½ hours, took a half-hour for lunch, built for 4½ hours, took a thirteen hour overnight break, and finished working on the second morning.

The experimenter intended to hire twenty-four additional subjects, six for each experimental group. However, through an experimental error, an extra subject was studied, giving seven subjects in group A. Subjects were numbered consecutively from one using when they started to work as the basis. Table 5 shows the assignment of subjects to each of the four experimental groups and the control group.

Subjects ranged in age from seventeen to thirty-one with twenty in the nineteen to twenty-three range. Eleven of the twenty-seven subjects were male. Educational levels ranged from eleventh grade through one person who had his doctorate. Twenty-one subjects had either one or two years of college education. Four male subjects were foreign students, but each had an adequate to excellent command of English. Two of the subjects had had prior experience as industrial assemblers.

4.2.4 Procedures. To discourage subjects from quitting the job before the experiment was completed, an earned bonus payment plan was utilized. Subjects were only guaranteed a pay rate of fifty cents an hour. If they worked until the experiment was completed, they were guaranteed a bonus of an additional fifty cents for every hour worked and an overtime premium of twenty-five cents an hour for all hours worked past five-thirty in the evening. The plan worked quite successfully in that not one operator quit in the middle of the experiment despite their displeasure with the difficult task and the inconvenient work schedules.

It is possible that a piecework payment plan might have motivated the subjects to higher performance levels. However, this experimenter noticed no apparent delay or slowdown attempts aimed at earning more money. Subjects became so bored and tired of the task that they did the best they could to finish early and "get it over with". At the end of the experiment each subject was seriously offered the opportunity to remain on the job at the rate of one dollar per hour. Not one subject gave the idea more than cursory consideration before emphatically turning down the offer. The task was self-motivating.

Each subject upon reporting for work was clocked in, and later clocked out, on punched time cards. After adjusting the height of the subject's chair to a comfortable level, the experimenter explained the operation of the stopwatch at the work station, the parts and boards used, and the meaning conveyed by the instructions on the instruction sheets. The subjects were required to install the first six washers on the pegboard under the supervision of the experimenter. Corrections and amplifying explanation of the instructions were made as needed. Subjects were told to pick up washers fumbled on the work bench, but to ignore washers dropped on the floor. They were permitted to take short breaks to stretch or get a drink of water between cycles at their discretion, although more than two breaks per work session were discouraged.

The time required by each operator to complete each cycle was determined from two decimal-minute stopwatches. The experimenter controlled one watch and the subject, the other. Both readings were recorded and averaged. Two watches were used for each subject so that in the case of several operators stopping simultaneously or in cases in which the experimenter could not be immediately present at the end of a cycle, the reading from the subject's watch could be used. Thereby, not one of 1,350 possible readings was missed by both watches. The duration of interruptions was recorded to the nearest tenth of an hour by the time clock cards.

Throughout the experiment, this investigator continuously supervised the subjects. Although the subjects' quality was not inspected on each cycle, continuous informal surveillance was maintained and corrections were made. At the end of each cycle the investigator did inspect each parts board to make sure that each washer was in its proper location prior to the beginning of the next cycle. Errors were spotted, explained to the subject, and corrected by the subject.

All short pauses between cycles, critical subject comments, disturbances, and other irregularities were recorded directly on the data sheets for the unit on which the subject was building at the time of such irregularities.

4.3 Summary of Hypotheses Tested

Of those hypotheses presented in the theoretical development of the interrupted learning curve, the following, listed by their original hypothesis number, were studied in the laboratory experiment just described:

Hypothesis I: An interruption in production will result in the succeeding unit requiring more time than it would have had there been no interruption.

Hypothesis II: The magnitude of the interruption decrement is dependent upon the length of interruption.

Hypothesis III: The interruption decrement is dependent upon the "effective units of experience" prior to the interruption.

Hypothesis VII: Units built during the re-learning increments are built at a faster rate than are units built on a non-interrupted basis using the traditional learning curve model.

Hypothesis VIII: The re-learning increment (units) is equal to the interruption decrement (units).

Hypothesis IX: After the re-learning increment, learning proceeds at a rate equal to the rate for the non-interrupted traditional learning curve model.

Hypothesis X: There is a non-recoverable loss due to interruption.

5. RESULTS

The cycle times for each of the subjects in the four experimental and one control groups were combined for each cycle and divided by the number of subjects in the respective groups. There were two subjects in the control group, seven in group A, five in group B, six in group C, and six in group D. Although six subjects worked on a B schedule, the data for subject 25 was not included in the analysis due to faulty times recorded from a stopwatch in which the minute hand would not advance beyond the twenty-two minute mark. The first five times recorded for subject 25 were all in the twenty-two minute range, when the actual times might have been longer than twenty-two minutes.

Fitting a logarithmic straight line to the average cycle times for the control group, as shown in Figure 13, yielded an 89.0 percent learning curve having an initial cycle time of 20.0 minutes. This then became the traditional learning curve for the task. It was the base against which the interrupted learning curves for the four experimental groups were compared.

Of the hypotheses tested, Hypothesis I, that "an interruption in production will result in the succeeding unit requiring more time than it would have had there been no interruption", was the most important. This hypothesis was the cornerstone of the interrupted learning model, in that if no interruption decrement occurred, Hypotheses II and III describing the magnitude of the interruption decrement would be meaningless. Likewise, Hypotheses VII, VIII, and IX, related to the re-learning increment, would be inapplicable, since re-learning, by definition, must be preceeded by forgetting of one sort or another. Finally, the last hypothesis tested, predicting a non-recoverable loss due to interruption would have little meaning if no loss occurred following an interruption.

With this thought in mind, the group average data for each of the four experimental groups, as portrayed graphically in Figures 14, 15, 16, and 17, were analyzed to determine the effect of an interruption on the succeeding assembly time. Group averages were used to smooth the effects of individual differences and to provide a broad statistical base from which to test hypotheses.

The average cycle time for the assembly immediately following an interruption was subtracted from the average cycle time for the assembly immediately preceeding the interruption. The results of that subtraction for each of the four breaks taken by each of the four groups are presented in Table 6. The inserted letters refer to the group for which the sixteen hour break was first (A); the four hour break, second (C); and so forth. Using a one-tail Wilcoxen Signed Rank Test (32) at the .025 level of significance, one could not conclude that the cycle time after an interruption is greater than it would have been had there been no interruption. Since, of the sixteen interruptions, eight were followed by an interruption decrement and eight were followed by an interruption increment, the first hypothesis would have been rejected at even the 25 percent level of significance.

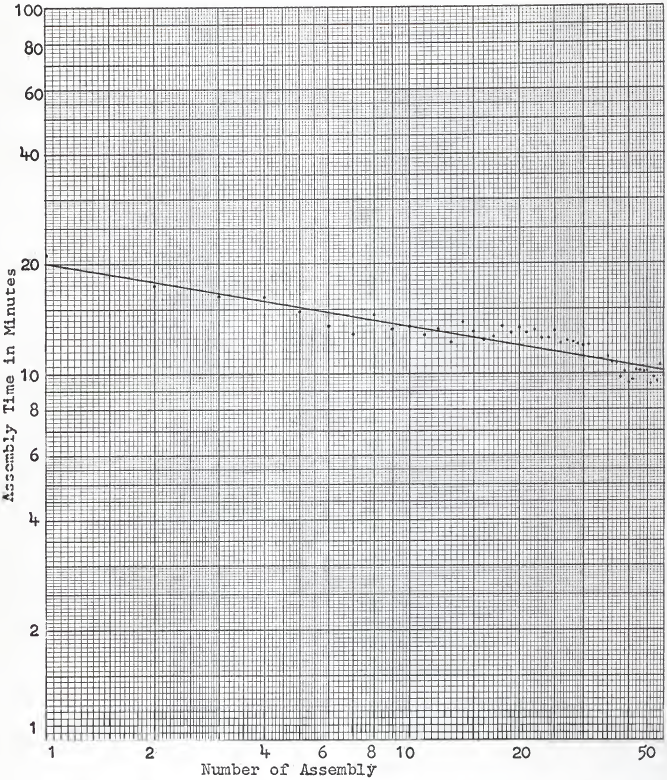


Fig. 13--Traditional learning curve for control subjects.

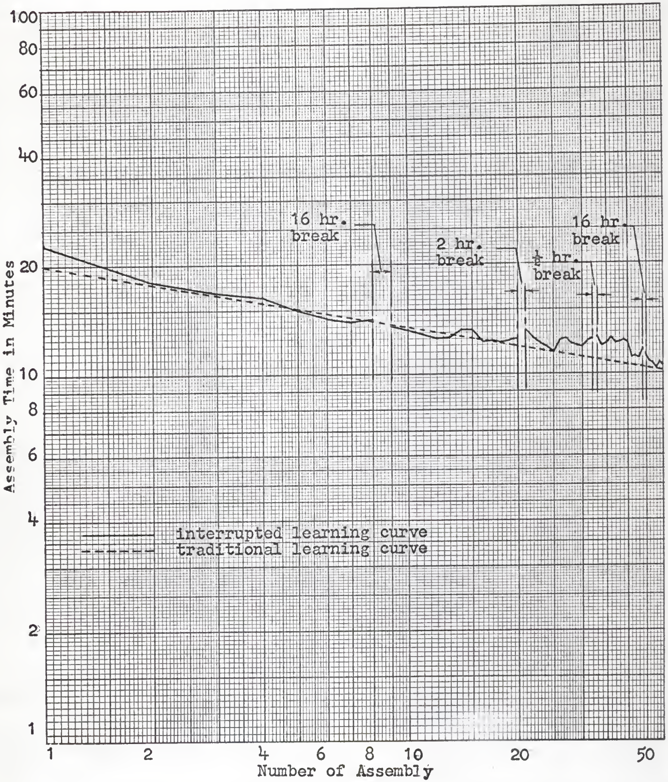


Fig. 14--Interrupted learning curve for group A.

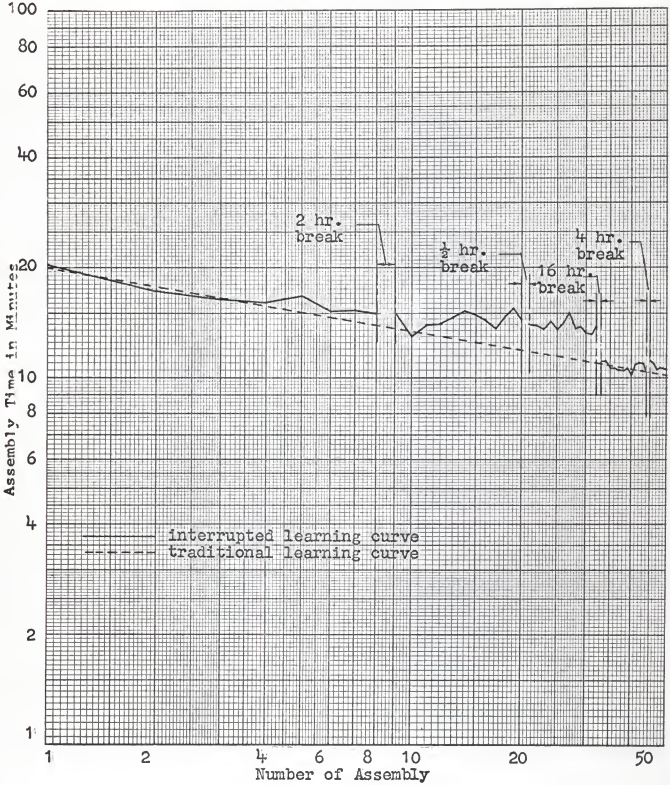


Fig. 15--Interrupted learning curve for group B.

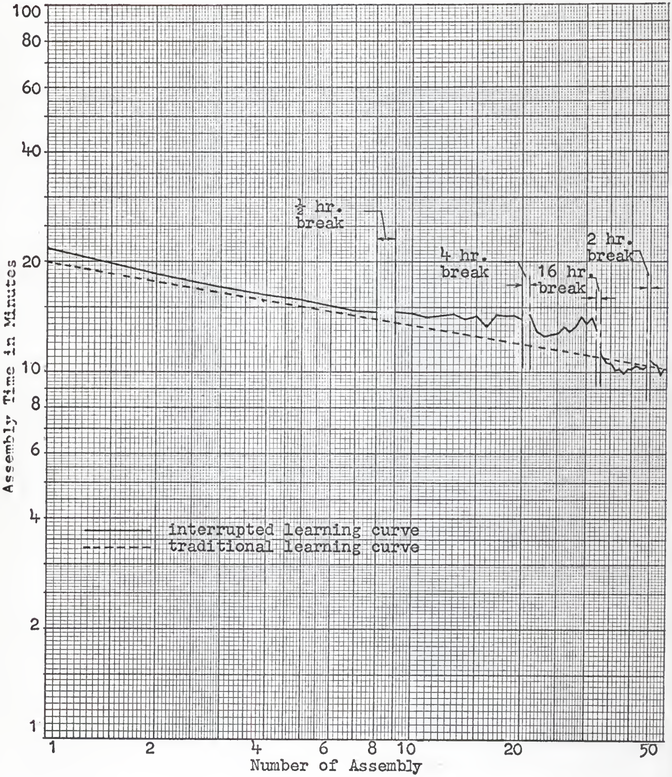


Fig. 16--Interrupted learning curve for group C.

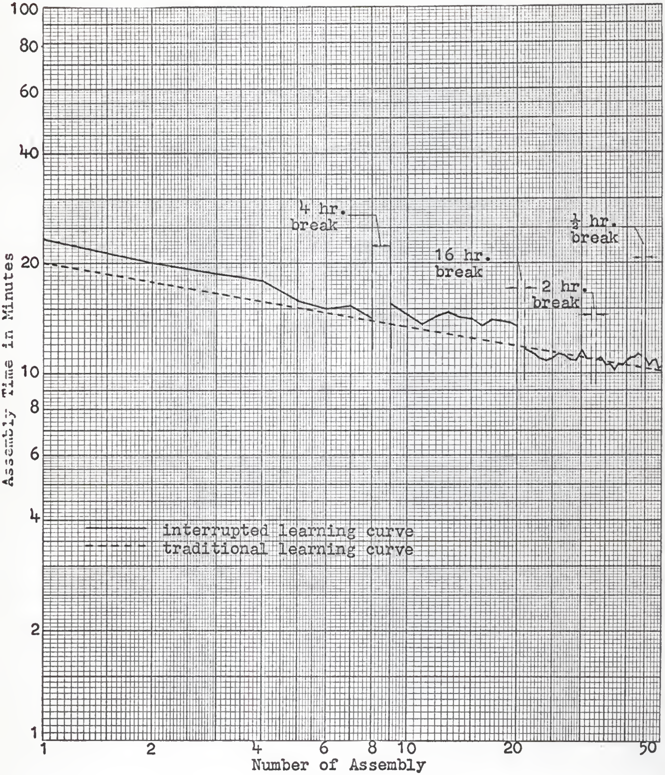


Fig. 17--Interrupted learning curve for group D.

In a very strict sense, then, the remaining hypotheses become meaningless, since they were based on an assumed acceptance of the first hypothesis. Nevertheless, more extensive analysis of the data to study the effects of break lengths and experience revealed the presence of an uncontrolled factor which, when taken into consideration, yielded interesting insight into hypothetical characteristics of the interrupted learning model.

To investigate the effects of break length and previous experience on the magnitude of the interruption decrement or increment, the data in Table 6 was modified in two ways. First, the traditional learning model predicts a small learning increment (reduction in time) between successive assemblies. Thus, the actual difference in times on succeeding units was modified by subtracting the expected difference in times, as calculated in Appendix D.

Secondly, due to the asymptotic nature of the exponential learning curve, a one minute difference in times between succeeding units is much more significant after fifty units than after ten units. To correct for this effect, the difference between the actual difference in time and the expected difference in time was divided by the cycle time for the unit preceeding the interruption. Calling this result the interruption index, K, the equation for K was:

$$K = \frac{\text{Actual Difference - Expected Difference}}{\text{Cycle Time Before Interruption}} \qquad (3)$$

As an example of the method used to calculate K, consider a situation in which the time for a subject on the fifth unit was twenty minutes. Assume that an interruption occurred after the fifth unit. The time for the sixth unit following the interruption was twenty-two minutes. Using the equations of the traditional learning model, equations (1) and (2), and the cycle time for the fifth unit, one can determine the time that would have been required if there had been no interruption. Assume nineteen minutes for that value. The Actual Difference in times was the actual time for cycle five (twenty minutes) minus the actual time for cycle six (twenty-two minutes), yielding minus two (-2) minutes. The Expected Difference was the actual time for cycle five (twenty minutes) minus the expected traditional learning time for cycle six (nineteen minutes), yielding one (+1) minute. The value for K in this hypothetical example was thus:

$$K = \frac{-2 - (+1)}{20} = -0.15$$

Values of K calculated from the experimental data are shown in Table 7. Positive values represent the portion of cycle time by which the interruption effect <u>reduced</u> the time for the succeeding unit. Likewise, negative values indicate the portion of cycle time by which the interruption effect <u>increased</u> the time for the succeeding unit.

Looking at the average K values ($\bar{K}$) for each of the four break lengths, one can see that the sixteen hour break resulted in a very positive K value and that as the other breaks got larger, the K values became more and more negative. This is quite significant in that the sixteen hour break was an overnight break during

TABLE 6

DIFFERENCES IN TIMES BETWEEN SUCCESSIVE UNITS SEPARATED BY AN INTERRUPTION

Occurrence of Break in Build Cycle

Break Length (hours)		First	Second	Third	Fourth
	16	A +.59	D +1.80	B +2.82 +2.02 C	A +.57
	4	D -1.42	C - .57		B - .76
	2	B - .05	A - .63	D +.16	C - .35
	½	C - .13	B +.42	A - .11	D +.16

TABLE 7

VALUES OF THE INTERRUPTION INDEX, K

Occurrence of Break in Build Cycle

Break Length (hours)		First	Second	Third	Fourth	$\bar{K}$
	16	A + .022	D + .126	B +.198 +.148 C	A + .045	+.091
	4	D - .121	C - .049		B - .077	- .082
	2	B - .023	A - .058	D +.009	C - .036	- .027
	½	C - .029	B .021	A - .014	D + .011	- .003
	$\bar{K}$	- .037	.010	.068	.014	

which the subject went home and slept. On the other hand, each of the other three breaks was always followed by a work session on the same day as the break. It is likely that an overnight recuperative factor significantly influenced performance following a sixteen hour break.

To conduct an analysis of variance for the data in Table 7, the three sources of variance, break length, group, and experience (occurrence of break in build cycle) were successively paired against each other, yielding Tables 8, 10, and 12. Missing values were omitted and duplicative values were averaged. A two-way analysis of variance (33) was conducted on the data in each table, as summarized in Tables 9, 11, and 13. The resulting F statistics were compared with critical F values at the .05 and .01 levels of significance. As shown in Tables 9 and 11, there was no significant effect between groups. Tables 9 and 13 revealed no significant difference due to experience. However, Tables 11 and 13 did reveal an effect of break length which was significant at the .01 level.

The Duncan Multiple Range Test (34) was used to determine whether or not a significant difference existed between the K values for each length of break and the K values for the other lengths of breaks. At the .05 level, the K values for each break length were significantly different from each other. Except for the difference between the four hour and two hour breaks, the same held true at the .01 level of significance. Details of the Duncan Multiple Range Test are included in Appendix D.

TABLE 8

K VALUES BY GROUP AND WORK EXPERIENCE

Occurrence of Break in Build Cycle

		First	Second	Third	Fourth	ΣK
Group	A	+ .022	- .058	- .014	+ .045	- .005
	B	- .023	+ .021	+ .198	- .077	+ .119
	C	- .029	- .049	+ .148	- .036	+ .034
	D	- .121	+ .126	+ .009	+ .011	+ .025
	ΣK	- .151	+ .040	+ .341	- .057	+ .173

TABLE 9

SUMMARY OF ANALYSIS OF VARIANCE OF TABLE 8

Source	Sum of Squares	Degrees of Freedom	Mean Square	F
Group	.002121	3	.000707	.089
Experience	.034112	3	.011371	1.437
Residual	.071230	9	.007914	-----

TABLE 10

K VALUES BY GROUP AND BREAK LENGTH

Break Length in Hours

		16	4	2	½	ΣK
Group	A	+ .034		- .058	- .014	- .038
	B	+ .198	- .077	- .023	+ .021	+ .119
	C	+ .148	- .049	- .036	- .029	+ .034
	D	+ .126	- .121	+ .009	+ .011	+ .140
	ΣK	+ .506	- .247	- .108	- .011	+ .140

TABLE 11

SUMMARY OF ANALYSIS OF VARIANCE OF TABLE 10

Source	Sum of Squares	Degrees of Freedom	Mean Square	F
Group	.003160	3	.001053	.481
Length of Break	.085985	3	.028662	13.082**
Residual	.017529	8	.002191	--------

**Significant at the .01 level

TABLE 12

K VALUES BY BREAK LENGTH AND WORK EXPERIENCE

Occurrence of Break in Build Cycle

		First	Second	Third	Fourth	Σ K
Break Length (hours)	16	+ .022	+ .126	+ .173	+ .045	+ .366
	4	- .121	- .049		- .077	- .247
	2	- .023	- .058	+ .009	- .036	- .108
	$\frac{1}{2}$	- .029	+ .021	- .014	+ .011	- .011
	ΣK	- .151	+ .040	+ .168	- .057	0.00

TABLE 13

SUMMARY OF ANALYSIS OF VARIANCE OF TABLE 12

Source	Sum of Squares	Degrees of Freedom	Mean Square	F
Length of Break	.050645	3	.016881	12.075**
Experience	.016320	3	.005440	3.891
Residual	.011189	8	.001398	--------

**Significant at the .01 level

It was hypothesized that following a break a re-learning increment would occur during which operator performance would proceed at a greater rate than the rate of traditional learning. Note on Figures 14 through 17 that, with the exceptions of the half hour break for Group C and the two hour break for Group D, the interrupted learning curves during or immediately following the other fourteen breaks did fall at a faster rate (steeper slope) than did the traditional learning curve. Thus, there is some empirical evidence to support Hypothesis VII. Due to uncontrolled, yet potentially significant, factors such as the overnight factor and reminiscence, as discussed later, one can not attribute this empirical effect solely to the simultaneous re-learning and new learning effects discussed in the development of the interrupted learning model.

Since the existence of an interruption decrement was not significantly established, the hypothesis that the re-learning increment (in units) equals the interruption decrement (in units) was not statistically tested. Looking at the results from the eight times when an interruption decrement did occur was quite revealing. Simplifying the theoretical interrupted learning model by defining the end of a re-learning increment as that point following an interruption at which the assembly time per unit falls back at or below the assembly time for the unit immediately preceeding the interruption, a visual examination of the data plotted in Figures 14 through 17 revealed that in six of eight cases the re-learning increment was smaller than the interruption decrement. The other two cases (four hour break for Group B and half hour break for

Group C) were indeterminate due to insufficient data and very small effects, respectively.

Very little was concluded about Hypothesis IX, that learning proceeds at the traditional rate following a re-learning increment. If, in Figures 14 through 17, one imagines a straight line between the point following one break and the point preceeding the next break, that straight line would have a flatter slope (indicating a slower rate of learning) than the traditional learning curve for all breaks except the sixteen hour breaks, when the opposite would be true. Thus, as for the other hypotheses, the extent to which Hypothesis IX can be described depends upon the degree to which the overnight effect is controlled or balanced in the situation to be studied. The variability in the data and the small number of subjects in each group limited more extensive analysis of this hypothesis.

The preceeding observations were of importance when considering the final hypothesis, that a non-recoverable loss follows an interruption. Again, such was not the case following a sixteen hour break. However, using a straight line between points immediately following one break and immediately preceeding the next break to represent the average rate of learning for the interim, and finding the slope of that line to be flatter than the slope of the traditional learning curve, then eventually a loss will occur and increase in magnitude as the interim between breaks increases. This increasing non-recoverable loss is shown in Figures 14 through 17 as the increasing distance of the interrupted learning curve above the traditional learning curve until an overnight sixteen hour break occurred.

6. DISCUSSION

6.1 Implication of Results

Empirically, many important observations were made with regard to the hypotheses of the interrupted learning model, although strict statistical analysis and decision was limited by "noise" from several uncontrolled factors. Of these, the overnight effect was predominant. Many aspects of the interrupted learning model were confirmed in the data for the shorter breaks, but were reversed by the sixteen hour overnight break. This investigator feels that the overnight effect is relatively constant, opposes the interruption effect, and, for the task studied, was large enough to completely offset and reverse the interruption effect. Being unable to quantify the overnight effect, this investigator could not remove it from the data and thereby statistically analyze in greater detail the interrupted learning model.

Certainly, however, the demonstrated presence of an overnight effect leads to restrictions or boundary conditions for the interrupted learning model. That is, the model might only be applicable to cases in which either no overnight breaks occur or all overnight breaks occur. If the assumption that the overnight effect is relatively constant proves true, then breaks of sixteen, thirty, and fifty hours would contain a common overnight effect and a unique variable interruption effect (by Hypothesis II). By extracting the common overnight effect, the data could then be analyzed in conjunction with the interrupted learning model.

Rationale for the overnight effect might be found in a review of the psychological factors affecting reminiscence and the possible extent to which they might have influenced the results.

6.2 Factors of Reminiscence

Accepting the idea that interruptions or breaks should result in forgetting, McGeoch (35) presented five possible reasons for the opposing effect of reminiscence, the phenomenon by which subjects return to a task following an interruption and perform at higher levels (lower times) than those attained prior to the interruption. Reminiscence occurred in this experiment, particularly after sixteen hour breaks.

6.2.1 <u>Rehearsal</u>. Rehearsal assumes a positive transfer of training between tasks. Since the subjects in this experiment did not work on other tasks, this factor was not applicable.

6.2.2 <u>Fatigue</u>. Although fatigue is not considered important by McGeoch, the task studied was much more fatiguing, both mentally and physically, than were the tasks of contributing psychologists who worked with memorization of nonsense words, learned response in animals, and other such tasks. The task used in this experiment contained a very large amount of information which required diligent attention to assimilate rapidly. Furthermore, this task was physically tiring, as subjects used just one arm for assembling washers. They moved the same arm an average distance of twelve inches almost four hundred times per cycle. Using an average cycle time of twelve minutes, this was two thousand twelve-inch moves per hour. This became quite fatiguing, particularly since they were new to the task and were not conditioned for it. Fatigue was complicated by the boredom of building a complicated, yet worthless, assembly for the sole purpose of taking it apart and starting over again.

6.2.3 Perseveration. The theory of perseveration assumes that mental activity continues for a time after formal practice ceases, thereby providing unmeasured practice. This additional mental activity serves to strengthen neurological channels of response. This theory has not been sufficiently demonstrated by experimental results and is probably at best of little relative importance in the task used in this experiment.

6.2.4 Motivation. Subjects returned to work on the second day (following a sixteen hour break) with a certain motivation to do well, work fast, and "get it over with". Upon return to the task after a break, they found the task much easier than it had been. Furthermore, diminished fatigue and physical adaptation to the task were motivating factors for better performance.

6.2.5 Differential forgetting. The theory of differential forgetting assumes that a subject learns both correct responses and interferences during practice. Furthermore, it assumes that interferences are less well fixated than are correct responses. Thus, during a break, or rest interval, the less fixated interferences will be forgotten more rapidly than will correct responses, leaving correct responses freer to appear after the rest interval. This theory seems to stand up to criticisms brought by psychologists against fatigue and motivation. McGeoch feels that this differential forgetting is a major factor in reminiscence.

Having reviewed these elements of reminiscence, one can better understand the complexity of the interrupted learning situation. This author is convinced, however, that the afore-mentioned parameters of reminiscence are of either temporary or constant effect. For example, fatigue relief might very well be a factor on an hour to hour or day to day basis, but does two weeks away from a job relieve twice as much fatigue as one week away? On the other hand, does a half hour or two hours on another job really provide a permanent relief after one starts back to work on the initial job? Differential forgetting might be important over a period of minutes, hours, or perhaps even a few days, but does a week or two weeks make any additional difference? This author feels that the factors of reminiscence are of relatively constant proportions and only become significant when breaks are as short as a day or less. Faulty experimental design was conducive to some of the above factors playing a confusing, yet significant, role in affecting the results.

6.3 Experimental Design Weaknesses

The major weakness was one of trying to design a short-cycle, short break experiment to test a model derived from theoretical considerations of long-term interruptions. The premise that long-term effects could be simulated and studied by compressing the information content of a long task into a short cycle time was not demonstrated. In fact, the high information rate resulting from a high information content task having a short cycle time probably contributed heavily to those important factors of reminiscence--boredom and fatigue. Furthermore, subjects were unable to memorize more than portions of about ten out of ninety-six instructions due to the high information content rate. By using long-cycle tasks and long breaks, as provided in the industrial design, the relatively constant factors of reminiscence would likely have been reduced in relation to forgetting, which is an acknowledged function of time.

Another weakness of the laboratory experiment was that it required subjects to work at unfamiliar hours in the evenings, through dinner hours, and on weekends. This certainly could have affected their performance.

The experimenter had no control over the activities of the subjects during breaks. Some would dash home, cook supper, and hurry back. One subject went home and cleaned house. Another stayed out all night, coming to work the next morning barely able to stay awake.

The laboratory experiment was quite biased with regard to the sixteen hour break. After a sixteen hour break, the subject was able to go home, eat, relax, and get plenty of sleep. Thus, he could come back the next day refreshed, highly motivated, and relaxed. The other breaks, however, were always followed by a work session on the same day. The subjects were not able to relax as much during the shorter breaks. The overnight effect should have been controlled by either complete inclusion or complete exclusion from the experimental design.

For example, the results of an unpublished study by DeCampos (36) indicated the definite presence of an interruption decrement, the effects of break length, and effects of work experience. The task studied by DeCampos involved the assembly of jigsaw puzzles. All six subjects built ten puzzles and then took breaks of twenty-four or forty-eight hours. Thus, the overnight effect was balanced by being common to all observations following a break.

The goals set for the laboratory experiment were too ambitious. Spreading the available subjects thin in an attempt to investigate several factors at once did not leave enough subjects in any given condition to obtain the smooth averages required, particularly in light of the short-term aspects of the task. At times, variations in times between assemblies not separated by an interruption exceeded the effects observed due to an interruption.

6.4 Conclusion

Although the laboratory experiment was not able to positively validate the interrupted learning model, many of the results were quite encouraging and enlightening. This investigator is firmly convinced that the basic concepts of the interrupted learning model are sound, although certain modifications hinted at herein are quite likely, as well as others not revealed in this study. Preliminary industrial data received from a large electronics manufacturer using a large-scale experiment similar to the industrial design presented herein is very encouraging, although sufficient data to make statistical observations is not yet available.

The laboratory experiments conducted by this experimenter have helped to qualify, define, and describe the theoretical model. The key to further testing and quantifying the model lies in studying gross effects on a selected basis over a large number of trials.

The continuing change to specialized product lines having many options, the profit opportunities of a booming economy, the availability and increasing use of computers in manufacturing, and the impending change to shorter work weeks portend a continued development, investigation, and eventual application of interrupted learning curves.

7. REFERENCES

1. Wright, T. P., "Factors Affecting the Cost of Airplanes", Journal of Aeronautical Sciences, Vol. 3, No. 4, Feb., 1936.

2. Rock, Irvin, "Repetition and Learning", Scientific American, Vol. 199, August, 1958.

3. Blume, E. J., and Norris, R. E., "Improve Your Buy", Purchasing, September 25, 1961.

4. Knowles, Alvis, and Bell, Lawrence, "Learning Curves Will Tell You Who's Worth Training and Who Isn't", Factory Management and Maintenance, June, 1950.

5. Nissley, Harold, "The Importance of Learning Curves in Setting Job Shop Standards", Mill and Factory, Vol. 44, May, 1949.

6. Ghormley, Glen, "The Learning Curve--Fitting the Worker to the Job", Western Industry, December, 1952.

7. Conway, R. W. and Schultz, Andrew, Jr., "The Manufacturing Progress Function", Journal of Industrial Engineering, January-February, 1959.

8. Doyle, L. A., "Cost Estimating", Tool Engineer, June 15, 1959.

9. Kottler, Julian L., "The Learning Curve--A Case History in Its Application", Journal of Industrial Engineering, July-August, 1964.

10. Raborg, W. A., Jr., "Mechanics of the Learning Curve", Aero Digest, November, 1952.

11. Janzen, Jerry L., "A Procedure for the Evaluation of Start-up Effect in Manual Industrial Operations", Master's Thesis, Oklahoma State University, May, 1964.

12. Berghell, A. B., Production Engineering in the Aircraft Industry, New York: McGraw-Hill Book Company, Inc., 1944, Chapter XII.

13. Crouse, P. B., "Projecting Labor Leads in Aircraft Production", Aero Digest, October, 1943.

14. Andress, Frank, "The Learning Curve as a Production Tool", Harvard Business Review, Vol. 32, January, 1954.

15. Jordan, Raymond, "Learning How to Use the Learning Curve", NAA Bulletin, National Association of Accontonts, January, 1958.

16. Zimmerman, William M., Text of presentation at American Institute of Industrial Engineering Region IX Conference in Dallas, Texas, October 17-18, 1963.

17. Torgerson, Paul, Draft of Chapter 7 of book written by Fabrycky, W. J. and Torgerson, Paul, Operations Economy, Englewood Cliffs, New Jersey: Prentice-Hall, Inc., 1966.

18. Cox, J. W., Manual Skill, London: Cambridge University Press, 1934.

19. Bryan, W. L., and Harter, N., "Studies in the Telegraphic Language", Psychological Review, Vol. 4 and 6, 1897 and 1899.

20. Batson, W. H., "The Acquisition of Skill", Psychology Monographs, Vol. 21, 1916.

21. Cochran, E. B., "New Concepts of the Learning Curve", Journal of Industrial Engineering, July-August, 1960.

22. Konz, Stephan A., "Learning Curves for Drill Press Operations", Master's Thesis, State University of Iowa, August, 1960.

23. Bugelski, B. R., Psychology of Learning, New York: Henry Holt and Company, 1956.

24. Hilgard, Earnest R., Theories of Learning, Appleton, New York: Century Crafts, 1956.

25. Finlay, William W., Sartan, A. Q., and Tate, W. M., Human Behavior in Industry, New York: McGraw-Hill Book Company,

26. Hancock, Walton M., "Progress Report on Learning Curve Research", MTM Journal, by Methods-Time Measurement Association for Standards and Research, Vol. IX, No. 2, 1963.

27. Janzen, Jerry L., "The Manufacturing Progress Function Applied to a Wage Incentive Plan", Journal of Industrial Engineering, April, 1966.

28. Ross, Donald K., "Information Concepts in Work Analysis", Doctoral Dissertation, Washington University, Sever Institute, September, 1960.

29. Fitts, Paul M., and Peterson, James R., "Information Capacity of Discrete Motor Responses", Journal of Experimental Psychology, Vol. 67, No. 2, February, 1964.

30. Hart, L. W., "Establishing Criteria for Planning Electronic Manufacture", Master's Thesis, Washington University, Sever Institute, June, 1964.

31. Maynard, H. B., Stegemerten, G. J., and Schwab, J. L., Methods-Time Measurement, New York: McGraw-Hill Book Company, Inc., 1948.

32. Ostle, Bernard, Statistics in Research, Ames: The Iowa State University Press, 1963.

33. Duncan, Acheson J., Quality Control and Industrial Statistics, Homewood, Illinois: Richard D. Irwin, Inc., 1953.

34. Hicks, Charles R., Fundamental Concepts in the Design of Experiments, New York: Holt, Rinehart, and Winston, 1964.

35. McGeoch, John A., The Psychology of Human Learning, New York: Longmans, Green and Co., 1942.

36. DeCampos, D. F., "Estudo das Curvas de Aprendizado e sua Utilizacao no Estudo da Aprendizagem", Unpublished undergraduate Thesis, Instituto Tecnologico de Aeronáutica, Sao Jose dos Campos, S. P., Brazil.

8. APPENDICES

APPENDIX A

Work Instruction Sheets

I. Start your stopwatch.

II. Install:

Orange and White	Rubber	Washer on	C-1	with	White	up.
Orange and White	Brass		A-2		White	
Red and White	Steel		D-3		White	
Green and White	Brass		B-1		Green	
Blue and White	Rubber		D-2		Blue	
Red and White	Brass		B-2		White	
Blue and Red	Rubber		C-2		Red	
Green and White	Rubber		C-3		Green	
Blue and Red	Steel		A-3		Red	
Red and White	Rubber		B-4		Red	
Blue and Red	Brass		D-4		Red	
Green and Red	Brass		A-1		Green	
Black and Red	Rubber		C-4		Red	
Black and White	Rubber		B-3		Black	
Green and White	Lock		D-1		Green	
Blue and White	Brass		A-4		Blue	
Black and White	Lock		B-4		Black	
Green and Red	Rubber		A-1		Green	
Blue and White	Steel		D-3		White	
Black and White	Steel		A-4		White	
Orange and White	Steel		C-3		White	
Red and White	Lock		D-1		White	

Blue and Red	Lock	Washer on	B-1	with	Red	up
Green and Red	Steel		C-2		Green	
Black and White	Brass		B-2		White	
Black and Red	Lock		A-2		Red	
Green and White	Steel		C-1		White	
Black and Red	Brass		A-3		Black	
Blue and White	Lock		C-4		Blue	
Green and Red	Lock		D-2		Red	
Black and Red	Steel		B-3		Red	
Orange and White	Lock		D-4		Orange	
Green and Red	Steel		A-3		Green	
Blue and White	Brass		D-3		White	
Green and White	Rubber		B-4		Green	
Red and White	Lock		A-1		White	
Blue and White	Steel		D-4		Blue	
Black and White	Lock		C-1		Black	
Green and Red	Rubber		A-2		Red	
Black and White	Steel		C-4		Black	
Red and White	Steel		A-4		Red	
Green and Red	Lock		B-3		Red	
Blue and White	Rubber		C-2		Blue	
Green and White	Lock		C-3		White	
Black and White	Rubber		D-2		Black	
Black and Red	Lock		D-1		Red	
Green and White	Steel		B-2		White	
Black and White	Brass		B-1		Black	
Red and White	Brass		D-2		White	

Blue and White	Lock	Washer on	B-3	with	Blue	up
Orange and White	Steel		C-2		Orange	
Red and White	Rubber		A-1		Red	
Green and White	Brass		B-4		White	
Black and Red	Steel		C-3		Red	
Orange and White	Lock		A-3		Orange	
Green and Red	Brass		B-2		Red	
Orange and White	Brass		C-1		White	
Black and Red	Brass		C-4		Black	
Black and Red	Rubber		A-2		Black	
Blue and Red	Steel		B-1		Red	
Blue and Red	Lock		D-3		Blue	
Blue and Red	Rubber		D-4		Red	
Blue and Red	Brass		D-1		Red	
Orange and White	Rubber		A-4		Orange	
Blue and Red	Brass		B-1		Red	
Green and Red	Steel		D-3		Green	
Black and White	Brass		C-1		Black	
Blue and Red	Lock		B-3		Red	
Red and White	Steel		B-2		White	
Green and White	Rubber		C-4		Green	
Green and White	Steel		C-3		Green	
Orange and White	Rubber		A-1		White	
Green and Red	Brass		D-1		Green	
Orange and White	Steel		B-4		Orange	
Orange and White	Lock		D-2		White	
Blue and White	Rubber		A-4		Blue	

Blue and Red	Rubber	Washer on	A-3	with	Blue	up
Orange and White	Brass		C-2		Orange	
Blue and Red	Steel		A-2		Red	
Red and White	Rubber		D-4		White	
Red and White	Brass		B-2		Red	
Blue and White	Lock		C-1		Blue	
Green and Red	Rubber		C-2		Green	
Black and White	Steel		A-1		White	
Black and Red	Lock		C-3		Black	
Green and Red	Lock		D-3		Red	
Black and White	Rubber		B-4		White	
Green and White	Brass		C-4		White	
Green and White	Lock		A-3		Green	
Black and Red	Brass		D-4		Black	
Black and Red	Rubber		D-1		Black	
Blue and White	Steel		A-2		White	
Red and White	Lock		A-4		Red	
Black and White	Lock		B-3		Black	
Blue and White	Brass		D-2		Blue	
Black and Red	Steel		D-1		Red	

III. Dump the pegboard.

IV. Replace all washers in proper positions on parts rack.

V. Stop your watch. Say "Stop" and raise your hand.

APPENDIX B

MTM Standard Time Summary

The experimental task was divided into ninety-six assemble elements, ninety-six disassemble elements, and several miscellaneous transition elements, such as "dump the pegboard". The following is a summary by motion of each of the motions occurring in a standard assembly. The resulting standard time of 5.12 minutes is not adjusted for operator ratings, fumbles, or other factors.

Motion	Symbol	TMU	Frequency	Total TMU
Grasp	G1A	2.0	181	362.0
	G1B	3.5	8	28.0
	G2	5.6	54	302.4
	G3	5.6	3	16.8
	G4B	9.1	12	109.2
Reach	R6A	7.0	3	21.0
	R10A	8.7	3	26.1
	R12A	9.6	4	38.4
	R14A	10.5	84	882.0
	R18A	12.3	2	24.6
	R3B	4.0	4	16.0
	R5B	7.8	1	7.8
	R7B	9.3	9	83.7
	R8B	10.1	11	111.1
	R9B	10.8	19	205.2
	R10B	11.5	25	287.5
	R12B	12.9	23	296.7

Motion	Symbol	TMU	Frequency	Total TMU
	R14B	14.4	19	273.6
	R16B	15.8	1	15.8
	R18B	17.2	1	17.2
Move	M5B	8.0	5	40.0
	M8B	10.6	84	890.4
	M12B	13.4	12	160.8
	M14B	14.6	1	14.6
	M18B	17.0	3	51.0
	M7C	11.1	2	22.2
	M8C	11.8	3	35.4
	M9C	12.7	4	50.8
	M10C	13.5	19	256.5
	M12C	15.2	37	562.4
	M14C	16.9	27	456.3
	M16C	18.7	7	130.9
	M18C	20.4	1	20.4
Position	P1SE	5.6	192	1075.2
Release	RL1	2.0	196	392.0
Eye Focus	EF	7.3	96	700.8
Apply Pressure	AP2	10.6	2	21.2
Turn	T90S	5.4	96	518.4
	T90M	8.5	1	8.5
				8532.9

8532.9 TMU's X .0006 $\frac{\text{minutes}}{\text{TMU}}$ = 5.12 minutes

APPENDIX C

Information Content Analysis

Of the twelve factors of information content presented by Ross (28), only two were included in this analysis. Those were his first factor; the total number, or range, of pertinent perceptions and probability of occurrence, and his tenth factor; psychomotor performance. These two factors were selected for two reasons. First, they can be measured easily and objectively, whereas many of the other factors are either very difficult to measure or undefined in quantifiable terms. Second, in a more complete analysis of a somewhat similar task by Hart, (30), over 95% of the total information content was composed of those two factors. The application by Hart was used as a guide to the following analysis:

A. Total Number, or Range, of Pertinent Perceptions and Probability of Occurrence. According to the application by Hart, this factor enters into the analysis every time that the subject must discriminate between alternatives. Measuring information content in bits, the information content due to this factor, H_a, is equal to the logarithm to the base two of the number of alternatives presented to the subject. That is,

$$H_a = \log_2 \text{(number of alternatives)}$$

Thus, if a subject were asked to pick up a die with the side having three dots facing him, H_a would equal $\log_2 6 = 2.59$ bits. The following table summarizes the H_a calculations for the experimental task.

Element	Alternatives (P)	$\log_2 P$	Frequency	Total
Select correct type washer	4	2	96	192
Select correct color washer	8	3	96	288
Select correct peg on pegboard	16	4	96	384
Put washer on pegboard with correct color up	2	1	96	96
Return washer to correct location on parts board	32	5	96	480
Place correct side of washer up on parts board	2	1	96	96
			Total H_a =	1536

B. Psychomotor Performance. This factor of information content was developed from Fitts' (29) theory that human motor transmission time varies with the logarithmic relationship between the target area to which the action is directed and the distance traveled and the number of alternatives. From the initial equation of Fitts and subsequent work by Ross, Hart developed the equation:

$$H_j = - \log_2 W_s/L \text{ Bits}$$

W_s = the target dimension in the direction of motion, In the task studied, this was the difference between the inside diameters of the washers used (3/8 inch and 5/8 inch) and the diameters of the pegs on the pegboard (5/16 inch) and on the parts board (5/16 inch).

L = the maximum extension to which movement was possible in the same direction. The maximum length of Reach and Move from the MTM analysis was eighteen inches.

Thus, for the brass, steel, and lock washers used in the experimental task,

$$\begin{aligned} H_j &= -\log_2 \frac{3/8-5/16}{18} \\ &= -\log_2 .00347 \\ &= 11.76 \text{ bits/washer installed} \end{aligned}$$

Since there were seventy-two washers of those types which were first installed on the pegboard and then put back on the parts board, the above factor must be multiplied by 144.

For the twenty-four rubber washers used in each cycle,

$$\begin{aligned} H_j &= -\log_2 \frac{5/8-5/16}{18} \\ &= -\log_2 .01735 \\ &= 7.77 \text{ bits/washer installed} \end{aligned}$$

The total H_j was then:

$$H_j = 11.76 \times 144 + 7.77 \times 48 = 1879.92 \text{ bits}$$

Finally, the total information content was:

$$H_a + H_j = 1536 \text{ bits} + 1879.92 \text{ bits} = 3415.92 \text{ bits}$$

APPENDIX D

Analytical Calculations

A. Determining the "Expected Difference" in times between successive assemblies separated by an interruption. The 89% learning curve for the control group was used as the expected rate of improvement. From equation (2) in the text,

$$b = -3.32 \log \frac{(100\%)}{89\%} = -.171$$

Using equation (1) in the text, one can determine the theoretical ratio between succeeding assembly times.

$$\frac{Y_9}{Y_8} = \frac{A(9)^b}{A(8)^b} = 1.125^b = 1.125^{-.171} = .9800$$

$$\frac{Y_{21}}{Y_{20}} = \frac{A(21)^b}{A(20)^b} = 1.050^b = 1.050^{-.171} = .9917$$

$$\frac{Y_{33}}{Y_{32}} = \frac{A(33)^b}{A(32)^b} = 1.031^b = 1.031^{-.171} = .9948$$

$$\frac{Y_{45}}{Y_{44}} = \frac{A(45)^b}{A(44)^b} = 1.023^b = 1.023^{-.171} = .9960$$

The above ratios can then be multiplied by the cycle times for the assemblies preceeding the interruption to obtain the expected time for the following assembly had there been no interruption. The Expected Difference can be obtained by subtraction.

Group	Cycle	Time	x	Factor	=	Time for	Cycle	Expected	Difference
A	8	14.13	x	.9800	=	13.85	9		+ .28
	20	12.51	x	.9917	=	12.41	21		+ .10
	32	12.47	x	.9948	=	12.41	33		+ .06
	44	11.64	x	.9960	=	11.59	45		+ .05
B	8	14.93	x	.9800	=	14.63	9		+ .30
	20	14.42	x	.9917	=	14.30	21		+ .12
	32	13.89	x	.9948	=	13.82	33		+ .07
	44	11.12	x	.9960	=	11.08	45		+ .04
C	8	14.55	x	.9800	=	14.26	9		+ .29
	20	13.80	x	.9917	=	13.69	21		+ .11
	32	13.14	x	.9948	=	13.07	33		+ .07
	44	10.42	x	.9960	=	10.39	45		+ .03
D	8	14.10	x	.9800	=	13.82	9		+ .28
	20	13.45	x	.9917	=	13.34	21		+ .11
	32	11.00	x	.9948	=	10.94	33		+ .06
	44	11.14	x	.9960	=	11.10	45		+ .04

B. Duncan's Test.

First, the K values for the various break lengths from Table 11 were arranged in order from lowest to highest as shown:

-.247 -.108 -.011 + .506

The average error mean square term was calculated from:

$$S_{\bar{x}_{i,j}} = \sqrt{\frac{\text{Error Mean Square}}{\text{\# observations in } \bar{x}_j}} = \sqrt{\frac{.002191}{4}} = .023$$

The critical values at the .05 and .01 levels of significance were calculated by multiplying the table values from the Multiple Range Test by .023.

Level of Significance	Table Values	Multiplier	Critical Values
	3.26	.023	.075
.05	3.39	.023	.078
	3.47	.023	.080
	4.74	.023	.109
.01	5.00	.023	.115
	5.14	.023	.118

Comparing:

Largest versus smallest value = .753**

Largest versus next smallest = .614**

Largest versus next largest = .517**

Second largest vs. smallest = .236**

Second largest vs. next largest = .097*

Third largest vs. smallest = .139**

**Significant at the .01 level

*Significant at the .05 level

FACTORS AFFECTING INDUSTRIAL LEARNING ON INTERRUPTED PRODUCTION SCHEDULES

by

ROGER WARREN DANIELS

AN ABSTRACT OF A MASTER'S THESIS

submitted in partial fulfillment of the

requirements for the degree

MASTER OF SCIENCE

Department of Industrial Engineering

KANSAS STATE UNIVERSITY
Manhattan, Kansas

1966

ABSTRACT

How does one apply learning curves to operators who work on an interrupted production schedule by which they might build small quantities of several assemblies each production period? What are the effects of interruptions? What factors influence the effect of an interruption on an operator working on a particular assembly? How does an operator perform following an interruption? Questions of this nature prompted the theoretical development and ensuing research reported herein.

After investigating several concepts and characteristics of learning curves, the investigator developed a theoretical model of interrupted learning and the requisite hypotheses to test that model. An industrial experimental design to test the model was presented along with the abbreviated laboratory experimental design actually investigated.

From a washer-pegboard assembly task involving twenty-five experimental subjects who took breaks of one-half, two, four, and sixteen hours in the course of working fifty cycles, this investigator was not able to determine whether a break was helpful or harmful. Thus, a complete investigation of the theoretical model was not possible. However, studying the effects of break length and the number of units built prior to a break on the magnitude of the break, it was found that the length of the break was a significant factor at the .01 level of significance and that the effects of each break length differed from each other at the .05 level of significance.