

# Dynamic Pacing and Learning in Assembly Operations

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• The fact that manufacturing systems can be improved through steady increase in cumulative production volumes was established over 50 years ago. Accelerating the improvement rate has become crucial for cost reduction and for quickly obtaining the desired output capacity needed to capture increased market demands. In extending the results of previous studies, this article presents original evidence regarding the unforeseen implications of using constrained control policies in an attempt to externally force a desired production improvement rate. The consequences of these policies included reduced production improvement rates, increased performance deviations, and occupational stress. From analysis of the key environmental conditions that induce learning, it is postulated that the desired impetus for accelerated learning rate can be better created by an "open-end" positive strategy. This new theory advocates learning through experimentation in conjunction with formal training and financial gradient incentive schemes. The proposed gradient incentive schemes are based on the realized progress rates, rather than on the conventional labor time utilization. A series of laboratory experiments, using two distinct sets of industrial assembly tasks, is reported to demonstrate and empirically validate our assertions.

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### Biographies

**Abraham Seidmann** is a Professor of Computers and Information Systems and of Operations Management at the William E. Simon Graduate School of Business Administration at the University of Rochester, Rochester, NY. Professor Seidmann also holds a concurrent appointment with the Industrial Engineering department of Tel-Aviv University. He is an Associate Editor of *IIE Transactions*, the *International Journal of Flexible Manufacturing Systems*, and a senior member of IIE. He received a B.Sc. in Industrial and Management Engineering, an M.Sc. in Operations Research from the Technion-Israel Institute of Technology, and a Ph.D. in Industrial Engineering (Cum Laude) from Texas Tech University. Dr. Seidmann is an author of over 50 research articles and his current research and consulting activities include Analysis and Design of Automated Production systems, Computer Integrated Manufacturing (CIM), Manufacturing Information Systems, and Man/Machine Systems.

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### The Manufacturing Learning Framework

**O**ne common way that people improve performance is by repeating tasks. These performance improvements include such factors as direct labor hours, percentage of defects, or the cost per item produced. That acquisition of skills and knowledge is usually termed as "learning." The "learning curve" (LC) concept asserts that learning is the product of experience and that performance improvements associated with task repetition follow a predictable pattern of diminishing returns. Many companies use the LC model to describe the time required to complete an item as a function of a cumulative number of items; this function is typically of a power form as depicted in Figure 1. The LC notion accommodates two categories of learning: labor (or human) learning and organizational learning. The latter is also called the "manufacturing progress function." This article is mainly concerned with managerial approaches for stimulating labor learning, inasmuch as the manufacturing productivity of operations that have a high

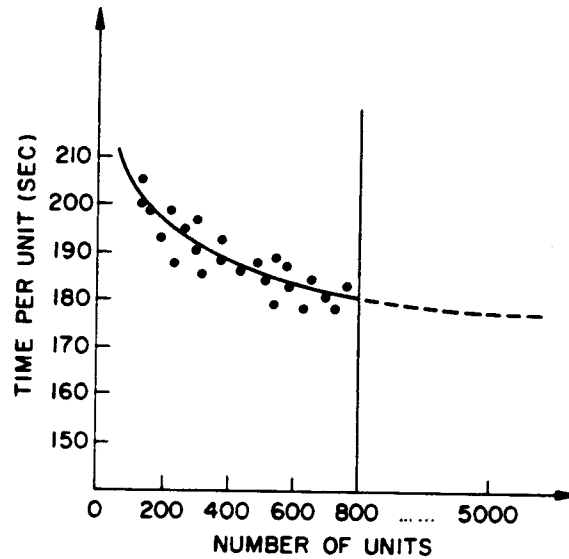


Figure 1. A typical learning curve.

degree of labor content follows a curve similar to the labor learning curve (Hirsch 1952, Jordan 1958).

### Learning Curve

The two basic parameters of LC models refer to the input resources used for the production of the first unit and the learning curve measure of reduction rate. These parameters are a function of the nature of the work environment and of the individual. The power model, which is the more common one, takes the form:

$$T_{ij}(S) = T_{ij}(1)S^{-m_{ij}}, \quad (1)$$

where  $S$  = the repetition number,  $i$  = operator's index,  $j$  = task type index,  $T_{ij}(1)$  = first cycle time parameter,  $T_{ij}(S)$  = the time for the  $S$ th cycle,  $m_{ij}$  = a constant learning exponent. Taking the log of both sides of Eq. (1), we get the linear equation:

$$\log T_{ij}(S) = \log T_{ij}(1) - m_{ij} \log S, \quad (2)$$

which is the equation of a straight line with a learning constant of  $m_{ij}$ .

Since the learning constant  $m_{ij}$  does not have an intuitive operational meaning, another parameter called the *slope* of the LC is commonly used. The value of the LC slope is derived from  $m_{ij}$  as described below.

If  $S_1$  and  $S_2$  are two points on the LC and

$$S_2/S_1 = C \quad \text{or} \quad S_2 = S_1C, \quad (3)$$

then

$$\frac{T_{ij}(S_2)}{T_{ij}(S_1)} = \frac{T_{ij}(1)S_2^{-m_{ij}}}{T_{ij}(1)S_1^{-m_{ij}}} = \frac{T_{ij}(1)S_1^{-m_{ij}}C^{-m_{ij}}}{T_{ij}(1)S_1^{-m_{ij}}} = C^{-m_{ij}}. \quad (4)$$

The slope, or the learning rate is usually described by using the complement of the reduction that occurs when the production quantity is doubled. Substituting the value of  $C = 2$  in Eq. (4), its value is equal to  $2^{-m_{ij}}$  expressed as a percentage. For example, a learning curve for which  $-m_{ij} = 0.322$  is designated as an 80% curve ( $2^{-0.322} = 0.80$ ). Typical time computations, based on the power model of Eqs. (1) to (4), are given in Appendix A.

### Applications and Past Studies

The learning curve was first recognized in the aircraft industry by T. P. Wright (1936). He observed that on the average, when cumulative output doubled, the direct-labor hours requirements decreased by about 20%; in other words, there was an 80% learning factor. That, in itself, was also a significant finding about the cost dynamics of the firms. Over the years LC models have provided managers with relatively simple tools for dealing with inherently complex issues. Relevant applications of LC models include (Belhaoui 1986):

1. Cost controls and pricing policies
2. Negotiated purchasing
3. Manpower planning
4. Aggregate planning and scheduling
5. Organizational goal setting.

Numerous articles and reports have been published, proposing alternative approaches for describing and facilitating the learning phenomenon. Levy (1965), Abernathy and Wayne (1974), Nanda (1977), Yelle (1979), Hancock and Bayha (1982), and Belhaoui (1986) present comprehensive literature surveys of LC models and discuss their applicability to various production and operations management problems. The key areas of LC research have been:

1. Empirical evaluations of various structural properties of the LC mathematical models. These include linear, exponential, S-type, and adaptive models (e.g., DeJong 1957, Levy 1965, Pegels 1969, Globerson 1980).
2. Industrial surveys of LC application areas. These studies started in the late 1930s when the armed forces and the Department of Defense established guidelines for improvement using learning curves. Since then, the LC approach has gained acceptance in numerous industries (e.g., Turban 1968, Cochran 1969, Dutton et al. 1984).

3. Economic implications and management strategy. Initial research efforts in this area tried to explain the growth in productive capacity under a fixed capital-labor ratio. The more recent studies focus on dynamic technology transfer issues and its impact on the operations management function of the firm (e.g., Arrow 1962, Conley 1970, Rosen 1972, Ebert 1976, McIntyre 1977, Fine 1986, Bohn 1987).
4. Development of a scientific rationale for the existence of the LC. These theories assume that learning can be explained as a random search for better methods, and that the search parameters improve with the number of cycles. In this context learning is defined as a continuous process which results from experience (e.g., Crossman 1959, Shahal 1979, Roberts 1983, Venezia 1985, Muth 1986).

Since the present study deals with controlling the learning environment, it is of utmost importance to understand the learning process, which is the objective of the next section.

### **The Learning Process**

The nature of the activities to be learned predetermines the type of learning involved. This view has been elaborated in several of these studies indicating that human and organizational learning can be explained by models of sequential-uncertain search for more successful methods. The search theories of LC stem back to the early trial-and-error perception of learning as formulated by Hilgard (1948) and others. According to these LC studies the search for improved methods spans over a finite initial repertoire of feasible options. Successive cycles are associated with repeated trials favoring those patterns of action that are superior, at the expense of the other options. The selection of a new method can depend upon deliberate choice, habit, or chance. Eventually the equilibrium response pattern is reached when the rate of improvements become so slow that it is not worth the search effort.

The actual process of learning augments the following knowledge components (Herzberg 1966, Holding 1981):

1. Generalization—creating identical response patterns for different stimuli.
2. Discrimination—providing for distinct responses in case of similar stimuli.
3. Deduction—reasoning from prior propositions.

Major factors affecting the process of learning can be classified as either *environmental* or *individual* considerations (Table 1). These factors are briefly discussed below.

The *environmental* factors include job complexity as a proxy measure for the required dexterity, hand-eye coordination requirements, etc. Longer

**Table 1** Major Factors Affecting the Learning Process: A Proposed Paradigm

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|                                   |                            |
|-----------------------------------|----------------------------|
| <i>I. Environmental Factors</i>   |                            |
| A. Job Complexity                 | Precision and coordination |
|                                   | Cycle length               |
|                                   | Uncertainties              |
| B. Job Controls                   | Methods and tools          |
|                                   | Feedback information       |
| C. Motivation                     | Positive: Incentives       |
|                                   | Punitive: Goal pacing      |
| D. Training                       | Mission oriented           |
|                                   | Task oriented              |
| <br><i>II. Individual Factors</i> |                            |
| A. Prior Experience               | Similar tasks              |
|                                   | Identical tasks            |
| B. Work Capability                | Psychomotor                |
|                                   | Physiological              |
| C. Psychological Profile          | Attitudes                  |
|                                   | Intelligence               |
|                                   | Time-sharing capabilities  |

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cycle times and increased uncertainties also contribute to the job complexity. The job control aspects refer to the operator's freedom in discussing and choosing the desired tools and work method. Another aspect of job control is the type and frequency of feedback information. Performance feedback, for example, can be presented periodically or per cycle. Positive motivation includes monetary incentive schemes, bonuses, and social recognition. Goal pacing includes machine pacing and short-term performance goals such as imposed daily production targets. Machine pacing can be classified according to the length of the work cycle, pacing rate, and the local buffers in use. Training includes both general and detailed instructions. In general instruction schemes (mission orientation), the trainees are free to develop those patterns that best enable them to meet the performance requirements for a broad spectrum of job types.

In discussing *individual* factors, one's prior experience may refer to similar or identical tasks. The time elapsed from the last actual conduct of such tasks (breaks) is also important. Natural talents such as coordination,

acuity, and orientation along with physical or posture adaption also play a significant role. Finally, the psychological profile of the individual refers to such metrics as intelligence, imagination, financial motivation, analytical capabilities, etc.

### **Pacing Performance**

Accelerating task learning rate is of practical importance to many modern industries (Spence 1981). These industries are now being characterized by rapid development of new products. That trend entails a steady decrease in production runs as product life spans are reduced. As a result, a significant portion of the industrial work force is constantly busy learning new tasks while management looks for effective means to accelerate the learning curve (Bohn and Jaikumar 1986, Fine 186). A widely practiced method, currently used in paced assembly plants, is to gradually accelerate the speed by which items are moving on the lines, thereby imposing a lower bound on the improvement rates of workers.

The impact of pacing performance rate is a controversial one. Several reports document the successful introduction of machine pacing (M/P) and human pacing (H/P) to enhance the productivity of *experienced* operators (Wild 1972, Johansson 1981, and Rogers and Mui 1981). For example, Manenica (1977) detected a significantly lower mental load during M/P as compared with H/P. He suggested that the presence of a cognitive time-keeping factor, referred to as an "internal (central) pacing mechanism" was responsible for maintaining the operators' pace during H/P performance. When performing M/P tasks, this function was instead assumed externally by the machine. Another series of interrelated laboratory and industrial studies reported by Salvendy (1980) reveal that the variability in quality performance within an operator is markedly lower for M/P than H/P. More recently, Salvendy (1985) reviewed 85 publications dealing with the subject matter. He concluded that M/P is advantageous for a large number of work situations. One may even claim that the mere fact of establishing performance standards has a pacing component. In a series of studies by Locke and Latham (1984) and by Locke et al. (1980), field experiments demonstrate significant performance improvements through the introduction of temporal quantitative goal standards to individual subjects. However, the experimental work cited in all these publications did not specifically deal with the learning effects.

### **Research Hypotheses**

The previous findings cited above argue that M/P improves operator performance. Therefore, one can also hypothesize that a certain degree of machine pacing should result in an accelerated learning rate as compared

with the unpaced (natural) rate. To date, the interaction of work pacing and the rate of individuals learning has not been investigated.

Individual learning can be accelerated through other media as well, rather than work pacing. Gershoni (1971), Nadler and Goldman (1963), and Turban (1968), among others, claim that proper training and wage incentives motivate operators to increase their efforts and to learn faster during the break-in period. As a result, it may be further hypothesized that learning acceleration could also be generated by using a combination of on-the-job training in methods improvements along with a gradient incentive scheme. In a gradient incentive scheme, the bonus earned by the operators is proportional to their individual learning rates.

### **Current Research**

Extending the previous work of Grossman (1959), Salvendy (1980), Globerson et al. (1987) and Globerson and Seidmann (1988), the following sections discuss the possible implications of using constrained control policies in an attempt to impose the desired progress rates. The observed outcomes are reduction in the production progress rates, increased performance deviations, and occupational stress. The benefits of implementing amplified motivation schemes, based on gradient incentives structures, and of the joint introduction of formal training along with amplified incentives policies are elucidated next. A set of laboratory experiments in controlled conditions is used to demonstrate, and to empirically validate, our theoretical arguments regarding the effects of various environmental determinants on labor learning in industrial assembly lines.

Section 2 outlines the experimental evaluation methodology. The discussion of the empirical results is provided in Section 3, and Section 4 concludes the paper with a discussion of managerial implications. Details of the experimental design are provided in Appendix B. Appendices C and D present statistical analyses of the experimental results.

### **The Experimental Evaluation Process**

The learning rate of a manual assembly facility depends on the capabilities of the workforce and the current set of manufacturing process plans. Management control policies aimed at intensifying the progress rate of that facility need to consider those environmental determinants which are both manipulable and effective (Table 1). Following the early analysis in Section 1, several laboratory studies were conducted to investigate the impact of various environmental factors on the observed slope of actual LCs.

Two sets of tasks were used to ensure task-independence of the results. These tasks (denoted as T1 and T2) involved the manual assembly and disassembly of an electrical switch. This product is currently mass-produced

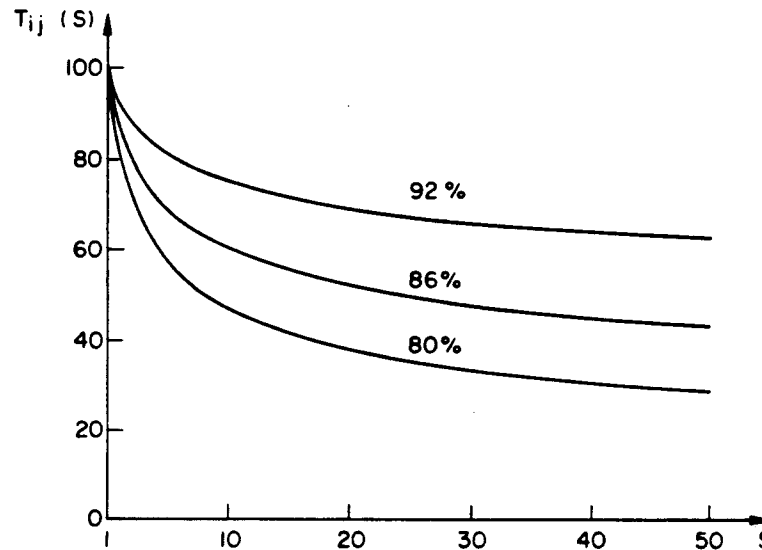


Figure 2. The relative slopes of the three pacing rates.

on a manual assembly line by the MW Company. Initial experiments (group 1) were conducted in order to establish the baseline (natural) progress rate for each task. These were followed by a series of M/P experiments (groups 2–4) where the feed rates of raw parts into the assembly station were accelerated in accordance with several prescribed pacing levels (80%, 86%, 92%). The relative slopes of these curves are illustrated in Figure 2 for the case of  $T(1) = 100$ . Finally, experimental groups 5 and 6 involved amplified motivation through the use of gradient schemes. The joint introduction of general training in methods improvements with an amplified monetary incentive plan was investigated in group 6.

Performance measures recorded were the realized slopes of the LC for each experimental group, the relative deviation of the actual performance around the LC, production quality, and the individual's occupational stress levels at the end of each assembly session. In the case of M/P the subjects were informed that they would not be penalized for the items missed if they temporarily lagged behind the conveyor feed rate. Moreover, relaxing any upper bounds on performance achievements, idle subject times (resulting from subjects waiting for a new part flow into their workstation) were also eliminated by the experimenters. The subject population was composed of 65 male university students. They were all paid an hourly salary augmented by an additive piecewise bonus; the latter was a function of the number of items actually produced and their quality. Each experimental session took about 4–6 hours and subjects were given a 10-minute break after every working hour. The breaks were intended to allow for personal rest and to

provide the subjects with the opportunity for reevaluating their workstation layout and methods.

### **Discussion of the Experimental Results**

The basic premise underlying the research hypotheses was that learning by doing creates knowledge which prompts improvements or progress. Cumulative output and the LC slope were used as proxies for measuring knowledge and experience, respectively.

Several studies indicate that temporal goal standards such as M/P work schedules may lead to a considerable improved performance. It was, therefore, hypothesized that M/P could also lead to improved learning rates. Improvements were expected to be realized as a result of the pacing process itself or as a result of the "propelled" goals as seen by the subjects. The experimental results clearly refute that hypothesis. At the higher pacing levels (i.e., 80% and 86%) the subjects' learning rate was fairly close to that of the unpaced group; the increase in the job strain of these subjects is manifested by the patterns of their individual stress scores and performance deviations. At the lower pacing level (i.e., 92%), these negative symptoms were even more suggestive; the subjects' progress rate fell below the unpaced level; the highest stress scores and performance deviations were recorded at that level.

These findings serve as evidence that the subjects had adopted a "thresholdlike" response strategy: being paced beyond a certain rate they "gave up" and resumed their natural (unpaced) progress rate, disregarding the imposed one. In contrast, when the machine pace was just slightly steeper than the natural pace, they might have perceived that as an acceptable goal and tried, though unsuccessfully, to conform. The earlier studies by Welford (1973), Gowler and Legge (1975), as well as Terborg and Miller (1978) seem to support our inference regarding the thresholdlike response strategy. They all claim that subjects' stress reaction occurs on the basis of individual perception of a given situation, rather than of the situation per se. Or, in other words, such a stress reaction occurs when subjects sense unacceptable deviations from their optimal performance goals, which are not easy to restore.

That M/P work serves as a stressor was clearly demonstrated. Negative pacing effects were found for each one of the three paced groups and, in fact, no instances were found in which the paced subjects failed to report higher stress levels than their unpaced counterparts. The minimal process level was associated with the highest stress scores. With very few exceptions, similar observations were recorded for both tasks.

Human pacing was investigated using both gradient incentive schemes and a combination of methods improvements training and the gradient incentives. The latter was demonstrated to be effective with regard to subjects'

performance progress without causing any significant increase in the stress scores; it should be noted that this progress rate was *significantly superior* than those observed at all the other pace levels. The sole use of the gradient incentive scheme had a significant performance improvement effect with regard to just one of the tasks; it was also associated with a significant stress increase at the other task.

The subjects participating in all the six experimental groups didn't tend to trade the quality required for the quantity produced. Only 15% of the subjects produced any defects; all these defects were minor in nature. The subjects associated with the defective products were almost uniformly distributed over the various groups and tasks. These results imply that machine and human pacing had no effect on the quality of the outgoing products. One may also state that although workers may maximize their returns by trading quantity for quality, they do not voluntarily tend to do so under M/P or H/P.

Table 2 summarizes the key differences between the hypothesized and the actual ordinal ranks of the various experimental groups. The highest rank in this table corresponds with the best performance improvement. Two environmental factors and their impacts on the subjects performance are presented: constrained or machine paced goals are represented by M/P, and H/P represents the use of positive motivation schemes. The hypothesis that tighter goals will automatically have higher valence is based on the design features of the experiment and on the "performance gap" theory as formulated by March and Simon (1958) and by Cyert and March (1963).

Table 2 demonstrates that subjects can be made to outperform their (unpaced) natural progress rate by using an appropriate combination of a gradient incentive scheme with methods improvements training. The use of machine pacing to impose a steeper learning curve failed to improve individ-

**Table 2** Comparative Rank Evaluation of the Experimental Groups: Hypothesized Versus Actual

| <i>Machine Pacing (Dependent Variable: Progress Rate)</i> |                     |                   | <i>Human Pacing (Dependent Variable: Progress Ratio)</i> |                         |                         |
|---|---------------------|-------------------|--|-------------------------|-------------------------|
| <i>Rank</i>   | <i>Hypothesized</i> | <i>Actual</i>     | <i>Rank</i>  | <i>Hypothesized</i>     | <i>Actual</i>           |
| 1   | High pace (80%)     | Unpaced           | 1  | Training and incentives | Training and incentives |
| 2   | Medium pace (86%)   | Medium pace (86%) |  |                         |                         |
| 3   | Low pace (92%)      | High pace (80%)   | 2  | Incentives              | Incentives              |
| 4   | Unpaced             | Low pace (92%)    | 3  | Unpaced                 | Unpaced                 |

Rank 1, best performance improvement.

ual's learning pace thereby refuting the performance gap hypothesis. This phenomenon corresponds to the well known observations of Crossman (1959) and Gershoni (1979) that most people learn by improving their work methods rather than by speeding up the execution of their current activity sets. But unlike our study, these researchers assumed a *given* learning rate. Crossman (1959) and Gershoni (1979) also ignored the interaction effects between learning, pacing, stress, quality, and performance consistency.

The experimental results reported here suggest that tighter goals confine the search space per work cycle and hence result in inferior progress rates. Training, however, has a positive effect on both the initial repertoire and on the search effort itself: it swells the initial repertoire of effective methods and facilitates the adaptive search process, thus leading to higher progress rates. Therefore, in retrospect, in enhancing the learning process for repetitive tasks one should have placed a greater emphasis on the conduct of the trial-and-error search. During that search subjects learn by trying out various work options and then retaining the most successful ones.

Through replicating the experiment for two distinct tasks, it was possible to affirm that the general nature of the findings are task independent. Corroborating experiments should be conducted on a broader range of tasks.

### Management Perspectives

Accelerating the learning rate is of particular interest for those manufacturing systems that are characterized by decreasing production runs as a result of short product life span, competitive pressures, rapid technological developments, and proliferating product varieties. It has been argued above that a wide variety of factors interact to produce the desired learning effects. The ways in which these factors interact are still not fully understood. Most scientific studies of this phenomena have been mainly concerned with the development of predictive models, assuming exogenous learning rates. The current literature does not address the identification and empirical evaluation of prescriptive management strategies aimed at enhancing the learning progress rates, without causing occupational stress or quality deterioration side effects.

Earlier studies pointed at environmental and individual considerations as the two major factors affecting the learning rate. Workforce motivation is one of these factors which is also manipulable by management. A series of laboratory experiments was conducted in order to investigate the relative merits of using common positive and punitive motivation schemes for learning rate acceleration. Analysis of the results points to the following major conclusions:

1. Subjects can be made to outperform their natural progress rate using a financial gradient incentive scheme; this scheme is based on the actual progress rate of each subject.

2. Further gains in the progress rate can be realized by using an appropriate combination of the gradient incentive scheme with methods improvement training; this approach does not result in augmented occupational stress.
3. The use of a punitive motivation scheme (by means of machine pacing) failed to improve progress rates. That scheme also resulted in increased performance deviations and occupational stress.
4. Imposition of tighter temporal performance goals was not shown to have any positive performance effects. This observation seems to refute the performance gap (or aspiration level) theory.
5. Both the punitive and the positive motivation schemes had no impact on quality, attesting that subjects do not tend to substitute quality for quantity.

These results point to some important practical consequences. It has been clearly demonstrated that the desired impetus for accelerated learning is best created by using amplified motivation schemes, tailored to improvement rates rather than to direct labor time utilization. This should be done during the learning process along with proper training, and controlled experimentation, in various operational modes. The training effort should aim at augmenting the initial repertoire of feasible options with which to experiment, as well as by supporting the selective search process through faster pruning of inferior approaches. It has also been shown that such an open-end positive strategy is far superior to the more constrained control policies which attempt at externally forcing the desired rate of change. When realizing this open-end strategy on the production lines, it would be wrong to ignore some of the long-term implications regarding labor physical and mental exhaustion. Job satisfaction may be affected even before there is an apparent reduction in performance. The relationship between such negative experiences and absenteeism, as well as turnover, are well documented (Goodman and Atkin 1984).

Several interesting managerial issues are posed by these results. One is the validity of the various quantity/quality goal-setting practices to a rapidly changing technological environment (Austin and Bobko 1985). Another unresolved issue is the desired managerial balance between the proposed strategy of encouraging motivated unconstrained learning by subjects' trial-and-error experimentation, and the need to maintain some kind of an organizational progress monitoring scheme. There is also a need to further quantify the economic merits and limitations of the advocated gradient-base incentive schemes. The economic value of the resulting cross-departmental or shared experiences should also be determined for competitive conditions. Lastly, future research and application efforts are needed in different industrial settings in order to fully understand the long-term potential benefits of the proposed managerial strategies for learning acceleration.

**APPENDIX****A****TIME COMPUTATIONS WITH THE LEARNING CURVE**

Given the power model LC of Eq.(1) the average cycle time for producing units  $S_1$  to  $S_2$  is  $AV_{ij}(S_1|S_2)$  and it is given by:

$$AV_{ij}(S_1|S_2) = \frac{\int_{S_1-1/2}^{S_2+1/2} T_{ij}(1)S^{-m_{ij}}ds}{(S_2 + 1/2) - (S_1 - 1/2)}$$

$$= \frac{T_{ij}(1)[(S_2 + 1/2)^{1-m_{ij}} - (S_1 - 1/2)^{1-m_{ij}}]}{(1 - m_{ij})(S_2 - S_1 + 1)} \quad (\text{A.1})$$

The cumulative time ( $CT_{ij}$ ) required by operator  $i$  to reach the normal time ( $N_j$ ),  $N_j < T_{ij}(1)$ , for task  $j$  is:

$$CT_{ij} = \frac{T_{ij}(1) \left[ \left( \text{antilog} \left( \frac{\log(T_{ij}(1)/N_j)}{m_{ij}} \right) + 1/2 \right)^{1-m_{ij}} - (1/2)^{1-m_{ij}} \right]}{(1 - m_{ij})} \quad (\text{A.2})$$

**APPENDIX****B****EXPERIMENTAL DESIGN****The Study**

Sixty-five right-handed, male students, aged from 21 to 32 years, ( $\bar{X} = 25.8$ ,  $SD = 4.5$ ) constituted the sample for this study. The subjects were randomly selected from various schools on the Tel Aviv University campus. They were not informed of their expected role prior to their participation in the experiment. They were paid an hourly salary and an added bonus as a function of the number and quality of units completed.

Two sets of tasks were used. One (denoted T1) involved the manual assembly of a small electromechanical switch. This product is currently mass produced in an industrial workstation similar to the one used by the authors. The other task (denoted T2) involved it's manual disassembly. Each task set included all basic motion elements of the MTM-2 (Konz 1979) time standard method. Motion elements included are: Eye Action, Put, Get, Apply Pressure, Crank, and Regrasp. The only tool required was a small screwdriver. An experienced industrial engineer conducted an MTM-2 analysis and then estimated the normal times for both tasks. These times were 0.838 minute and 0.370 minute for T1 and T2, respectively.

The experimental design used both M/P and H/P approaches in an attempt to evaluate their impact on the learning rates. As a result six experimental groups were used. Groups 1 through 4 operated under M/P while 5 and 6 operated with H/P. The subjects were tested individually to eliminate peer or group effects.

### **Machine Pacing**

The raw parts for the assembly tasks were fed into the experimental workstation using a computer controlled conveyor belt. The feed rate was constantly increased according to a prescribed learning slope. Once started the experiment was completely automated with the experimenter serving only to monitor for potential malfunctions. The first M/P group (group 1) was used to establish the basic parameters ( $T_{ij}(1)$  and  $(m_{ij})$ ) of the unpaced learning curve. This was necessary in order to identify the range of existing LC rates so that the experimental levels can be established. It was observed that the average unpaced slopes (or the baseline) for T1 and T2 were 95% and 94%, respectively. The 80% slope was established as the highest one since it is significantly faster than the observed unpaced rates and is the slope commonly cited in the literature. Therefore, to cover the range the experimental pacing levels were established as 80% for group 2—highest pacing, 86% for group 3—moderate pacing, and 92% for group 4—lightest pacing. The 92% slope was aimed at investigating the subjects response to assigning dynamic goals of moderate to low difficulties; analysis of the performance distribution among subjects indicated that the *unpaced* progress of 90% of the subjects was 92% or better.

During the experimental session, when a subject was unable to complete the assembly of an item by the time another one reached him, he had the choice of putting the uncompleted part on the conveyor and starting another part (thereby losing the quality bonus for that uncompleted part), or of letting the item on the conveyor pass his workstation into the box of unused raw parts. Similarly, subjects' idle times (waiting for parts to be fed) were not considered in order to eliminate any "slowdown" effects by the conveyor. The measurement taken for each unit was the *net* production time.

### **Human Pacing**

Human pacing was investigated through the introduction of a two-stage incentive plan. After the completion of the first 20 items, an extra bonus was offered to subjects in group 5. This gradient bonus was based upon their own improvement as measured by the ratio of time to complete 61–80 units over the time required to complete the first 20 units:

$$\text{RATIO}_{ij} = \sum_{S=61}^{80} T_{ij}(S) / \sum_{S=1}^{20} T_{ij}(S). \quad (\text{B.1})$$

Finally, in group 6, the subjects received a short training session on methods improvements, and were offered identical extra gradient bonuses.

### Statistical Design

Since subjects were tested individually, the study has been designed as a series of single-factor experiments with no restriction on randomization. The six controlled factors were the pacing levels (groups 1–4) or the incentive and the training methods (groups 5 and 6). Fifteen subjects were used for each Task in group 1 and 10 for each one hereafter. To eliminate potential interaction effects each subject was randomly confined to a single group/task.

### Measures

The following two sets of measures regarding subjects' performances were continuously recorded during the test sessions:

1. The net time required to complete each item, and
2. The quality of each outgoing item.

The third measure, required for estimating the impact of the task structure on the stress level, was based on a subjective closed-end questionnaire. This self-evaluation stress questionnaire was administered to all subjects at the end of their experimental sessions. The questionnaire used was developed by Spilberger et al. (1970) for state-stress evaluation. It was translated to Hebrew and validated by Teichman (1974).

## APPENDIX

## C

### ANALYSIS OF THE RESULTS: MACHINE PACING

#### Pacing and Performance

The results pertaining to the impact of the imposed slope value on the individual's performance will be presented first. The pace level factor was first tested via a one-way completely randomized ANOVA. In this analysis the main effects of experimental sequence and subjects age and all interaction and error terms were pooled. The four pacing levels assumed here were: 80%, 86%, 92%, and the unpaced learning as a reference point. ANOVA

**Table C.1** ANOVA on the Four Pacing Levels and the Individual's Progress Rate

| <i>Source</i>     | <i>d.f.</i> | <i>SS<sup>a</sup></i> | <i>MS<sup>a</sup></i> | <i>F</i> | <i>Pr. (&gt;F)</i> |
|-------------------|-------------|-----------------------|-----------------------|----------|--------------------|
| <i>A. Task T1</i> |             |                       |                       |          |                    |
| Model             | 3           | 549                   | 183                   | 3.10     | 0.0378             |
| Error             | 41          | 2438                  | 59                    |          |                    |
| Totals            | 44          | 2987                  |                       |          |                    |
| <i>B. Task T2</i> |             |                       |                       |          |                    |
| Model             | 3           | 448                   | 149                   | 2.86     | 0.0489             |
| Error             | 41          | 2147                  | 52                    |          |                    |
| Totals            | 44          | 2595                  |                       |          |                    |

<sup>a</sup> ( $\times 10^{-5}$ ).

results for the two tasks (T1 and T2) show strong evidence ( $P < 0.05$ ) of the pacing effects in both experimental tasks (Table C.1).

Having concluded that there is a significant difference in the pacing levels, the unpaced group (1) was then compared with the three other paced groups (2, 3, and 4). Table C.2 compares the actual slope of group 1 with the average actual slope of the paced groups.

The following conclusions were derived:

1. The average progress rates of the unpaced groups is more effective than that of the paced ones, indicating that it may be *impossible* to out perform the natural learning rate using accelerated inflows of work pieces.
2. In certain instances (i.e., in our T2 tasks), such an imposition of paced learning can even result in a significant reduction of the progress rate with respect to the unpaced results.

The second hypothesis is that increasing the external pace should result in a further reduction of the average slope. Table C.3 presents the average

**Table C.2** Comparison of the Average Actual Slopes for Unpaced and Paced Groups

| <i>Tasks</i> | <i>Groups</i>     | <i>n</i> | <i>Average Actual Slope</i> | <i>d.f.</i> | <i>t-test</i>      |
|--------------|-------------------|----------|-----------------------------|-------------|--------------------|
| T1           | 1 — unpaced       | 15       | 0.949                       | 43          | -1.67              |
|              | (2 + 3 + 4)—paced | 30       | 0.963                       |             |                    |
| T2           | 1—unpaced         | 15       | 0.940                       | 43          | -2.22 <sup>a</sup> |
|              | (2 + 3 + 4)—paced | 30       | 0.957                       |             |                    |

<sup>a</sup>  $P < 0.05$ .

**Table C.3** Mean and Standard Deviation of the Actual Learning Curve

| <i>Tasks</i> | <i>Groups</i> | <i>n</i> | <i>Average Actual Slope</i> | <i>Standard Deviation of the Slope</i><br>( $\times 10^{-4}$ ) |
|--------------|---------------|----------|-----------------------------|--|
| T1           | 1—unpaced     | 15       | 0.949                       | 151  |
|              | 2—paced (80%) | 10       | 0.956                       | 238  |
|              | 3—paced (86%) | 10       | 0.954                       | 262  |
|              | 4—paced (92%) | 10       | 0.978                       | 249  |
| T2           | 1—unpaced     | 15       | 0.940                       | 157  |
|              | 2—paced (80%) | 10       | 0.956                       | 243  |
|              | 3—paced (86%) | 10       | 0.948                       | 215  |
|              | 4—paced (92%) | 10       | 0.967                       | 287  |

actual slopes for the four pace levels. The tests on group means after experimentation were conducted using Scheffe's (1953) procedure for exhaustive ( $4 \times 3 = 12$ ) pairwise comparisons. This procedure was selected since it is known to control the type I experimentwise error rate, and it is less restricted than other posterior methods such as the Newman-Keuls range test (Hicks 1973). The test results also indicate a significant difference between groups 1 and 4 in T1 ( $P > 0.05$ ) and in T2 ( $P < 0.10$ ). No other significant differences were detected. One can therefore conclude that when M/P is increased slightly above subjects' ability they are unable to cope with the desired pace, although they are trying to.

### Pacing and Progress Deviations

It is also anticipated that paced learning will be associated with increased performance deviations. This can be expected as a result of the accelerated conditioning efforts (Branton 1970, Weber et al. 1980).

Mean absolute deviation (MAD) is used for computing the individual's performance deviations. This measure is based on the difference between the actual data points and the expected values according to the LC parameters:

$$MAD_{ij} = \frac{\sum_{s=1}^{s=q} |\hat{T}_{ij}(S) - T_{ij}(S)|}{q}, \quad (C.1)$$

where  $q$  = number of items produced by subject  $i$ ,  $\hat{T}_{ij}(S)$  = the actual time required for the  $S$ th cycle,  $T_{ij}(S)$  = the expected time required for the  $S$ th cycle (based on the learning curve parameters established for subject  $i$  in task  $j$ ).

**Table C.4** ANOVA of the Four Pacing Levels and the Individual's Progress Deviations (MAD<sub>*j*</sub>)

| Source            | d.f. | SS <sup>a</sup> | MS <sup>a</sup> | F    | Pr(>F) |
|-------------------|------|-----------------|-----------------|------|--------|
| <i>A. Task T1</i> |      |                 |                 |      |        |
| Model             | 3    | 2789            | 929             | 4.09 | 0.0124 |
| Error             | 41   | 9310            | 227             |      |        |
| Totals            | 44   | 12099           |                 |      |        |
| <i>B. Task T2</i> |      |                 |                 |      |        |
| Model             | 3    | 2110            | 703             | 3.43 | 0.0257 |
| Error             | 41   | 8405            | 205             |      |        |
| Totals            | 44   | 10515           |                 |      |        |

<sup>a</sup>(×10<sup>-4</sup>).

The mean deviation measure for a group having  $M$  subjects is:

$$MAD_j = \frac{1}{M} \sum_{i \in M} MAD_{ij}. \quad (C.2)$$

Using ANOVA tests for both tasks, real differences ( $P < 0.05$ ) were found between the unpaced and the paced groups (Table C.4).

The MAD values for the four groups performing the two tasks are detailed in Table C.5. Scheffe's tests were conducted in order to investigate the relationship between the MAD values and the pacing levels. Significant differences were found for both tasks ( $P < 0.05$ ) only between groups 1 and 4. These results support the previous observations that the most unfavorable effects are associated with the minimal pacing level = 92%.

**Table C.5** Mean and Standard Deviation of the Averaged Individual's Performance Deviations (MAD<sub>*j*</sub>)

| Tasks | Group         | n  | Average MAD | SD<br>×10 <sup>-4</sup> |
|-------|---------------|----|-------------|-------------------------|
| T1    | 1—unpaced     | 15 | 0.125       | 579                     |
|       | 2—paced (80%) | 10 | 0.135       | 119                     |
|       | 3—paced (86%) | 10 | 0.119       | 114                     |
|       | 4—paced (92%) | 10 | 0.187       | 486                     |
| T2    | 1—unpaced     | 15 | 0.092       | 456                     |
|       | 2—paced (80%) | 10 | 0.107       | 104                     |
|       | 3—paced (86%) | 10 | 0.097       | 292                     |
|       | 4—paced (92%) | 10 | 0.148       | 643                     |

**Table C.6** ANOVA on the Four Pacing Levels and the Individual's Stress Scores

| <i>Source</i>     | <i>d.f.</i> | <i>SS<sup>a</sup></i> | <i>MS<sup>a</sup></i> | <i>F</i> | <i>Pr(&gt;F)</i> |
|-------------------|-------------|-----------------------|-----------------------|----------|------------------|
| <i>A. Task T1</i> |             |                       |                       |          |                  |
| Model             | 3           | 350                   | 117                   | 4.33     | 0.0098           |
| Error             | 41          | 1111                  | 27                    |          |                  |
| Totals            | 44          | 1461                  |                       |          |                  |
| <i>B. Task T2</i> |             |                       |                       |          |                  |
| Model             | 3           | 398                   | 133                   | 4.15     | 0.0124           |
| Error             | 41          | 1327                  | 32                    |          |                  |
| Totals            | 44          | 1725                  |                       |          |                  |

<sup>a</sup> ( $\times 10^{-3}$ ).

### Pacing and Stress

Machine pacing is known to amplify the development of job-related stress (Salvendy 1973, Miller 1979, Murphy and Hurrell 1980). Occupational stress is suspected of causing ill health and social dissatisfaction. Job designers are therefore interested in studying possible pacing schemes with the aim of enhancing productivity without causing side effects as occupational stress.

Table C.6 summarizes the ANOVA results for the stress scores at the four pacing levels; it displays statistically significant pace effects for both tasks ( $P < 0.05$ ). The scores presented in Tables C.7 and C.8 clearly support the original hypothesis that paced learning augments the individual's stress. Furthermore, the Scheffe's tests detected a significant difference in the stress scores between groups 1 and 4—in both tasks ( $P < 0.05$ ). These

**Table C.7** Comparison of the Averaged Stress Score for the Unpaced and Paced Groups

| <i>Tasks</i> | <i>Groups</i>     | <i>n</i> | <i>Score</i> | <i>Stress<br/>SD (Score)</i> | <i>d.f.</i> | <i>t-test</i> |
|--------------|-------------------|----------|--------------|------------------------------|-------------|---------------|
| T1           | 1—unpaced         | 15       | 27.5         | 5.66                         | 43          | -1.86         |
|              | (2 + 3 + 4)—paced | 30       | 30.8         | 5.59                         |             | <sup>a</sup>  |
| T1           | 1—unpaced         | 15       | 27.1         | 4.82                         | 43          | -2.02         |
|              | (2 + 3 + 4)—paced | 30       | 30.9         | 6.56                         |             | <sup>b</sup>  |

<sup>a</sup>  $P < 0.10$ .<sup>b</sup>  $P < 0.05$ .

**Table C.8** Mean and Standard Deviation of the Stress Scores for Each Pacing Level

| <i>Tasks</i> | <i>Groups</i> | <i>n</i> | <i>Average Stress Score</i> | <i>SD</i> |
|--------------|---------------|----------|-----------------------------|-----------|
| T1           | 1—unpaced     | 15       | 27.5                        | 5.66      |
|              | 2—paced (80%) | 10       | 29.5                        | 4.67      |
|              | 3—paced (86%) | 10       | 28.1                        | 4.56      |
|              | 4—paced (92%) | 10       | 34.7                        | 5.58      |
| T2           | 1—unpaced     | 15       | 27.1                        | 4.82      |
|              | 2—paced (80%) | 10       | 31.4                        | 5.89      |
|              | 3—paced (86%) | 10       | 27.2                        | 3.88      |
|              | 4—paced (92%) | 10       | 34.2                        | 7.84      |

results conform with the previous ones; they all point to the minimal pacing level as the most significant factor regarding impaired progress rates, and increased individual performance deviations and stress.

## APPENDIX

## D

### ANALYSIS OF THE RESULTS: HUMAN PACING

The human paced work studied here belongs to the subset of incentive paced tasks. Here, the pacing intensity is guided by the earnings objectives of the operators above and beyond the unpaced work (Turban 1968, Gershoni 1971, Salvendy 1981, Locke and Latham 1984). We report first the results of experimenting with a gradient incentive scheme followed by a combination

**Table D.1** The Performance Ratio Improvement Using a Gradient Incentive Scheme

| <i>Tasks</i> | <i>Group</i> | <i>n</i> | <i>Mean Group Ratio</i> | <i>SD</i> | <i>d.f.</i> | <i>t-test</i>     |
|--------------|--------------|----------|-------------------------|-----------|-------------|-------------------|
| T1           | 1—unpaced    | 15       | 0.83                    | 0.051     | 23          | 2.56 <sup>a</sup> |
|              | 5—incentive  | 10       | 0.76                    | 0.090     |             |                   |
| T2           | 1—unpaced    | 15       | 0.79                    | 0.075     | 23          | -0.66             |
|              | 5—incentive  | 10       | 0.82                    | 0.110     |             |                   |

<sup>a</sup> P < 0.05.

**Table D.2** The Performance Ratio Improvement Using Training and Gradient Incentive Scheme

| Tasks | Group                    | n  | Mean Group Ratio | SD    | d.f. | t-test            |
|-------|--------------------------|----|------------------|-------|------|-------------------|
| T1    | 1—unpaced                | 15 | 0.83             | 0.051 | 23   | 6.00 <sup>a</sup> |
|       | 6—training and incentive | 10 | 0.70             | 0.052 |      |                   |
| T2    | 1—unpaced                | 15 | 0.79             | 0.075 | 23   | 2.93 <sup>a</sup> |
|       | 6—training and incentive | 10 | 0.71             | 0.059 |      |                   |

<sup>a</sup> P < 0.01.

of on-the-job training in methods improvements confounded with gradient incentives.

The performance measure used here to estimate the relative progress made by the subjects is the time ratio between the last 20 and the first 20 repetitions as discussed above (B.1). The results of applying the *gradient incentive method* are given in Table D.1. The performance improvement observed is significant only for task T1. As denoted in Table D.2 the application of *training* with a *gradient incentive method* leads to significant performance improvements in both task sets. These correspond to improvements of about 18% and 11% in the production time required to complete the last 20 items of T1 and T2, respectively.

A significant increase of the stress level is observed only for task T2 ( $P < 0.05$ ), when the gradient incentive scheme was introduced. Moreover, no significant increase of the stress level for both tasks in group 6, (using training along with the gradient incentive) was observed.

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