

**THE EFFECTS OF MULTITASKING ON QUALITY INSPECTION IN  
ADVANCED MANUFACTURING SYSTEMS**

by

José A. Pesante-Santana

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Approved:

---

Robert C. Williges, Ph.D.  
Chairperson

---

C. Patrick Koelling, Ph.D.

---

Pedro Resto, Ph.D.

---

Walter W. Wierwille, Ph.D.

---

Jeffrey C. Woldstad, Ph.D

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# THE EFFECTS OF MULTITASKING ON QUALITY INSPECTION IN ADVANCED MANUFACTURING SYSTEMS

José A. Pesante-Santana

## (ABSTRACT)

Technological and strategic developments have changed the role of human operators in the manufacturing environment. The highly specialized work force of the low-tech manufacturing system has evolved into the multi-functional work force of the high-tech manufacturing system. Among the multiple tasks that an operator is expected to conduct in advanced manufacturing systems (AMS) are job scheduling, inventory planning, machine set-up, problem solving, and quality inspection.

The quality inspection task in AMS consists of a search component, frequently conducted by a machine, and a decision making component conducted by the operator. This quality inspection system is often referred to as a hybrid inspection system (HIS). It has been demonstrated that in general the performance of HIS is better than that of pure human or pure automated inspection systems. This research investigated the effects of different types of defects (presented at the same time in the inspected parts), multitasking (concurrently conducting independent tasks), and their interaction on the operator's performance in the quality inspection task (with a memorized quality criteria) in an AMS.

The results indicate that the performance of the operator in the quality inspection task while multitasking in an AMS will be determined not only by the variety of defects that can be present in the inspected parts, but also by the mental processing resources required to meet the demand imposed by the multiple independent tasks and the memorized quality criteria. The best performance will be obtained when the additional tasks' load minimizes the monotony of the quality inspection task without interfering with the processing resources needed for the memorized quality criteria.

Dedicated to the memory of my father, José Pesante

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## **Chapter 1. INTRODUCTION**

### Rationale

The development of numerically controlled machines, group technology, cellular manufacturing, and just-in-time production systems have changed the role of human operators in the manufacturing environment. The highly specialized work force of the low-tech manufacturing system has evolved into the multi-skilled work force of the high-tech manufacturing system. Throughout the manufacturing evolution, from the mass production era to the present advanced manufacturing systems (AMS), human sensory detection capabilities have been a vital but often ignored component of the quality inspection task.

Mass production was the prevailing manufacturing system of the first half of the twentieth century. Some of the manufacturing concepts that shaped the mass production era were: Babbage's division of labor, Taylor's scientific management, the Gilbreths' motion studies, and Ford's specialization of labor (Konz, 1995; Niebel, 1993; Turner, Mize, Case, and Nazemetz, 1993). During World War II, the demand for war materiel pushed mass production to its peak, causing a significant expansion for many industries. Such growth resulted in increasing employment of unskilled personnel (Banks, 1989). Quality control inspection became a very important and specialized task. Statistically based acceptance sampling and 100% inspection were the main quality control tools used to detect and reject unacceptable products. Even though the quality inspector's performance was significantly less than 100%, more emphasis was placed on meeting the large production demands than on understanding or improving the performance of the inspectors.

By the mid-1960's, competition for consumer goods had increased, and consumer interest in more variety and availability of products had started to drive the market (Talavage and Hannam, 1992). Batch manufacturing became the answer to a consumer-driven market. High volume production of the same product was replaced by shorter

production runs of products with different designs and a shorter life cycle. With this variety of products manufactured in batches, the different types of defects that the inspector was expected to detect increased significantly. As a result, the difficulty of the quality inspection task also increased. Once again the sensory limitations of human inspectors were in most cases overlooked. Instead, more interest was placed on developing production scheduling and inventory strategies to protect the manufacturer from demand fluctuations and quality problems.

During the 1970's, many Japanese companies adopted the just-in-time (JIT) production system developed by the Toyota Motor Corporation. Highly influenced by the loss of market share, some of the major North American companies adopted JIT by the early 1980's (Schonberger, 1986). The main objective of JIT is to increase productivity and reduce cost by completely eliminating waste; this is done by producing just what is needed, in the needed quantity, when needed (Monden, 1993). A key concept of the JIT production system is a flexible work force. In order to avoid excess work force, operators must be trained to be skilled in multiple jobs of various processes (Monden, 1993). This caused a significant shift in the quality inspection task responsibilities. The specialized quality inspector was replaced by an operator who, in addition to the inspection task, concurrently conducted other tasks such as job scheduling, inventory planning, dissimilar machines setup, and problem solving.

Various production systems have been developed and implemented since the introduction of JIT. Although most of them modify JIT to some extent, their cornerstones remain the same as for JIT: quantity control and quality assurance. Numerically controlled machines, group technology, and cellular manufacturing have become instrumental elements of quantity control, while quality assurance has been relying mostly on the performance of a flexible work force performing multitasking. A significant number of these current production strategies take place in manufacturing environments referred to as advanced manufacturing systems (AMS). These systems are characterized by a high degree of human-computer interaction during practically every aspect of manufacturing. Most of the on-line tasks (such as machine setup, problem solving, and

quality inspection), as well as the off-line tasks (such as job scheduling and inventory control), are conducted using video display terminals (VDTs). This has minimized the operator's physical contact with both the process machine and the unit being produced.

In the present highly competitive world class manufacturing (WCM) scenario, where manufacturers in almost every industry sector find themselves competing with companies from every part of the world, quality is a key element for survival and success. A better understanding of the operator's performance in a quality inspection task while multitasking in AMS is essential for the continuous improvement of the manufacturing industry.

## Review of the Literature

### Advanced Manufacturing Systems

Advanced manufacturing systems (AMS) is a generally accepted term for production systems that are based on advanced manufacturing technology (AMT). The main AMT components are: computer aided design (CAD), computer aided engineering (CAE), computer assisted manufacturing (CAM), computer integrated manufacturing (CIM), and flexible manufacturing systems (FMS) (Karwowski and Salvendy, 1991). Some of the AMT contributions to manufacturing systems are: 1) high flexibility in product design, mix, and fabrication, 2) rapid response to changes in market demand, 3) greater control, accuracy, and repeatability of processes, and 4) faster throughput. In addition to AMT, a wide range of production strategies are used in AMS: product-based cell manufacturing, group technology, JIT, total quality control (TQC), and optimized production technology (OPT), among others (Mize, 1988; Wilson, 1991). A list of AMS technologies and strategies organized by major company function is presented in Table 1 (Mize, 1988).

Table 1. Advanced manufacturing concepts and technologies by company function  
(Mize, 1988).

<b>Company Function</b>	<b>Applicable Advanced Concepts and Technologies</b>
Strategic business planning	Flexible manufacturing strategies/automation/design for differentiation/rapid order completion/high manufacturing velocity strategies
Sales and quotations	Interactive, integrated databases/data communication links to field and customer locations
Product design	CAD/CAE analysis/simulation and animation/design for manufacturability, for automated handling and assembly, and cost targets/group technology, design retrieval/engineering change control
Process design	CAD equipment and process design/simulation models/cellular and flexible machining systems
Capacity analysis and facility design	Facility layout analysis algorithms/simulation models/family of parts analysis/computer-aided facilities planning
Process planning and tool design	Computer-aided process planning/group technology/classification and coding/time standards database
Production planning and scheduling	Master production scheduling/production smoothing/MRP/MRP II/OPT/JIT/Kanban/scheduling algorithms/simulation/plant-wide monitoring systems
Purchasing and vendor management	Automated purchasing/electronic links to vendors/automated follow-up
Order entry and order processing	Demand management/forecasting/integrated databases/on-line, real-time order tracking
Shop floor management	Dispatching, handling controls/automated identification systems, bar coding, etc./automated input of performance data as order progresses through shop/data integrity audit procedures, cycle counting, etc./preventive maintenance scheduling/advanced concepts in performance measurement
Fabrication	NC/CNC/DNC/programmable controllers/automated processes/automated tool changing/machine and tool monitoring/robotics/quick change setups
Assembly	Automated assembly/robotics assembly/automated testing by assembly stages
Inspection and testing, quality assurance	Computer-aided inspection and testing/machine monitoring and diagnostic systems/statistical process control/machine vision/adaptive control/inspection "on the fly"
Material handling and storage	Automated storage and retrieval systems/automated guided vehicles/automated conveyors/robotic handling/part transfer systems, hard automation
Data processing and factory communications	MAP/TOP, other communication protocol standards/factory networks/postprocessors and preprocessors/paperless control and reporting/electronic process plans, instructions to operators/integrated databases

The AMT and production strategies configuration used in AMS varies among manufacturing organizations. However, JIT and TQC are the production strategies most recommended for AMS, to make production processes more visible and to enable the elimination of waste, the cutting of required lead times, and the optimization of manufacturing activities (Zairi, 1992; Pinochet, Matsubara, and Nagamachi, 1996). This integration of AMT and JIT/TQC strategies represented a major conflict with the original organizational assumptions of AMS (Berniker, 1990). When AMS was originally conceived, its goal was to improve productivity by creating a fully automated factory, often referred to as the factory of the future, where the operator's role on the manufacturing shop floor would be minimized or eliminated. This contrasts with JIT, which is highly dependent on a flexible work force's mental capacity and problem solving abilities to increase productivity. After several alarming failures in the implementation and operation of the technocentric "factory of the future," the manufacturing leaders realized that the key to success in WCM is the effective integration of people, organization, and technology (Brödner, 1991; Wilson, 1991; Wobbe, 1992; Bessant, Levy, Ley, Smith, and Tranfield, 1992). Furthermore, Wilson (1992) stated that "Implicit in WCM developments involving AMT and JIT and similar principles of manufacturing organization, must be a human-centered rather than a technocentric approach."

Technocentric AMS. The technocentric AMS was supposed to herald the coming of the "factory of the future." Davies (1986) described the "factory of the future" as an almost workerless, paperless, and fully automated production facility that was going to alter manufacturing "at least as dramatically as large-scale industrialization changed earlier guild forms of industrial organization." It has been suggested that for the technocentric AMS to succeed, there should be a full integration of engineering, design, production scheduling and control, quality control, and manufacturing systems in a single computerized network (Berniker, 1990; Davies, 1986; Davidow and Malone, 1992).

By the mid-1980's there was a growing realization of the unfulfilled promise of the technocentric AMS (Bessant, et al., 1992; Mize, 1988; Unterweger, 1988). Some of the most publicized cases of failure have been in the automotive industry. Under the heading of "Tricky Technology: American Car Makers Discover 'Factory of the Future' Is Headache Just Now," the Wall Street Journal (1986) reported that all U.S. automakers were having significant difficulties with their factory modernization programs. Business Week (1987) reported that after investing \$60 billion in vast amounts of AMT, General Motors was unable to achieve the anticipated results. Some of the factors identified as the most significant barriers to the successful implementation of the technocentric AMS according to Mize (1988) are: 1) unanticipated difficulties in transferring technology from the isolated pilot projects to the manufacturing real world, 2) underestimation of the magnitude of the task resulting in an organization's inability to absorb the vast amount of change in a short period of time, 3) the misunderstanding of the critical role played by humans as operating systems integrators, 4) inadequate internal technical skills leading to excessive dependency on external consultants and vendors, and 5) unrealistic expectations of stand alone automation. The major weakness of the technocentric AMS was best described by Unterweger (1988), when he stated that "the attempt to eliminate the gaps or deficiencies in machine designs by means other than skilled human operators leads to a vicious circle that can only add cost and complexity to a system that is already overly complex."

**Human-Centered AMS.** The objective of human-centered AMS is to employ the best technological and organizational qualities of AMT and of people, with complete integrated roles and functions. Wilson (1991) indicated that in this AMS the actual manufacturing processes will be computer controlled, but setup, programming, monitoring, intervention, maintenance, diagnosis, rectification, innovation, and optimization will be the responsibility of operating and supervisory staff. For these tasks the operating and supervisory staff will have any recourse from the information and technical systems to aid their decision. In essence, this manufacturing system stresses a

re-skilling rather than a de-skilling perspective, emphasizes operator local control, follows the human factors principles of good job design, and encourages social communication and interaction (Corbett, 1987).

Wilson (1991) indicated that operator local control is related to the job characteristic of autonomy, seen at the core of individual and group work design changes as well as of job design models and theories. Bainbridge (1982) expressed the opinion that “the more advanced a control system is, so the more crucial may be the contribution of the human operator.” The degree of control and breadth of influence exerted by operators will be determined by the skill-, rule-, or knowledge-based behaviors that the task interface will support (Rasmussen, 1986). Rasmussen (1983) described his skill/rule/knowledge-based classifications as follows: 1) skill-based behavior represents psychomotor behavior without conscious control, consisting of automated routines that are driven by information received from the environment, 2) rule-based behavior represents consciously controlled, goal-oriented behavior guided by sets of rules or stored patterns that have been empirically derived during previous occasions or communicated as instructions from an external source, and 3) knowledge-based behavior represents goal-controlled, problem solving performance in unfamiliar situations, requiring a functional understanding of the system, analysis of the current state, and response of the environment based on conscious, advanced reasoning while utilizing feedback control for error correction. According to Schott and Wilkinson (1989), the process of developing control down to the operator level requires that AMS designers be able to allocate functions optimally.

From a human-centered AMS perspective it is widely recognized that people, just like machines, have limitations and weaknesses. Still, they have to be involved in the operation and management of AMS. Some of the reasons for this inclusion are: 1) AMT limitations in receiving information and decision making, 2) AMT have the potential to diagnose the origin of failures, but have difficulties in repairing the system that failed, 3) human complex knowledge-based skills for problem solving in novel situations, and 4) human flexibility and adaptability (Salvendy, 1992; Pinochet, et al., 1996). According

to Mize (1988) and Wilson (1991), the success of the human-centered AMS will be significantly dependent on the effective integration of people, organization, and technology. A human factors knowledge base is vital for this integration (Karwowski, Salvendy, Badham, Brodner, Clegg, Hwang, Iwasawa, Kidd, Kobayashi, Koubek, LaMarsh, Nagamachi, Naniwada, Salzman, Seppala, Schallock, Sheridan, and Warschat, 1994). Critical human factors issues particularly pertinent to AMS are presented in Figure 1 (Wilson, 1991).



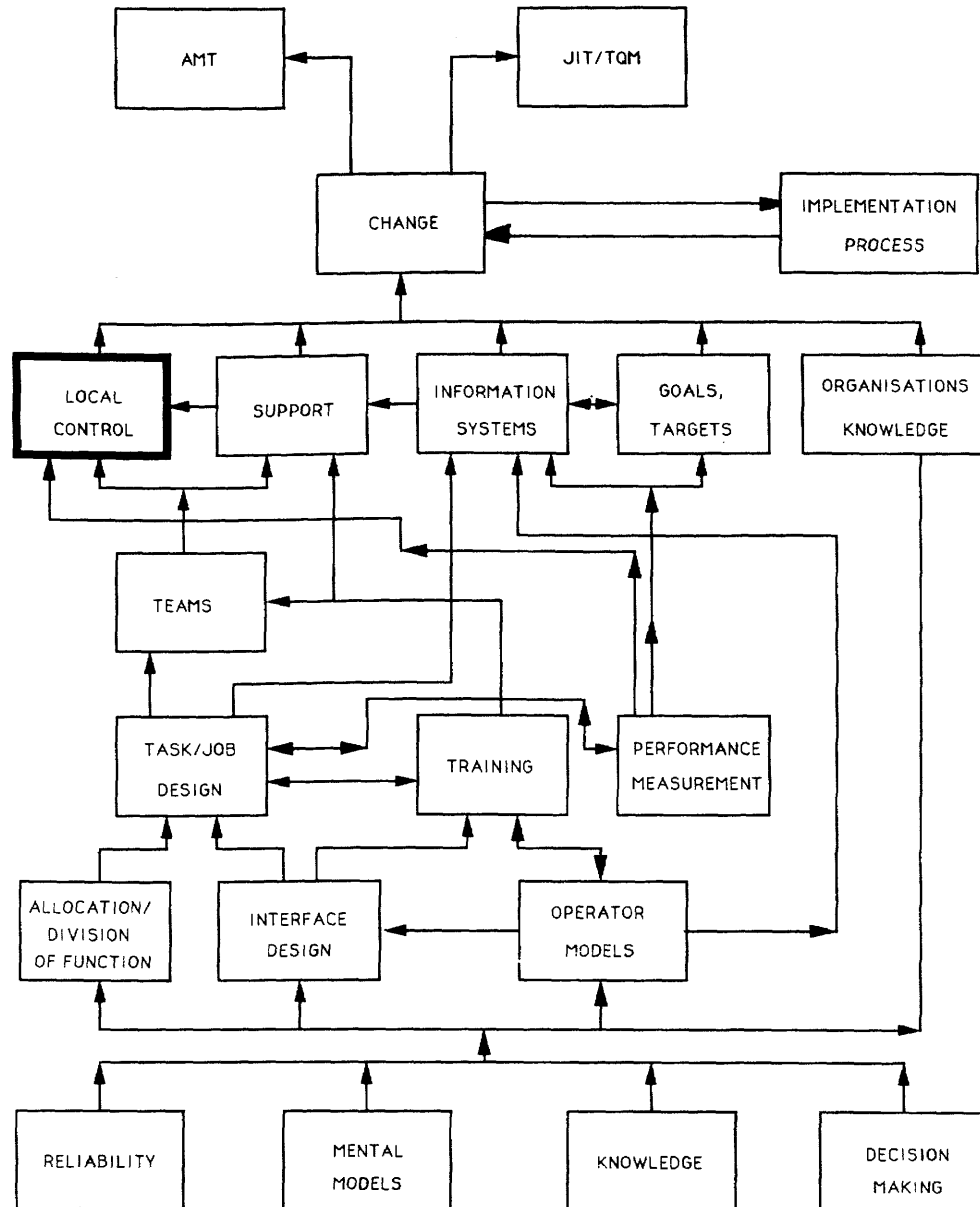


Figure 1. Framework of human factors issues in AMS (Wilson, 1991).

## The Quality Inspection Task

Quality has been defined as fitness for use, or the extent to which a product meets the consumer requirements (Juran and Gryna, 1980). Inspection is the act of measuring or examining carefully the quality of a product. Sensory inspections (performed by means of the human senses to assess a product's qualitative characteristics) and physical inspections (performed by means of measuring devices to assess a product's quantitative characteristics) are the main types of quality inspections. It has been widely accepted that the quality inspection task performed by humans is prone to error (Bennet, 1975; Konz, Peterson, and Joshi, 1981; Schilling, 1982). In fact, Juran (1974) indicated that human inspectors typically find about 80% of the defects. This recognized level of inspection error has been mostly attributed to the sensory aspects of the inspection. Shingo (1985) indicated that it tends to be difficult to set criteria for sensory inspection because different people will make different judgments and even the same person might make different judgments on different days. Efforts to automate the quality inspection task have not been as successful with sensory inspections as with various physical inspections (Drury, 1992b).

During the last four decades a substantial amount of human factors research has been conducted on the visual quality inspection task. The human operator's performance on the visual quality inspection task has been extensively studied from the signal detection theory (SDT) standpoint. In addition, the machine and human-plus-machine system's performance on the visual quality inspection task has been studied and compared to the human operator's performance. Despite the contributions of research to the understanding of human performance in the quality inspection task, the manufacturing trend has been to design quality schemes that compensate for poor inspector performance instead of trying to improve it (Drury, 1992).

## Visual Quality Inspection Taxonomy

The visual quality inspection task has been described as consisting of the following subtasks (Wang and Drury, 1989): 1) orient the item, 2) search the item, 3) detect any defect, 4) recognize/classify the defect, 5) decide the status of the item, 6) dispatch the item, and 7) record the information about the item. Table 2 shows the human skills required should all the subtasks be assigned to human operators (Wang and Drury, 1989). Drury (1992) indicated that these subtasks can be combined into two main components: search and decision making. Thus, the simplest description of the visual quality inspection task is to search, recognize a defect, and make a decision on the part's acceptability within the quality limits.

Table 2. Human skills required for the quality inspection task (Wang and Drury, 1989).

Subtask	Task Description	Major Type or Skill	Mental Attributes Required
1	Orient the item	Manual	—
2	Search the item	Perceptual	Attention, perception, memory
3	Detect a flaw	Perceptual	Detection, recognition, memory
4	Recognize/ classify	Perceptual	Recognition, classification, memory
5	Decide status of item	Perceptual	Judgment, classification, memory
6	Dispatch item	Manual	—
7	Record of in- formation about item	Manual and percep- tual	Memory

Visual search component of the quality inspection task. Visual search is a sequential process that proceeds as a series of fixations linked by eye movements and which terminates upon successful detection of a defect or the complete inspection of the unit (Drury and Prabhu, 1994). It has been indicated that almost all of the information in a visual search is obtained during the fixations which account for more than 90% of the search time (Morawski, Drury, and Karwan, 1980). In the inspector's field of view, a defect is only visible within a limited area referred to as the visual lobe. During a fixation the visual lobe is located around the central fixation point. According to Drury (1992),

the visual lobe size will be affected by the luminance of the object inspected, the contrast between the object and the defect on the object, the defect size, and the distance of the defect from the inspector's eyes. Figure 2 shows a flow diagram for visual search (Howarth and Bloomfields, 1971).

Megaw and Richardson (1979) conducted eye movement studies of inspectors and concluded that inspectors do not follow a simple pattern in searching an object. They observed that while a very random appearing search pattern was used for the inspection of complex units (e.g., circuit boards), a more systematic search pattern was used for the inspection of simpler ones (e.g., knitwear). Bloomfield (1975) suggested that the most efficient strategy will occur when: 1) the distance that the eyes move from one fixation to the next is short enough that no point on the unit is missed, and 2) the distance between fixation points is large enough to minimize the overlap between the areas in which the defect could be seen. However, Bloomfield acknowledged that when the search is for more than one type of defect, with different levels of discriminability, the most efficient strategy for one type of defect might not necessarily be efficient for the other type of defect.

Drury (1992) indicated that in addition to the lobe size and the search strategy, the time available for the inspection will affect human performance in the visual search component of the inspection. The more time the inspector has to search, the better the chances are of finding the defect. Nevertheless, Schoonard, Gould, and Miller (1973) found that the best inspectors for the visual search subtask were those who detected the defect in the fewest fixations, not those with more rapid fixations. Three factors that led to a thorough investigation of search automation were: 1) the significant time consumption of the visual search, 2) the need for the selection and implementation of an optimal search strategy, and 3) the quality at the source and 100% inspection strategies strongly recommended for AMS (Drury and Prabhu, 1994; Shingo, 1985).

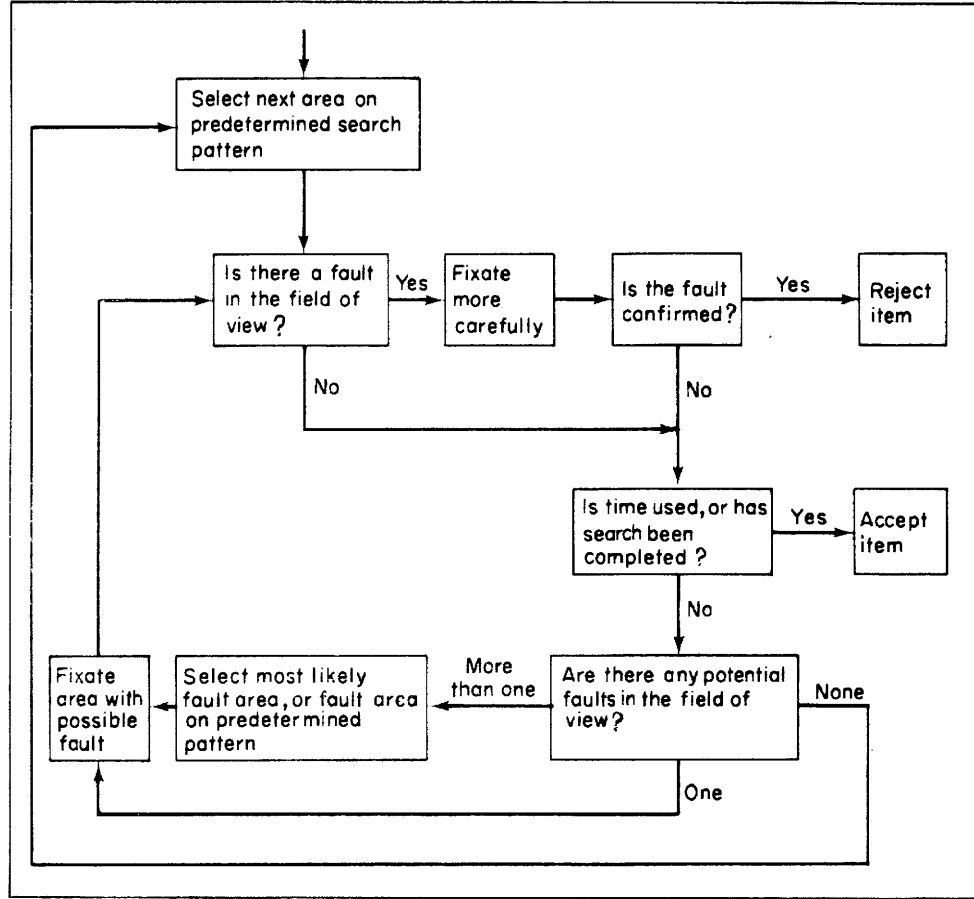


Figure 2. Flow diagram for visual search (Howarth and Bloomfield, 1971).

Decision making component of the quality inspection task. Given its strict relevance to decision making, signal detection theory (SDT) has been used to explain the decision making component of the quality control inspection task (Wallack and Adams, 1969; Drury and Fox, 1975). In the fundamental signal detection problem, as defined by Swets, Tanner and Birdsall (1964), an observation is made of events occurring in a fixed interval of time, and a decision is made whether the interval contained only the always present noise (N) or the signal plus noise (SN). As opposed to classic methods of psychophysics, SDT provides both an independent quantitative measure of the criterion ( $\beta$ ) that the observer uses in making a perceptual judgment, and a relatively pure measure

of sensitivity ( $d'$ ). The major assumptions of SDT are: 1) the observations (sensory data) on which the decision is based may arise from either conforming or nonconforming items, 2) the observations may be represented as varying continuously along a single dimension forming two probability density functions (N and SN), and 3) both probability density functions can be described by two normal distribution with equal variances. The criterion ( $\beta$ ) or policy to determine whether the observation results from the N or the SN distribution is established by a cutoff value  $X_c$  on the continuum of observations.

In a quality inspection context, as described by Drury and Fox (1975), SDT proposes that the human, functioning as a defect detection device, builds up in the neural system two distributions of activity: one relating to the probability of accepting an unit, the other to the probability of rejecting it. The degree of separation of these two distributions' means is a measure of the inspector's discriminability of the defects ( $d'$ ). The criterion level ( $\beta$ ), which is the ratio of the two ordinates of the curves at a given level  $X_c$ , delineates the boundary between accepting and rejecting a unit, and in doing so takes in some good units to be rejected and some faulty units to be accepted. Inspectors make a correct decision either by accepting a good unit (correct rejection) or by rejecting an unacceptable unit (hit). They fail either by not detecting a rejectable defect (miss) or by falsely reporting the presence of a rejectable defect (false alarm). A theoretical SDT distribution is shown in Figure 3 (Wickens, 1992).

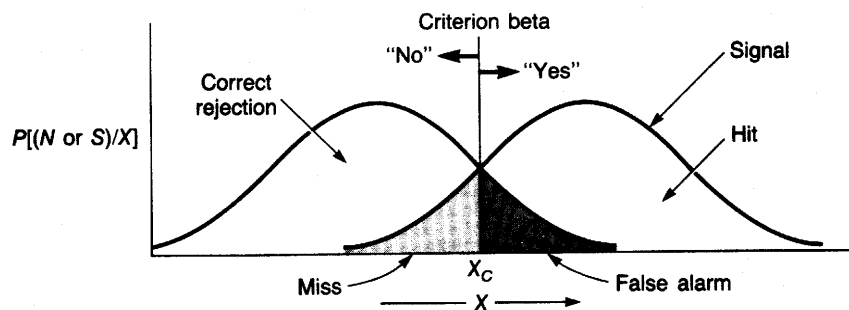


Figure 3. Theoretical SDT distribution (Wickens, 1992).

Both decision making performance measures ( $d'$  and  $\beta$ ) are derived from the hit rate and the false alarm rate. Drury (1992) indicated that the pure decision making component of the quality inspection task can be measured by concentrating on tasks that require no search. The general conclusion of quality inspection studies reviewed by Drury and Fox (1975b) is that “the decision making component is among those rare tasks where a human being behaves like a rational economic decision maker, balancing the costs and payoffs involved to arrive at an optimum performance.” As a normative model, SDT defines the optimal criterion ( $\beta_{opt}$ ) used by the ideal observer to optimize economic gains (Green and Swets, 1966). Based upon the values of a hit and a correct rejection, and the costs of a miss and a false alarm, the  $\beta_{obs}$  of a rational observer can be calculated and compared to that of the theoretical ideal observer ( $\beta_{opt}$ ). Gescheider (1985) reported that after comparing  $\beta_{obs}$  with  $\beta_{opt}$ , it has been generally found that rational observers do fairly well at optimizing their winnings. However, they tend not to set extremely low or high criterion, even in situations where these strategies would lead to optimal performance.

### SDT Studies on Visual Quality Inspection

Signal Detection Theory (SDT) was first used to model the decision making performance of the quality inspection task by Wallack and Adams in 1969 (Thapa, Gramopadhye, and Melloy, 1996). After using SDT to study the performance of industrial electronics inspectors in a visual, subject-paced task, they concluded that SDT performance measures ( $d'$  and  $\beta$ ) were more useful than the other available measures. Wallack and Adams (1969) concluded that SDT is useful because, in addition to relating performance to payoff, it also indicates the magnitude and the direction of improvement required. Although not all of the research using SDT to study the decision making performance has been conducted in an industrial inspection context, its findings have been beneficial in understanding human quality inspector performance.

More recently another measure of criterion level or decision making response bias called the index  $c$  has been developed (Macmillan and Creelman, 1991). The main

difference between  $\beta$  and the index  $c$  is in the way these bias indices locate the criterion ( $X_c$ ). The likelihood ratio measure,  $\beta$ , locates  $X_c$  by the ratio of the heights of the SDT distributions ( $N$  and  $SN$ ), while the index  $c$  locates  $X_c$  by its distance from the intersection of the two distributions. The range of  $c$  is therefore the same as that of  $d'$ , although zero is at the center rather than an endpoint. This parametric index is considered to be more effective than  $\beta$  over a full range of sensitivity in recognition memory experiments and in vigilance (Snodgrass and Corwin, 1988; See, Warm, Dember, and Howe, 1997). Unlike the index  $c$ ,  $\beta$  has a tendency to produce extremely high values for conservative observers resulting in a scale that does not produce equal intervals. See et al. (1997) conducted three experiments involving factors that affect response bias (signal probability, payoff matrix, and signal salience) in order to calculate and compare  $\beta$  and  $c$ . All three experiments employed a 40 minute task without performance feedback in which the subjects were required to detect increments of 3 mm in the height of a single 32 x 4 mm white line. The white line flashed on and off at a rate of 20 events/minute in the center of a computer screen. The researchers found that the index  $c$  was generally more sensitive than  $\beta$  to the nonperceptual manipulations of signal probability, payoff, and probability shifts. Also, they reported that  $\beta$  was less effective than  $c$  at differentiating variations in response bias tendencies when sensitivity approached chance. The computational formulas for  $d'$ ,  $\beta$ , and the index  $c$  are presented in Appendix I.

In most if not all of the research using SDT, the quality inspection task has been characterized as a vigilance situation in which the inspector's sole task is to examine a stream of products to detect and remove the defective ones. This characterization is no longer consistent with the reality of the operator's responsibilities in AMS. The quality inspection task in AMS is no longer a specialized task; instead, it is one of multiple dissimilar tasks conducted by a highly skilled operator. However, many of these studies make a significant contribution to our understanding of human decision making performance in the visual quality inspection task. By the late 1960's SDT had become the preferred tool for the analysis and description of the inspector's decision making performance (Drury and Fox, 1975). Some of the assumptions underlying SDT, in



particular the normal distributions with equal variance assumption, are not always true in every inspection situation. Swets (1977) indicated that this assumption is only necessary for the calculation of  $d'$ . From a theoretical perspective Green and Swets (1966) identified the Central Limit Theorem as the reason for the normal distribution assumption. From a practical and empirical perspective the reason for SDT assumptions is that when checks are made on the results of SDT studies on quality inspection, they seem to be in basic agreement with predictions from the theory (Chapman and Sinclair, 1975; Drury and Fox, 1975).

Decision making performance changes over time. Based on the review of twelve studies conducted between 1969 and 1975, Swets (1977) indicated that all twelve experiments showed an increasingly strict criterion ( $\beta$ ) over time when the signal-to-noise ratio was low; eight of the experiments showed a constant sensitivity ( $d'$ ) over time. In the four studies in which  $d'$  did not remain constant it was found to decrease by 20%. An increase in  $\beta$  (conservative criterion) represents a decrease in signals detected as well as a decrease in false alarm errors. As Williges (1969) indicated, a performance change over time is characterized by a shift in the subject's response criterion ( $\beta$ ).

Williges (1969) conducted a study in which the subjects were required to detect a signal (the longer of two fixed-duration changes from a standard brightness) during a 60 minute monitoring session. A distraction element was introduced by asking the subject to time share a secondary task (four numerical processing operations) with the primary monitoring task. The events in both tasks were occurring at intervals of 10 seconds. Two signal-to-noise ratios (1/5 and 5/1), a correct and an incorrect set of instructions (expected number of signals in the sample), and the distraction vs. no distraction element were combined factorially to measure the hit and false alarm rates. The ANOVA conducted for the performance measures ( $d'$  and  $\beta$ ) showed the following results: 1)  $d'$  remained constant over time and 2)  $\beta$  increased over time when the signal-to-noise ratio was low. The same results were obtained by Colquhoun and Edwards (1970). They conducted a

study in which the subjects were required to indicate which one of six disks, if any, was larger than the others. They found  $d'$  to be constant and  $\beta$  to increase over time. On the other hand, Guralnick's (1972) results differed from those obtained by Williges (1969). He conducted an experiment in which the signal was the longer of a pair of vertical lines, and the events were presented at a rate of eight per minute. Although his results showed a  $\beta$  increase over time,  $d'$  was found to decrease by 20%.

Determinants of decision making performance. A study of on-line quality inspection for mass-produced jam tarts was conducted in the baking industry by Chapman and Sinclair (1975). They tested the hypothesis that speed of movement of the tarts on the conveyor and the presentation time of the tarts had no effect upon the performance of the inspectors. The two levels of the tarts movement factor (moving and stationary) and the three levels of the presentation time (22.5 sec., 15 sec., and 7.5 sec.) were combined factorially to measure the hit and false alarm rates. The ANOVA conducted for the performance measures ( $d'$  and  $\beta$ ) showed the following results: 1)  $d'$  decreased as the presentation time was reduced, and 2)  $\beta$  increased as the presentation time was reduced. The authors acknowledged that since slowing down the production line was not an option the only possible solution was to double the number of inspectors. The outcome of this research suggested the need for conducting the assessment of quality inspection agents' capabilities early during the design stage of the particular manufacturing system in order to avoid solutions incompatible with world class AMS.

Smith and Barany (1970) conducted an experiment in which the varied inspection task variables were task pace, percentage of defective, and payoff matrices (consequences of the decision made). The experimental task was the on-line inspection of aluminum disks (1 inch in diameter) containing four equally spaced holes (1/16 inch in diameter). The subjects inspected the product units and indicated a defective (three holes instead of four) by pressing a micro switch. It was found that  $d'$  decreased as the task pace increased and remained invariant with respect to the other two independent variables.

The decision criterion ( $\beta$ ) utilized by the inspectors increased (became more stringent) as the percentage of defective increased and remained invariant with respect to the other two independent variables. The researchers attributed the unexpected result (conservative  $\beta$  when signal probability was high) to the failure of the inspectors to adopt the payoff system as instructed.

Williges (1971) conducted a study in which the subjects were required to detect a signal (the longer of two fixed-duration changes from a standard brightness) during a 60 minute monitoring session. The events were presented on a 6 second time base. Two signal-to-noise ratios (1/9 and 1/1) and three payoffs (lax, neutral, and strict) were the varied inspection task variables. Based on the results of the study he concluded that the signal probability rather than payoffs seem to play the major role in determining inspection performance. When the signal probability is high the observers maintain a “lax” response criterion, but, when the probability is low the observers adopt a “conservative” one.

The effect of knowledge of results (KR) on decision making performance is beneficial but complex. Craig and Colquhoun (1975), referencing the work of Mackworth (1964, 1965), indicated that the performance increase caused by false KR suggests that at least some part of the effect of providing true KR may be due to an initial increase in arousal or alertness. Williges and North (1972) conducted a  $2^3$  factorial experiment in which the presence or absence of correct detection KR, false alarm KR, and cumulative total event KR were randomly assigned to subjects. The experimental task was the same one used in Williges’ previous SDT studies (1969, 1971). They concluded that: 1) the specificity of KR influences  $d'$  more than  $\beta$ , 2) positive KR on the correctness of a detection response is used by the observer to increase their  $d'$ , 3) observers use signal-to-noise ratio KR to manipulate their  $\beta$ , 4) false alarm KR results in fewer detections overall when cumulative total events KR are provided, and 5) subjects appear to use the cumulative total events KR to guide their frequency of responding. The results of a study on the effect of information on industrial inspection performance conducted by Zunzanyika and Drury (1975) are consistent with some of Williges and

North (1972) findings. In their experiment, the independent variables were the percentage of defective (10%, 20%, and 30%) and the method of transmitting information about the batch quality (feedback, feedforward, and both). Based on the analysis of the results, the authors stated that the percentage of defective KR had a significant effect on  $d'$  and a more obvious effect on  $\beta$ .

Various researchers argue that the traditional laboratory findings about vigilance task performance are not particularly relevant to real operational problems, partly because real world tasks are of a more complex nature than the simple tasks which have been used in the laboratory studies (Alluisi, Coates, and Morgan, 1977; Craig and Colquhoun, 1977; Craig, 1979). As an example of a complex vigilance task they mentioned the industrial quality inspection that frequently requires the operator to look for the occurrence of several kinds of signals. Craig and Colquhoun (1977) conducted an experiment in which two different type of defects (with equal probability of 10% each) were presented to the subjects. Each defect consisted of a circle with a single radial spoke. One of the defects needed to be rejected whenever a change in the angle of the radial spoke was observed. The second defect needed to be rejected whenever a change in diameter was observed. The defects were presented on a television monitor. A control group only inspected one type of defects, while a second group inspected both types simultaneously. Based on the results of this experiment the researchers concluded that the effect of what they called complex inspection (inspection of both defects simultaneously) on the overall level of detections was not significant. Craig (1979) conducted the same type of experiment, but used unequal probabilities (5% and 15%) for the two types of defects, and reached the same conclusion. He indicated that these research findings (Craig and Colquhoun, 1977; Craig, 1979) do not invalidate the traditional laboratory findings about vigilance task performance, but rather suggest the value of further research on this issue.

### Quality Inspection Training

Training has been identified as essential to improving the decision making performance of human operators (Embrey, 1975; Wiener, 1975). Juran and Gryna (1980) indicated that chronic deficiency in knowledge (e.g., education or training) is a cause of errors consistently made by inspectors. Czaja and Drury (1981) claimed that despite the existence of a profound knowledge base on training, it is a neglected area for improvement in industrial inspection performance. They indicated that KR is fundamental to learning. Thapa, Gramopadhye, and Melloy (1996) mentioned that the results of the KR transmission strategies (feedback, feedforward, or both) used in training programs are consistent with the research findings of the effect of KR on decision making performance. Drury (1992) listed five techniques that have proven effective in training for inspection: 1) Cueing, 2) Feedback, 3) Active training, 4) Progressive parts, and 5) Develop schema. Table 3 summarizes various applications of industrial inspection training programs (Drury, 1992).

### Hybrid Inspection Systems

Zero-defect products and shorter lead-time production are vital for the survival and success of AMS in a highly competitive WCM. According to Drury and Sinclair (1983), “this can often be achieved only by 100% inspection, which is known to be unreliable when performed by humans.” This dilemma prompted an industry movement towards automated inspection systems. Various automated inspection systems are listed in Table 4 (Drury and Prabhu, 1994). The advent of these microprocessor-based automated inspection devices, at prices competitive with human inspection, called for a human factors reassessment of the human-machine function allocation possibilities in quality control (Drury and Sinclair, 1983). Gramopadhye, Drury, Sharit, and Sudit (1992) proposed a framework for function allocation in inspection (see Figure 4). They recommended accuracy, speed, flexibility, and reliability as the performance criterion for the inspection system.

Table 3. Applications of industrial inspection training programs (Drury, 1992)

Investigator(s)	Training Technique	Type of Task	Results
Tiffin and Rodgers	Knowledge of results and training sessions that included lectures and demonstrations	Inspection of tin plates	General improvements in inspection performance; greater detection of faults
Evans	30-min class instruction; 11 tests with knowledge of results over 2 weeks	Micrometer inspection of gauge blocks	50% reduction in average error, but no effect on retention
Martineck and Sadacca	Knowledge of results using an error key	Photointerpretation	Decrease in errors of commission
Chaney and Teel	Four, 1-hr sessions that included lectures, demonstrations, and knowledge of results from a question and answer period	Inspection of machine parts	Training resulted in a 32% increase in defects detected
Cockrell and Sadacca	Knowledge of results and group discussion	Photointerpretation	Significant improvement in inspection performance and a decrease in false alarms
Parker and Perry	Demonstrations, use of photographs simulating items and faults, examples of faulty items, practice with knowledge of results	Inspection of glass bowls	50% increase in faulty detection, 50% increase in false rejections
Duncan and Gray	Gradual approach to the task (diagnosis of faults then verification) using programmed instruction	Fault detection in a petroleum refinery process	Training resulted in an increase in faults detected, decrease in detection time, and decrease in false rejections
Houghton	Product knowledge, standards, search training, practice with knowledge of results, progressive part	Solder joint, inspection	Efficiency up from 33–67% to 89–97%
Kleiner	Progressive part, cueing, knowledge of results, active	Aircraft bearing inspection	Rest errors reduced to zero, 50% scrap reduction

One of the first efforts to reassess the human-machine function allocation possibilities in quality control was conducted by Drury and Sinclair (1983). They compared the performance of experienced inspectors and a prototype optical/microprocessor inspection device in an inspection task of small steel cylinders with four different possible defect types. The comparison was done in terms of both hit rate and false alarm rate. These SDT metrics were plotted one against the other to form a Receiver-Operating Characteristic (ROC) curve. Drury and Sinclair's (1983) main

findings were: 1) neither the human nor the automated systems achieved an outstanding performance and 2) the automated system was better at locating the defects (search) but could not classify them as acceptable or rejectable (decision making) as well as the human inspectors.

Table 4. Automated inspection systems (Drury and Prabhu, 1994).

INDUSTRY	TASK	PARAMETERS DETECTED DEFECTS	TECHNOLOGY	LIMITATIONS & CAPABILITIES
Micro-electronic IC Device Manufacturing (Bose & Kim, 1990)	Inspection of defects during the process of banding IC chips to its carrier	Missing chip, misregistration of chip, edge cracks, scratches, surface contamination, misorientation	Computer vision using CCD camera, dark and bright field illumination and vision algorithms	Scratches of width 20 $\mu$ or more. Automated system performed better than inspectors. False reject rate < 1 %.
Research Lab (Chi, et al., 1990)	Classification of defects in wafer images	Void, scratch, bridge, diffusion, crack, probemark, random (dust and dirt)	Computer vision and rule-based expert system	Relatively simple wafer images.
Continuous Strip Steel Production (Seitzler, 1990)	Inspection of surface defects on steel strips	Slivers, scratches, dents, bumps, scale, rust, stain, dirt, nicks, pits, etc.	APA512 Cardset implementing video rate geometric analysis	88-95% of defect types found at inspection rate of 40 feet per second.
Research Lab (Park & Mitchell, 1989)	On-line inspection of machine parts	Dimensions related to size, position and orientation of features	Sierra Scientific CCD high resolution camera, CAD based 3-D part recognition	Performance measure not stated.
Printed Wiring Board Manufacturing	Inspection of defects on inner layer patterns before lamination	Narrow tracks, poor spacing	Black line illumination and a CCD sensor, radial matching algorithm	Resolution of 5 $\mu$ m, inspects 490 X 540 mm area in 5 minutes.
Fabric Manufacturing (Takato, et al., 1988)	Inspection of defects in plain and patterned cloth	Oil stains, dye stains, white stains, holes, flaws	Industrial television cameras, image processing system, vision algorithm for defect detection	Stable detection of oil layer stains under third grade in grey scale, white stains, and dye flaws over 1 mm.
Paper Industry (Mueller, et al., 1989)	Inspection of defects at multiple production stages	Holes during initial forming	Laser scanning	High speed 100% inspection.

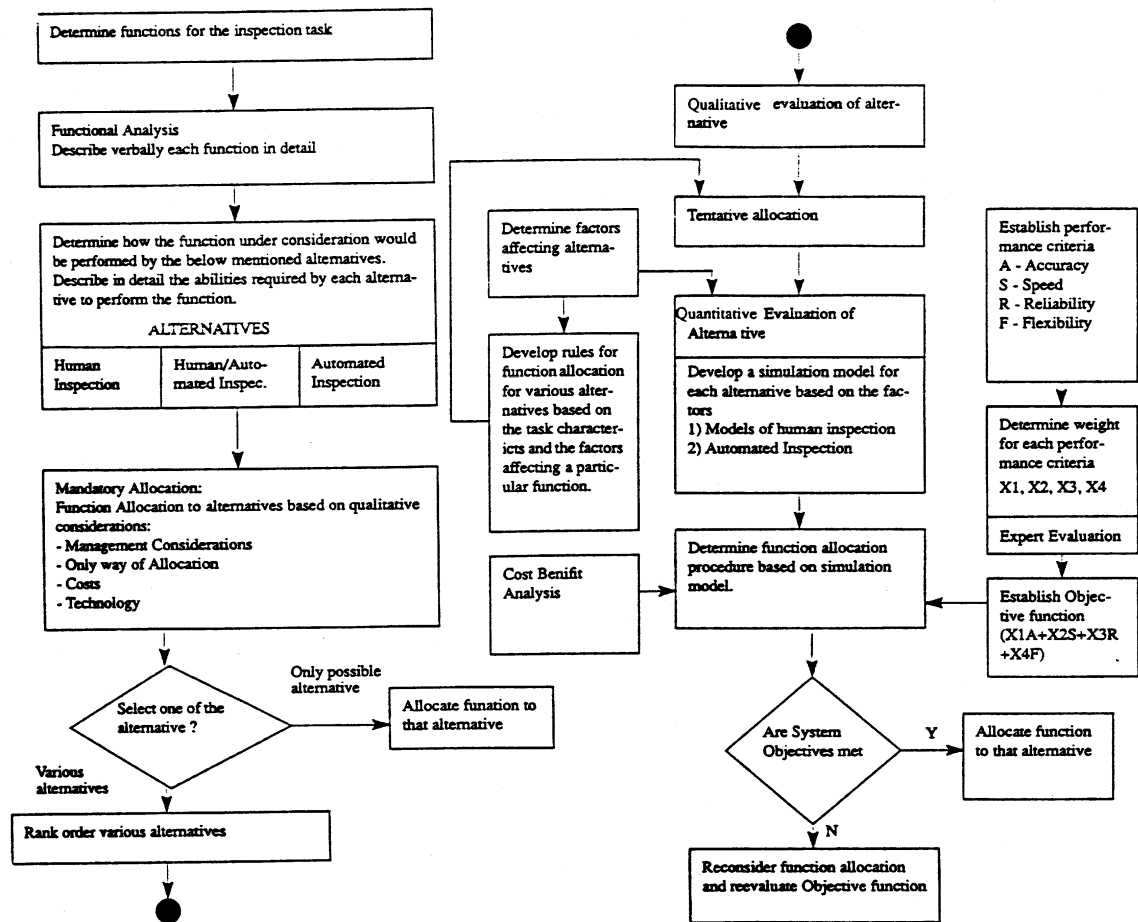


Figure 4. Framework for function allocation in inspection (Gramopadhye, Drury, Sharit, and Sudit, 1992).

Hou, Lin, and Drury (1993) conducted a  $3^3$  factorial experiment in which the experimental task was the quality inspection of printed circuit boards containing surface mounted devices. The independent variables were the complexity of the product (number of components in the board), the contrast level between components and background, and the visual noise in the displayed image (the noise coming from the lighting conditions and the imaging system). Using the accuracy and speed performance criterion measures combined with the false alarm rate and the hit rate, they calculated a cost-based evaluation function. This cost-based evaluation function coupled with the Drury and Sinclair (1983) findings led to the conclusion that allocating the search function to



machines and the decision making function to humans results in better performance than pure human or pure machine inspection. This computer-search/human-decision making system is known as a Hybrid Inspection System (HIS). The idea behind HIS is to capitalize on the machine speed and precision to scan the inspection unit, and on the decision making ability exhibited by humans.

### Quality Inspection Task Load

Quality inspection tasks that impose a sustained load on working memory (to recall what the quality acceptability criterion looks like) will demand the continuous supply of processing resources (Parasuraman, 1979; Parasuraman, Warm, and Dember, 1987, Wickens, 1992). Parasuraman (1979) conducted an experiment using a successive-discrimination task (that imposed a memory load) in which the signal was specified as the decrease in the intensity of a flashing light. The signals were presented irregularly at a mean rate of two signals per minute, and the event rate was 30 events per minute. The duration of the task was 45 minutes. He concluded that the performance in such areas of vigilance application as radar monitoring and industrial quality inspection could be adversely affected when the operator has to discriminate a signal from a standard represented in memory and when the event rate is high. This performance decrement may result either from signal-data limits (weak signal in noise), or memory-data limits (quality of stored representation of the standard in delayed comparison memory tasks).

Like many other tasks, quality inspection has been identified as having an inverted-U shaped relationship between task demand and performance level (McGrath, 1965, Wiener, Curry, and Faustina, 1984). The Inverted-U theory states that for a given task, there is an optimal level of workload or demand that yields the highest level of performance. A departure in either direction from the optimal level of work will result in a performance decrement. Wiener (1975) indicated that while most of the results of vigilance research support the right-hand side of the inverted-U theory (overload) there is a lack of support for the left-hand branch (assertion that the task performance level can be improved by increasing the load). One of the first experiments that supported the left-

hand side in a vigilance task was conducted by McGrath (1965). After comparing easy and hard visual monitoring tasks conducted concurrently he concluded that the presence of the hard task facilitated performance on the easy one. Wiener et al. (1984) conducted an experiment in which a control group performed a vigilance task (the signal was the decrease in distance between two dots presented on a computer screen), and a second group performed a one-dimensional compensatory tracking task in addition to the vigilance task. They found that performance of the second group (vigilance and tracking tasks) in terms of signal detection exceeded the performance of the control group (vigilance task only). They concluded that these research results provided support for the facilitating effect of increasing the task load (left side of the inverted-U).

Some researchers describe the quality inspection task as being intrinsically boring (Craig, 1984; Poulton, 1977). According to them, this explains why it is often the case that mild stress will increase the performance in terms of detection and response time. However, Wickens (1992) has indicated that vigilance tasks with working memory load are susceptible to interference from concurrent tasks.

### Multitasking

Multitasking (often referred to as timesharing) has been extensively studied from a mental workload and human performance perspective. However, a relatively small amount of research has been conducted in the manufacturing domain (Wickens, 1992). As the level of system automation increases, the role of the human has shifted from that of a manual controller to system supervisor (Sheridan and Johanness, 1976). According to Sheridan (1994), “human operators in AMS make their way among machines, inspecting parts, observing displays, and modifying control settings or keying in commands, most of it through computer-mediated control panels adjacent to various machines.” This role of human operators in AMS has been identified as supervisory control.

## Human Supervisory Control

Supervisory control refers to one or more human operators programming and receiving information from a computer that interconnects through artificial effectors and sensors to the controlled process or task environment (Sheridan, 1987). Ammons, Govindaraj, and Mitchell (1988) described the supervisory controller as “an operator responsible for a group of complex machinery where the operations require intermittent attention and depend on higher-level perceptual and cognitive functions.” Sheridan (1976) defined a general paradigm of supervisory control consisting of five functions: 1) Plan, 2) Teach, 3) Monitor, 4) Intervene, and 5) Learn. For each of the main supervisory functions the computer provides decision-aiding and implementation capabilities, as shown in Figure 5. A description of these functions is presented in Figure 6.

Job scheduling, inventory planning, and problem solving (disturbance control) have been among the supervisory control responsibilities commonly assigned to human operators in AMS (Suri and Whitney, 1984; Ammons et al., 1988). The capabilities of humans and computers in AMS planning/scheduling tasks are presented in Table 5 (Nakamura and Salvendy, 1994). Table 6 shows examples of different types of unexpected contingencies (disturbances) in AMS (Kuivanen, 1996). Ammons et al. (1988) stated that two ways in which the unique skills of the human decision maker are used in supervisory control are to fine-tune or refine standard operating procedures for particular system states and to compensate for unplanned events and unexpected contingencies.

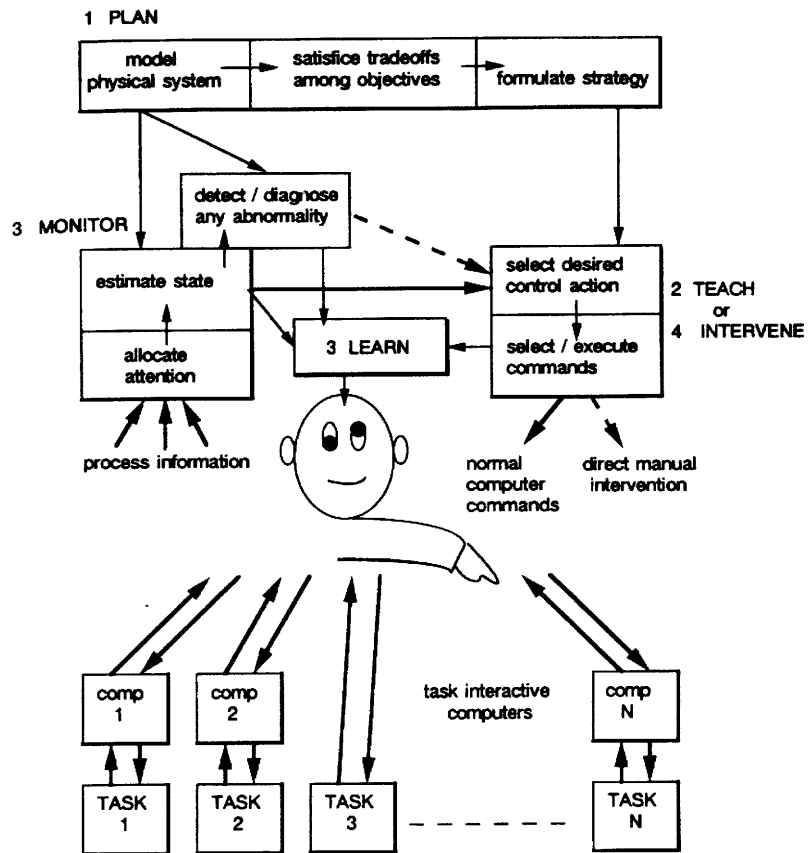


Figure 5. General paradigm of supervisory control (Sheridan, 1976).

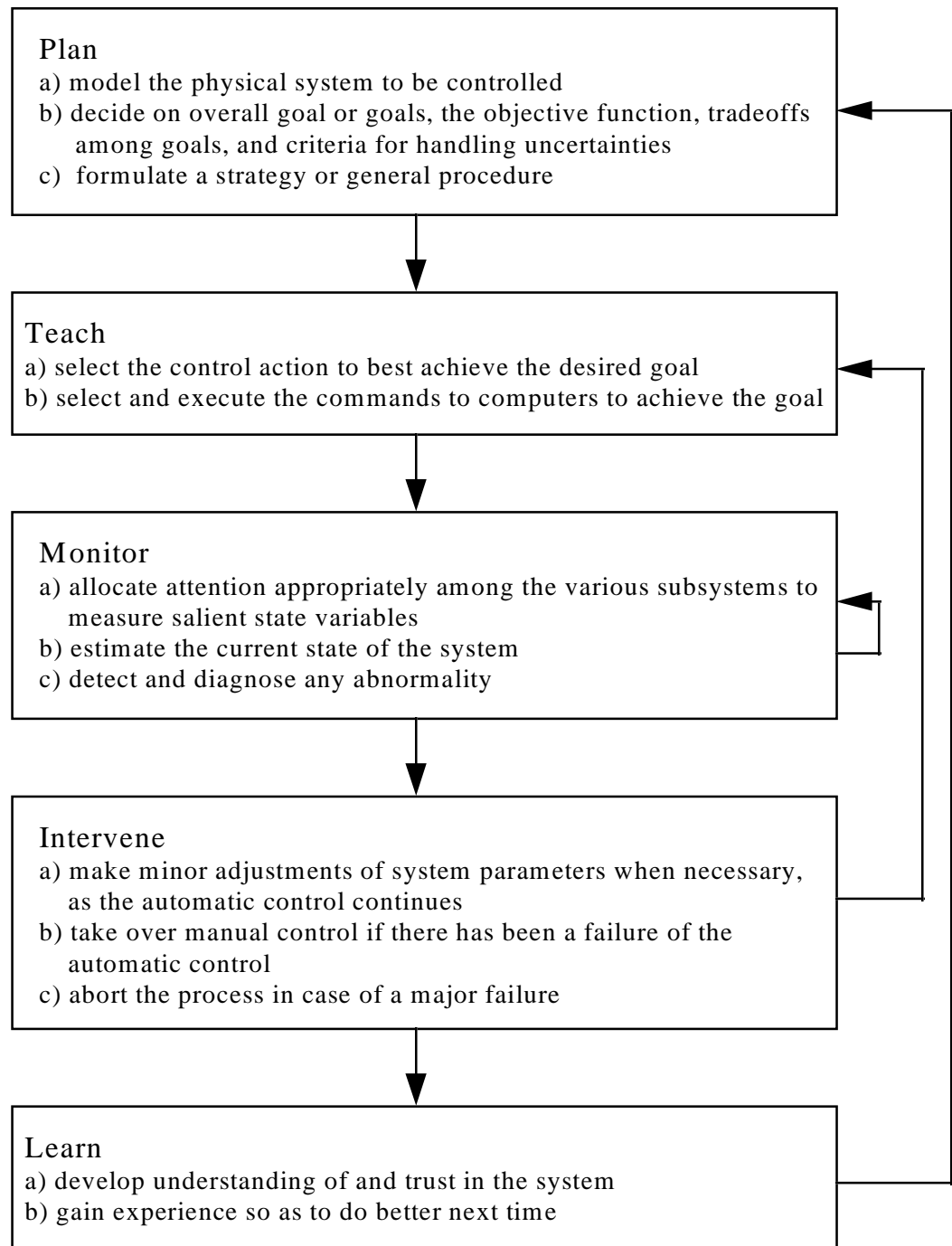


Figure 6. Temporal nesting of the general paradigm of supervisory control functions (Sheridan, 1976).

Table 5. Capabilities of human and computer in planning/scheduling tasks of AMS  
(Nakamura, and Salvendy, 1994).

Subtask	Description	Computer	Human
1. Detection	<ul style="list-style-type: none"> <li>• Detect information and data for jobs and machines.</li> </ul>	<ul style="list-style-type: none"> <li>• Computer can easily detect information and data.</li> </ul>	<ul style="list-style-type: none"> <li>• Human takes a long time to detect the presence of information and data</li> </ul>
2. Identification of system status	<ul style="list-style-type: none"> <li>• Identify the present state of the system.</li> </ul>	<ul style="list-style-type: none"> <li>• If the identified pattern was predetermined, computer can quickly identify it.</li> </ul>	<ul style="list-style-type: none"> <li>• Human can recognize the important features in the planning / scheduling environment. (but this is nonlinguistic knowledge.)</li> </ul>
3. Interpretation	<ul style="list-style-type: none"> <li>• Interpret performance criteria and set the final goal for planning / scheduling.</li> </ul>	<ul style="list-style-type: none"> <li>• Computer can decide if the program connecting the present state with the final goal is stored.</li> </ul>	<ul style="list-style-type: none"> <li>• Human can set the reasonable goal from among many criteria which conflict with each other.</li> </ul>
4. Order selection	<ul style="list-style-type: none"> <li>• Select an order to be scheduled according to a priority.</li> </ul>	<ul style="list-style-type: none"> <li>• Heuristic algorithm can provide a "good" solution, but no guarantee on optimal one.</li> </ul>	<ul style="list-style-type: none"> <li>• Human intuition makes the best feasible solution.</li> </ul>
5. Time assignment	<ul style="list-style-type: none"> <li>• Determine the start time and finish time for each operation of the selected order.</li> </ul>	<ul style="list-style-type: none"> <li>• It is difficult to take balance between job waiting time and machine idle time.</li> </ul>	<ul style="list-style-type: none"> <li>• Coordinating human with computer helps to determine efficient time assignment.</li> </ul>
6. Resource allocation	<ul style="list-style-type: none"> <li>• Select the resources (machines, tools, fixtures, NC program, etc.) to produce an order.</li> </ul>	<ul style="list-style-type: none"> <li>• Computer program can easily check whether machines, tools, fixtures and NC program are available.</li> </ul>	<ul style="list-style-type: none"> <li>• Human selects many alternative solutions.</li> </ul>
7. Evaluation and modification	<ul style="list-style-type: none"> <li>• Evaluate the plan / schedule and if not satisfied, modify it.</li> </ul>	<ul style="list-style-type: none"> <li>• Poor, but updates the overall plan / schedule at least once every minute.</li> </ul>	<ul style="list-style-type: none"> <li>• Human modifies overall plan / schedule with flexible decision making abilities.</li> </ul>
8. Generation	<ul style="list-style-type: none"> <li>• Generate the plan / schedule sheet and issue it to the floor.</li> </ul>	<ul style="list-style-type: none"> <li>• Computer can do it very easily.</li> </ul>	<ul style="list-style-type: none"> <li>• Slow, not suitable.</li> </ul>
9. Control	<ul style="list-style-type: none"> <li>• Check the difference between the plan / schedule and the practice.</li> </ul>	<ul style="list-style-type: none"> <li>• Computer can do it easily under normal conditions.</li> </ul>	<ul style="list-style-type: none"> <li>• Human can adapt at abnormal conditions.</li> </ul>

Table 6. Different type of disturbances in AMS (Kuivanen, 1996).

Target Group	Viewpoint	Definition	Example of the Cause of the Disturbance
General	All the situations concerning the organization, technique, or human action	A disturbance is an unplanned or undesirable state or function of the	<ul style="list-style-type: none"> <li>—a missing work order</li> <li>—machine or device failure</li> <li>—broken tool</li> <li>—overloading</li> <li>—insufficient training</li> </ul>
Operator of the system	All the situations that harm the normal working routine	A disturbance is a state or function of the system, which causes extra work	<ul style="list-style-type: none"> <li>—error in the work program</li> <li>—error in the work</li> <li>—broken tool</li> <li>—machine or device failure</li> </ul>
Maintenance	All the situations, that make it necessary for the maintenance personnel to take action towards the systems operation	A disturbance is a state or function of the system that requires remedial actions	<ul style="list-style-type: none"> <li>—machine or device failure</li> <li>—overloading</li> <li>—maintenance and cleaning</li> </ul>
Labor management and design	All the situations that prevent production	A disturbance is a state or function of the system which stops production	<ul style="list-style-type: none"> <li>—raw materials, tools, or plans missing</li> <li>—machine or device failure</li> <li>—machine or device failure</li> <li>—workers or key personnel taken ill</li> <li>—strike</li> </ul>
Production management	All that disables a delivery in agreed time	A disturbance is a state or function of the system, which makes it impossible for the producer to deliver the products to the customer in agreed time	<ul style="list-style-type: none"> <li>—strike</li> <li>—overloading</li> <li>—machine and device failure</li> <li>—bad quality</li> </ul>
Marketing	All the events in production, that complicate marketing	A distance is a state or function of the system, which disables or makes it makes it difficult to make a business agreement	<ul style="list-style-type: none"> <li>—too long time of delivery</li> <li>—inferior quality</li> </ul>

## Determinants of Multitasking Performance

Different mental models have been used to describe multitasking performance. Scheduling, switching, confusion, cooperation, and processing resources are mechanisms often identified as determinants of multitasking performance (Damos, 1991; Adams, Tenney, and Pew, 1991; Wickens, 1992). In particular, the concept of processing resources is the basis for understanding the other mechanisms, and hence for multitasking performance. According to Wickens (1991), the resources concept is founded on the underlying assumption that the human operator has a limited capacity for processing resources that may be allocated to task performance; therefore, multitasking can lead to one or more tasks with less resources than required, causing a performance deterioration. This deterioration in the performance of one task because of competition with another task for critical resources is known as interference.

Two major processing resources theories of task performance are Single-Resource Theory and Multiple-Resources Theory. The Single-Resource theory proposed by Kahneman (1973) postulates one undifferentiated limited pool of resources available to all tasks and mental activities. According to this theory, multitasking performance declines as the difficulty of one of the tasks increases, because it demands more resources from the limited pool, thus leaving fewer resources for performing the other tasks. Sanders and McCormick (1993) indicated that the Single-Resource Theory has difficulty explaining: 1) why tasks that require the same memory codes or processing modalities interfere more than tasks not sharing the same memory codes or processing modalities, 2) why with some combinations of tasks increasing the difficulty of one task has no effect on the performance of the others, and 3) why some tasks can be time-shared perfectly. According to Sanders and McCormick (1993), these three issues can be explained by the Multiple-Resources Theory proposed by Wickens (1984).

The Multiple-Resources Theory proposes that there are three dimensions along which resources can be allocated. The first dimension is stages (encoding and central processing vs. responding), which explains why tasks requiring response selection and allocation resources are not disrupted by tasks requiring central processing resources.



The second dimension is input modality (auditory vs. visual), which explains why multitasking is better when the tasks do not require resources from the same modality than when they do. The third dimension is processing codes (spatial vs. verbal), which explains why multitasking is performed better when one task involves moving or positioning objects in space and the other involves language or logical operations. In addition to the three dimensions mentioned above, this theory suggests a response dimension (vocal vs. manual), which explains why multitasking is performed better when the tasks responses are of opposite types. Although the Multiple-Resources Theory was developed based on dual task multitasking, it can be used to explain more complex multitasking.

Scheduling and switching are highly influential on performance for both dual-task and more complex multitasking. The operator's scheduling and switching ability depends on an understanding of the temporal constraints, the objective, and the cost associated with each task (Wood, 1982; Moray, Dessouky, Kijowski, and Adapathya, 1990). Poor scheduling, inefficient switching between tasks, or insufficient time to do the multiple tasks sequentially will force the person to engage in concurrent processing. Wickens (1991) indicated that when the operator is engaged in concurrent processing, multitasking performance will be influenced by: 1) confusion (elements of one task become confused with the processing of another task because of their similarity), 2) cooperation between task processes (caused by high similarity of processing routines), and 3) competition for task resources. When the amount of resources demanded by the multiple tasks exceeds the amount of the operator's mental resources available, he or she will experience mental workload, consequently decreasing multitasking performance (McCloy, Derrick, and Wickens, 1983; Bi and Salvendy, 1994). Figure 7 shows the relationship among the performance-resource function for multitasking (Wickens, 1992). Sheridan (1994) stated that mental workload is very important for supervisory control in AMS where the human operator is constantly called upon to do multiple complex sensory and judgmental tasks. The central issue for vigilance research is to determine the effect of the additional tasks to the vigilance performance (Craig, 1991).

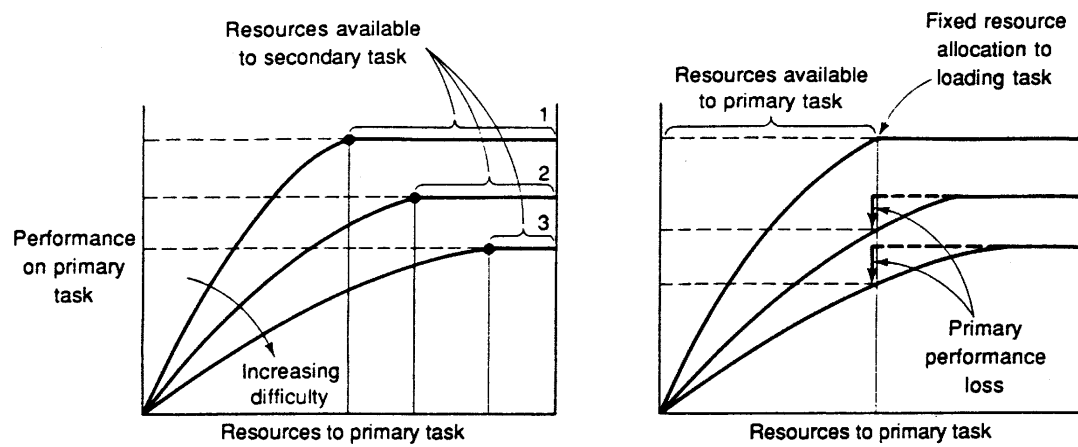


Figure 7. Performance-resource function for multitasking (Wickens, 1992).

## Research Objectives

There are still a surprising number of parts in AMS that can only be inspected by means of human visual sensory detection. Even when the quality inspection search component has been automated, human operators must make a final decision on the acceptability of a manufactured part. In many cases, this judgment must be made on the basis of a comparison with a memorized criteria for acceptable parts. The objective of this research was to characterize the operator's performance in the quality inspection task while conducting multitasking in an AMS.

The experiment tested the following hypotheses:

Hypothesis 1: The operator's decision making component of the quality inspection task in AMS will be significantly affected by the appearance of different types of defects in the units being produced.

Hypothesis 2: The operator's decision making component of the quality inspection task in AMS will be significantly affected by multitasking.

Hypothesis 3: The operator's decision making component of the quality inspection task in AMS will be significantly affected by the interaction of multitasking with the appearance of different types of defects in the units being produced.

## **Chapter 2. EXPERIMENTAL METHOD**

### Subjects

Twelve subjects (9 male, 3 female) with 20/20 vision and no previous quality inspection task experience participated in the experiment. They were compensated for their participation at a rate of \$5.00 per hour. All of the subjects were selected from the Virginia Polytechnic Institute and State University community. Subjects participation was in accordance with the Virginia Tech IRB #97-161.

### Apparatus

A real-time, interactive simulation of an AMS cell was the scenario for the experimental tasks. It consisted of three main stations: 1) quality inspection station, 2) production scheduling and inventory control station, and 3) adjacent process station. At the quality inspection station the subject (operator) was expected to decide whether to accept or reject the units presented on a computer screen. At the production scheduling and inventory control station the operator was expected to decide whether to schedule a new order before those already in the system or not. Also, the operator was expected to determine the quantity of a particular raw material order that needed to be placed. Bins with dummy parts used for the inventory task were located in this station. At the adjacent process station the operator was expected to conduct machine setup and disturbance control tasks.

Each station was represented by a 486-DX personal computer with a high resolution monitor located in a standing work table. This representation was consistent with human-machine interfaces in AMS. Visual Basic 4.0 was used to generate the three computer-based stations code. Two video cameras were used to transmit images of what was taking place in the AMS cell to the video cube located in experimenter area (see Figure 8).

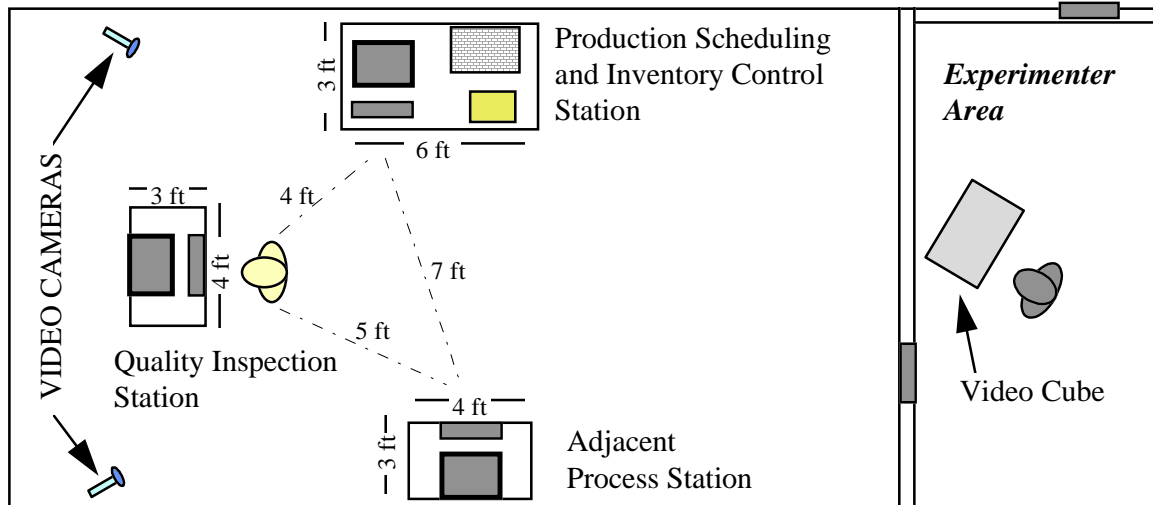


Figure 8. Experimental scenario - AMS Cell.

### Experimental Design

A 2x3 within-subject factorial experiment was conducted (see Table 7). The two independent variables were Defect Type with two levels (one or two types of defects presented at a time), and Tasks with three levels (one task, three tasks, or five tasks concurrently conducted). The experimental unit was a white rectangle (16 cm wide x 10 cm high). A Balanced Latin Square design was used to order the experimental treatments (see Table 8).

### Independent Variables

Defect Type and Tasks were the independent variables used in the experiment. The two types of defects used were a speck (small circular spot) and a scratch (a narrow, shallow straight line). Only one of these defects (speck or scratch) was presented in the faulty units produced during a treatment when the Defect Type level was one type. Both defects (speck and scratch) were presented in the faulty units produced during a treatment

when the Defect Type level was two types. The experimental unit and defect types are shown in Figure 9.

Table 7. Experimental conditions for the 2 x 3 design.

Treatment	Defect Type	Tasks
1	one type (scratch or speck)	- quality inspection
2	two types (scratch and speck)	- quality inspection - production scheduling and inventory
3	one type (scratch or speck)	- quality inspection - production scheduling and inventory - machine setup and disturbance control
4	two types (scratch and speck)	- quality inspection
5	one type (scratch or speck)	- quality inspection - production scheduling and inventory
6	two types (scratch and speck)	- quality inspection - production scheduling and inventory - machine setup and disturbance control

Table 8. Balanced Latin Square design.

Order	Subjects					
	S1	S2	S3	S4	S5	S6
	S7	S8	S9	S10	S11	S12
1	T1	T2	T3	T4	T5	T6
2	T2	T3	T4	T5	T6	T1
3	T6	T1	T2	T3	T4	T5
4	T3	T4	T5	T6	T1	T2
5	T5	T6	T1	T2	T3	T4
6	T4	T5	T6	T1	T2	T3

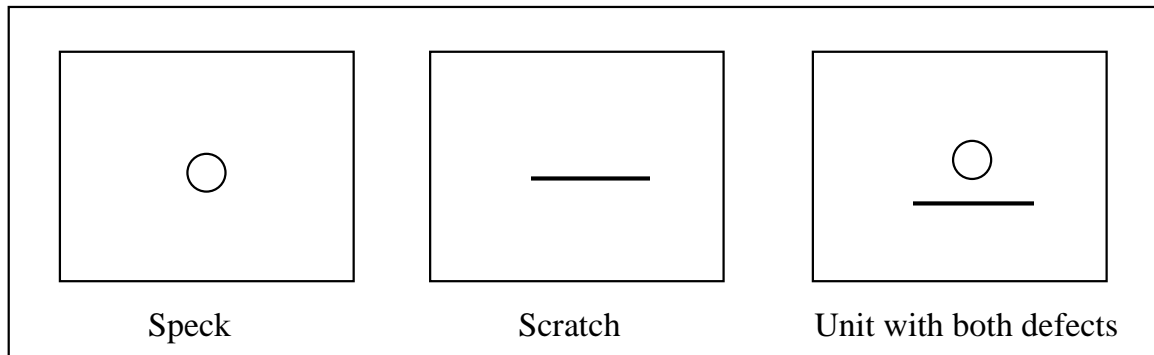


Figure 9. Experimental unit and defect types.

The Tasks factor consisted of five different tasks conducted at the three main stations. Only the quality inspection task was conducted at the one task level of the Tasks factor. In addition to the quality inspection task, the operator conducted a scheduling task and an inventory control task concurrently at the three tasks level of the Tasks factor. At the five tasks level of the Tasks factor, the operator concurrently conducted a machine setup task and a machine disturbance control task in addition to the quality inspection, production scheduling, and inventory control tasks previously mentioned. The reason for using an additional level of multitasking (machine setup and disturbance control tasks) was to increase the processing resources demand while minimizing the possibility of monotony by having a greater variety of independent tasks rather than just increasing the event rate at the other secondary tasks (production scheduling and inventory control).

### Task Description

The experiment consisted of six experimental treatments as presented in Table 7. The average duration of each treatment ranged between 50 minutes and 120 minutes. During that period of time 500 units were inspected. Out of the 500 units, 50 had no defects (blanks), 250 units had a defect (or defects) that did not exceed the quality criterion (acceptable), and 200 units had a defect (or defects) that exceeded the criterion (rejectable). The quality criterion was 6 millimeters for the speck diameter, and 26 millimeters for the scratch length. The just noticeable difference (jnd) that each subject

could detect was added or subtracted to the quality criterion to generate rejectable defects (quality criterion + 1 jnd) and acceptable defects (quality criterion - 1 jnd) respectively. The arrival of units to the inspection station was random with a mean time between events of 3 seconds. The subjects were instructed to execute the tasks to the best of their capabilities using a neutral payoff. There was no immediate knowledge of results. Although quality inspection was the primary task of this experiment, subjects conducted the other tasks at a performance level of at least 90%.

The quality inspection task was conducted at the one task level of the Tasks factor. In the inspection task a ringing sound alerted the operator to the arrival of a unit to be inspected. The operator clicked the “Start” button to indicate the beginning of the inspection. After the inspection (up to six seconds allowed), the operator clicked the “Reject” button to reject a unit that exceeded the memorized quality criterion, or the “Accept” button to accept a unit that did not exceed the criterion (see Figure 10).

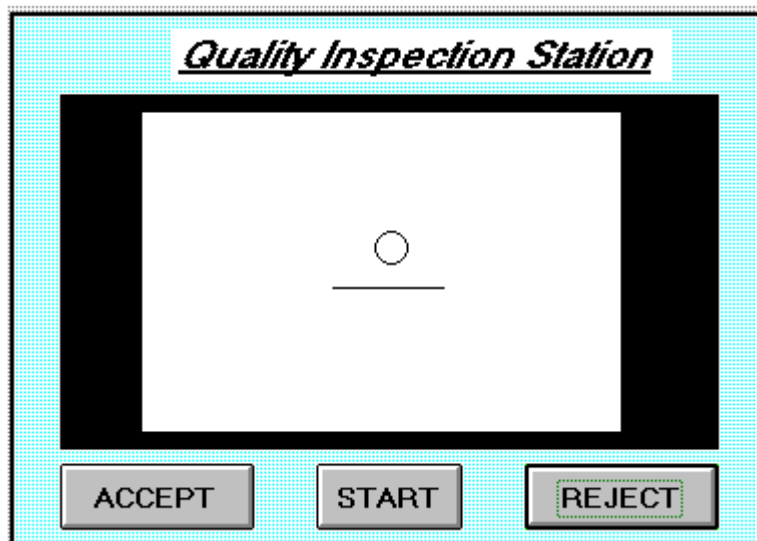


Figure 10. Quality Inspection Station screen.

In addition to the quality inspection task, the operator conducted a scheduling task and an inventory control task concurrently at the three tasks level of the Tasks factor. For



the scheduling task the operator responded to a particular voiced message (“Scheduling”) from the production scheduling and inventory control station announcing the arrival of a new order (see Figure 11). After comparing the new order quantity and due date with other orders already in the system, the operator scheduled it based on a scheduling criterion. According to this criterion the new order should be scheduled to be processed before any order with a later due date. In the case of more than one order with the same due date, the one with the smallest quantity should be scheduled first. For the inventory control task, the operator responded to a voiced message (“Inventory”) from the production scheduling and inventory control station announcing the need to conduct an inventory on a specific part. The operator then counted the particular dummy parts in the bin and entered the quantity in the inventory control application of the production scheduling and inventory control station (see Figure 12). After calculating (mentally) the difference between the quantity required and the available quantity the operator placed an order for the quantity needed to satisfy the demand.

***Production Scheduling***

Processing Order	Part Number	Description	Quantity	Due Date
1	XY7425	Triton	30	March/13
2	UP3472	Jason	45	March/18
3	PQ8917	Emerald	45	March/27
4				

**New Order**

Part Number	Description	Quantity	Due Date
WK0475	Coquix	35	March/15

Input the Processing Order

Figure 11. Scheduling screen at the Production Scheduling and Inventory Control Station.

Part #	Description	Required QTY.	Available QTY.	QTY to be ordered
437425	Blue part	60	23	37
973472	Red part	25	22	3
568917	White part	45		

OK

Figure 12. Inventory screen at the Production Scheduling and Inventory Control Station.

At the Five Tasks level of the Tasks factor, the operator concurrently conducted a machine setup task and a disturbance control task in addition to the quality inspection, production scheduling, and inventory control tasks previously discussed. The operator responded to a voiced message from the adjacent process station announcing the need to conduct either a setup (“Machine Setup”) or a disturbance control (“Machine Problem”). For the setup task the operator entered the parameters of a particular product (from a setup card) to be processed (see Figure 13). The setup card (hard copy) was available at the adjacent process station. For the machine disturbance control task the operator read the displayed error message on the station’s screen, then entered a particular alphanumeric code, available at the station (from a disturbance control codes card), to restart the process (see Figure 14). All of the additional tasks (scheduling, inventory, machine setup, and machine disturbance control) were presented randomly eighteen times each during an experimental treatment.

***Setup for Part # 412JPT***

Temp. Zone 1		Temp. Zone 2	
<input type="checkbox"/>	Lo	<input type="checkbox"/>	Lo
<input checked="" type="checkbox"/>	Med	<input type="checkbox"/>	Med
<input type="checkbox"/>	High	<input checked="" type="checkbox"/>	High

Head Speed: 45 rpm

Nozzle Speed: 65 rpm

Plate Delay: 10 sec

OK

Figure 13. Setup screen at the Adjacent Process Station.

**Machine Error #632**

Please enter the Problem Solving Code

OK

Figure 14. Disturbance control screen at the Adjacent Process Station.

### Dependent Variables

The proportion of correct detection (rejection of unacceptable units, hit), the proportion of incorrect detection (rejection of acceptable units, false alarm), the time to make a decision about the part inspected, and the scores of the subjective workload

questionnaire were recorded for each experimental treatment (Appendix H). In addition, the SDT metrics of sensitivity ( $d'$ ) and inspector decision making criterion or bias ( $\beta$  and  $c$ ) were calculated using the observed hit and false alarm rates. The computational formulas for the SDT metrics ( $d'$ ,  $\beta$ , and  $c$ ) and the experiment data for each subject (based on the 500 units inspected) is presented in Appendix I.

The subjective workload questionnaire consisted of twelve likert-like scaled statements divided in six major categories: 1) mental demand, 2) physical demand, 3) temporal demand, 4) performance, 5) effort, and 6) frustration level. These categories are the same subscales used in NASA Task Load Index Subjective Workload Assessment Technique (NASA-TLX). Hart and Staveland (1988) indicated that the six subscales were found to be primary sources of task loading conducive to workload. The NASA-TLX was not used, despite its high sensitivity to experimental manipulations of workload, to avoid the use of a reference task. The reference task is recommended to obtain subjective estimates of the importance of the six subscales (Gopher and Braune, 1984). It must share elements in common with the experimental tasks. The subjective workload level of the experimental tasks would be rated with respect to the reference task. Given the subjects' lack of experience in the industrial quality inspection task combined with the multitasking of the other independent tasks the use of a reference task might be inadequate for this experiment.

### Experimental Procedures

Before going through the screening process the potential subjects received general information (written and verbal) about the experiment (Appendix A). Those who agreed to participate read and signed the informed consent form (Appendix B). At this point, the participant's vision was tested for acuity using a Baush & Lomb Vision Tester. Those who meet the visual acuity criterion (20/20), participated in a Two Alternative Forced Choice procedure (2AFC) to determine if they could score a proportion of correct detection of at least 0.80 (Appendix C). The criterion of 0.80 correct detection is

consistent with what has been reported for 100 % quality inspection in industry (Juran 1974; Konz, Peterson, and Joshi, 1981; Schilling 1982). Written and verbal instructions were given to the subjects before the 2AFC screening test (Appendix D). Those who satisfactorily passed the screening process participated in the Constant Stimuli Method procedure to determine difference threshold (DL, for the German “Differenz Limen”) (Appendix E). This psychophysical measure was used to generate the defects’ intensity consistent with the just noticeable difference that each subject could detect (Appendix J). Subjects received written and verbal instructions before this procedure (Appendix F).

Before participating in the experiment the subjects received instructions (written and verbal) as well as individualized training and practice (with feedback) in the experimental rules and procedures, tasks and equipment, and the defect rejection criterion (Appendix G). Once their performance on the secondary tasks of the laboratory controlled AMS cell exceeded 90% they were scheduled for six experimental sessions (one experimental treatment per session). The 90% criterion was used to minimize any practice or learning effect during the experiment. The subjects received practice (with feedback and no time constraint, as well as without feedback and with time constraint) in the quality inspection task before participating in each experimental treatment. The subjective workload questionnaire was filled out after the subjects completed each experimental treatment.

### Data Analysis

The observed proportions of correct rejection of unacceptable parts (hit), and the proportions of incorrect rejection of acceptable parts (false alarm) were first adjusted via the procedure necessary to permit the calculation of SDT ( $d'$ ,  $\beta$ , and  $c$ ) in cases where the observed proportions equaled 0 or 1 (Snodgrass and Corwin, 1988). Snodgrass and Corwin (1988) recommended the correction of all hit and false alarm rates by adding 0.5 to each frequency and dividing by  $N+1$ , where  $N$  is the number of total events

(  $\text{Hit} = \frac{\# \text{ correct rejection} + 0.5}{\# \text{ rejectable parts} + 1}$  ;  $\text{F\_A} = \frac{\# \text{ incorrect rejection} + 0.5}{\# \text{ acceptable parts} + 1}$  ). For consistency, they

recommend applying the correction routinely, even in the absence of 0 and 1, and even when SDT measures are not calculated. This correction was also recommended for log-linear models of data expressed as counts in contingency tables (Plackett, 1974; Upton, 1978). More recently, See, Warm, Dember, and Howe (1997) reported the use of this adjustment procedure in an empirical evaluation of five parametric and nonparametric SDT metrics of response bias.

Analyses of variance (ANOVA) were done for each of the dependent variables (hit, false alarm, average time to make the decision, and the subjective workload questionnaire scores) and the SDT metrics ( $d'$ ,  $\beta$ , and  $c$ ). The computational formulas (for  $d'$ ,  $\beta$ , and  $c$ ) and the subjects data (hit rate, false alarm rate,  $d'$ ,  $\beta$ ,  $c$ , average time, and the scores of the subjective workload questionnaire) are presented in Appendix I.

### Chapter 3. RESULTS

#### Hit Rate

The ANOVA of the dependent variable hit is presented in Table 9. Based on the unadjusted F (p-value = 0.0251) and the Geisser-Greenhouse correction factor (G-Gp = 0.0253) the effect of the interaction between Defect Type and Tasks was statistically significant.

Table 9. ANOVA summary table of hit.

Source	df	SS	MS	F	p-value	G-Gp
<u>Between-Subjects</u>						
Subjects (S)	11	1.224766	0.111342			-----
<u>Within-Subject</u>						
Defect Type (DT)	1	0.002250	0.003101	0.19	0.668	-----
DT x S	11	0.127138	0.011558			
Tasks (Tsk)	2	0.006202	0.003101	0.55	0.583	-----
Tsk x S	22	0.123191	0.005600			
DT x Tsk	2	0.065055	0.032528	4.38	0.0251 *	0.0253 *
DT x Tsk x S	22	0.163518	0.007433			
Total	71	1.712121				

\* Statistically significant at  $\alpha=0.05$

According to a Newman-Keuls post hoc analysis of the unconfounded comparisons of the interaction between Defect Type and Tasks, there was a statistically significant difference between inspection of parts with one type of defect (scratch or speck) while multitasking and the inspection of parts with both types of defects (scratch and speck) while multitasking (see Table 10). The hit rate when both defects were present in the inspected parts and the subject conducted one or three tasks concurrently was higher than when the same number of tasks was performed but only one type of defect was present in the inspected parts. However, when the subjects conducted five tasks and both defects were present in the inspected parts, the hit rate was lower than

when the same number of tasks was performed but only one type of defect was present in the inspected parts. The interaction between Defect Type and Tasks is shown in Figure 15.

Table 10. Newman-Keuls analysis of the effect of the Defect Type and Task interaction on hit.

Increasing Rank Order									
Treatment Means		1 DT <sub>2</sub> Tsk <sub>5</sub> 0.736	2 DT <sub>1</sub> Tsk <sub>1</sub> 0.753	3 DT <sub>1</sub> Tsk <sub>3</sub> 0.753	4 DT <sub>2</sub> Tsk <sub>1</sub> 0.784	5 DT <sub>1</sub> Tsk <sub>5</sub> 0.806	6 DT <sub>2</sub> Tsk <sub>3</sub> 0.826	r	CD <sub>0.05</sub>
Rank Order	1	-----	-----	-----	0.048 *	0.07 *	0.097 *	6	0.032
	2		-----	0	0.031 *	0.053 *	-----	5	0.030
	3			-----	-----	0.053 *	0.073 *	4	0.028
	4				-----	-----	0.042 *	3	0.026
	5					-----	-----	2	0.021

\* Statistically significant at  $\alpha=0.05$

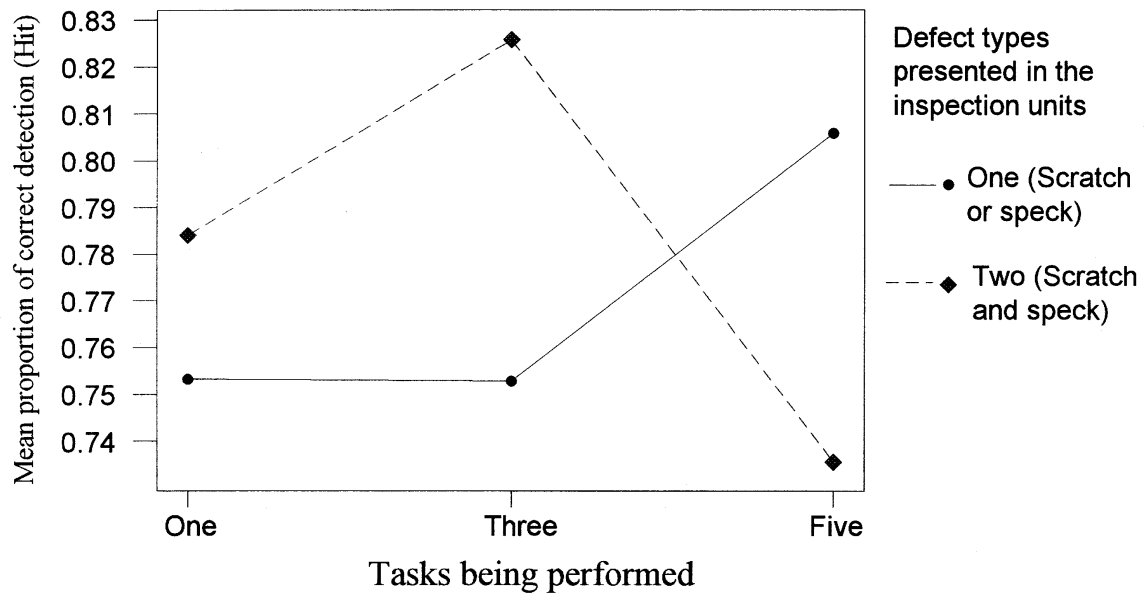


Figure 15. Mean plot of the effects of the Defect Type and Tasks interaction on hit.



### False Alarm Rate

The ANOVA of the dependent variable false alarm is presented in Table 11. Based on the p-values of the unadjusted F there was no statistically significant effect.

Table 11. ANOVA summary table of false alarm.

Source	df	SS	MS	F	p-value	G-Gp
<u>Between-Subjects</u>						
Subjects (S)	11	0.059639	0.005422			-----
<u>Within-Subject</u>						
Defect Type (DT)	1	0.003123	0.003123	1.97	0.188	-----
DT x S	11	0.017424	0.001584			
Tasks (Tsk)	2	0.003492	0.001746	1.62	0.220	-----
Tsk x S	22	0.023686	0.001077			
DT x Tsk	2	0.002142	0.001071	1.11	0.346	-----
DT x Tsk x S	22	0.021165	0.000962			
Total	71	0.130672				

\* Statistically significant at  $\alpha=0.05$

### SDT metrics ( $d'$ , $\beta$ , and $c$ )

The ANOVA of the dependent variable  $d'$  is presented in Table 12. Based on the p-values of the unadjusted F there was no statistically significant effect. The subjects' perceptual sensitivity (mean  $d' = 3.096$ ) remained constant throughout the experiment. The ANOVA of the dependent variable  $\beta$  is presented in Table 13. Based on the p-values of the unadjusted F there was no statistically significant effect. The observed criterion or response bias (mean  $\beta = 19.07$ ) exceeded the ideal criterion ( $\beta_i = 1.25$ ) for a neutral payoff (costs for incorrect decisions = rewards for correct decisions). This represents a conservative criterion adopted by the subjects.

Table 12. ANOVA summary table of  $d'$ .

Source	df	SS	MS	F	p-value	G-Gp
<u>Between-Subjects</u>						
Subjects (S)	11	6.9891	0.6354			-----
<u>Within-Subject</u>						
Defect Type (DT)	1	0.0045	0.0045	0.01	0.905	-----
DT x S	11	3.3294	0.3027			
Tasks (Tsk)	2	0.2613	0.1307	0.75	0.482	-----
Tsk x S	22	3.8095	0.1732			
DT x Tsk	2	0.1117	0.0559	0.23	0.793	-----
DT x Tsk x S	22	5.2498	0.2386			
Total	71	19.7553				

\* Statistically significant at  $\alpha=0.05$

Table 13. ANOVA summary table of  $\beta$ .

Source	df	SS	MS	F	p-value	G-Gp
<u>Between-Subjects</u>						
Subjects (S)	11	12249.2	1113.6			-----
<u>Within-Subject</u>						
Defect Type (DT)	1	322.7	322.7	0.70	0.420	-----
DT x S	11	5046.3	458.8			
Tasks (Tsk)	2	27.7	13.8	0.06	0.942	-----
Tsk x S	22	5074.2	230.6			
DT x Tsk	2	1861.8	930.9	3.31	0.055	-----
DT x Tsk x S	22	6185.8	281.2			
Total	71	30767.6				

\* Statistically significant at  $\alpha=0.05$

The ANOVA of the dependent variable  $c$  is presented in Table 14. Based on the unadjusted F (p-value = 0.0448) and the Geisser-Greenhouse correction factor (G-Gp = 0.0491) the effect of the interaction between Defect Type and Tasks was statistically significant.

Table 14. ANOVA summary table of  $c$ .

Source	df	SS	MS	F	p-value	G-Gp
<u>Between-Subjects</u>						
Subjects (S)	11	13.2123	1.2011			-----
<u>Within-Subject</u>						
Defect Type (DT)	1	0.0278	0.0278	0.14	0.718	-----
DT x S	11	2.2165	0.2015			
Tasks (Tsk)	2	0.1626	0.0813	0.88	0.429	-----
Tsk x S	22	2.0309	0.0923			
DT x Tsk	2	0.8429	0.4215	3.59	0.0448 *	0.0491 *
DT x Tsk x S	22	2.5840	0.1175			
Total	71	21.0770				

\* Statistically significant at  $\alpha=0.05$

According to a Newman-Keuls post hoc analysis of the unconfounded comparisons of the interaction between Defect Type and Tasks, there was a statistically significant difference in response bias ( $c$ ) between inspection of parts with one type of defect (scratch or speck) while multitasking and the inspection of parts with both types of defects (scratch and speck) while multitasking (see Table 15). The criterion or response bias when both defects were present in the inspected parts and the subject conducted one or three tasks concurrently was lower than when the same number of tasks was performed but only one type of defect was present in the inspected parts. However, when the subjects conducted five tasks and both defects were present in the inspected parts, the response bias was higher than when the same number of tasks was performed but only one type of defect was present in the inspected parts. The interaction between Defect Type and Tasks is shown in Figure 16. The mean  $c$  values throughout the levels of the interaction exceeded the point of completely neutral bias ( $c_N = 0$ ). This represents a conservative criterion adopted by the subjects which is consistent with the results of the less sensitive response bias metric  $\beta$ .

Table 15. Newman-Keuls analysis of the effect of the Defect Type and Task interaction on  $c$ .

Increasing Rank Order									
Treatment Means		1 DT <sub>2</sub> Tsk <sub>3</sub> 0.476	2 DT <sub>1</sub> Tsk <sub>5</sub> 0.524	3 DT <sub>2</sub> Tsk <sub>1</sub> 0.663	4 DT <sub>1</sub> Tsk <sub>3</sub> 0.734	5 DT <sub>1</sub> Tsk <sub>1</sub> 0.778	6 DT <sub>2</sub> Tsk <sub>5</sub> 0.826	r	CD <sub>0.05</sub>
Rank Order	1	-----	-----	0.187*	0.258*	-----	0.303*	6	0.1260
	2		-----	-----	0.210*	0.254*	0.255*	5	0.1200
	3			-----	-----	0.115*	0.116*	4	0.1123
	4				-----	0.044	-----	3	0.1014
	5					-----	-----	2	0.0838

\* Statistically significant at  $\alpha=0.05$

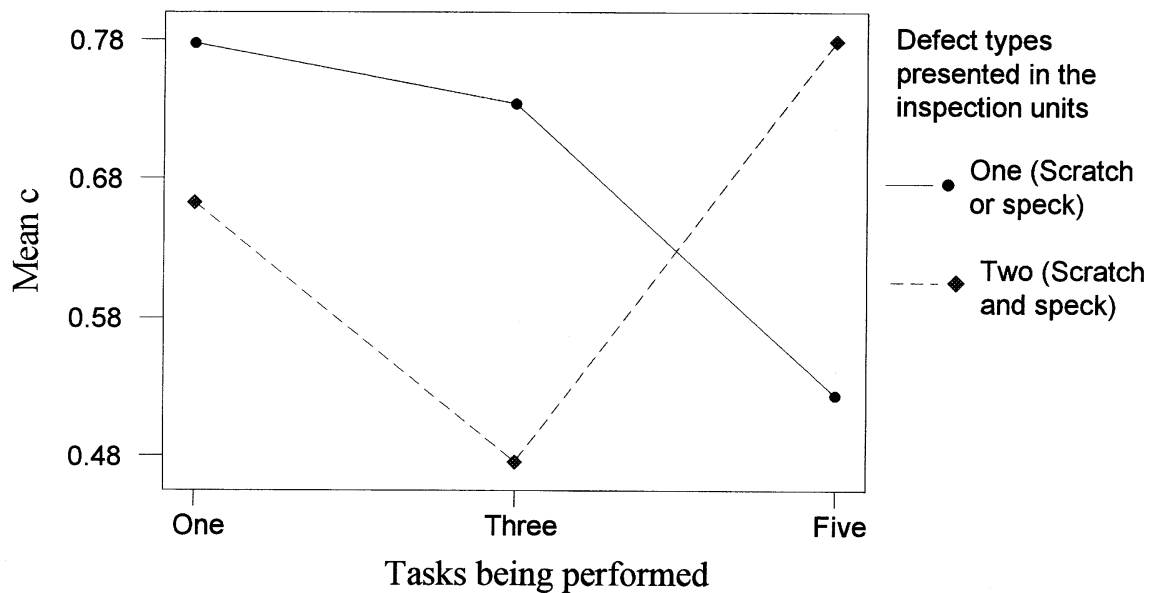


Figure 16. Mean plot of the effects of the Defect Type and Tasks interaction on  $c$ .

### Average Time

The ANOVA of the dependent variable average time to make a decision to accept or reject the inspected part is presented in Table 16. Based on the p-values of the

unadjusted F and the Geisser-Greenhouse correction factor (G-Gp) the effect of the Defect Type ( $F_{p\text{-value}} = 0.01$ , G-Gp = 0.01) and Tasks ( $F_{p\text{-value}} = 0.029$ , G-Gp = 0.048) were statistically significant. It took more time to inspect parts containing both types of defect than parts containing only one type (see Figure 17). According to a Newman-Keuls post hoc analysis, the average time to make a decision to accept or reject the inspected part was significantly less when the subjects were multitasking than when they were only performing the quality inspection task (see Table 17 and Figure 17).

Table 16. ANOVA summary table of average time to make a decision.

Source	df	SS	MS	F	p-value	G-Gp
<u>Between-Subjects</u>						
Subjects (S)	11	1.48670	0.13515			-----
<u>Within-Subject</u>						
Defect Type (DT)	1	0.54080	0.54080	9.60	0.01 *	0.01 *
DT x S	11	0.61957	0.05632			
Tasks (Tsk)	2	0.19603	0.09802	4.17	0.029 *	0.048 *
Tsk x S	22	0.51757	0.02353			
DT x Tsk	2	0.01583	0.00792	0.12	0.890	-----
DT x Tsk x S	22	1.48910	0.06769			
Total	71	4.86560				

\* Statistically significant at  $\alpha=0.05$

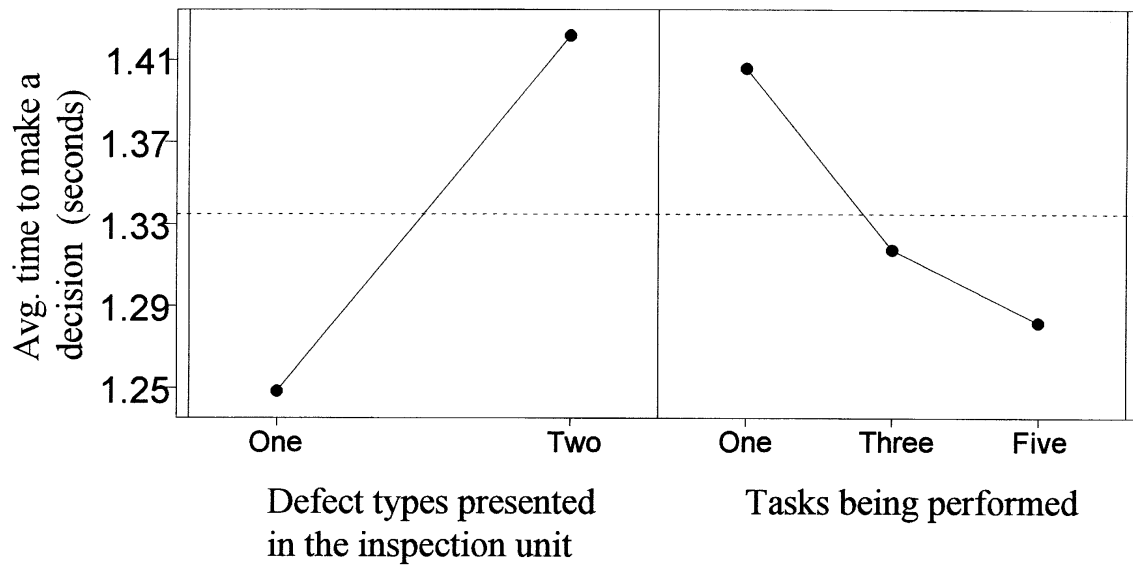


Figure 17. Mean plot of Defect Type and Tasks effects on the average time to make a decision.

Table 17. Newman-Keuls analysis of the effect of Tasks on the average time to make a decision.

Increasing Rank Order						
		1	2	3		
Treatment Means		Tsk <sub>5</sub> 1.282	Tsk <sub>3</sub> 1.317	Tsk <sub>1</sub> 1.406	r	CD <sub>0.05</sub>
Rank	1	-----	0.035	0.124 *	3	0.045
Order	2		-----	0.089 *	2	0.038

\* Statistically significant at  $\alpha=0.05$

### Subjective Workload Questionnaire Scores

The ANOVA for the scores of the item number six (Temporal Demand) in the subjective workload questionnaire was the only one that showed a statistically significant effect (see Table 18). Based on the p-values of the unadjusted F and the Geisser-Greenhouse correction factor (G-Gp), the effects of Defect Type ( $F_{p\text{-value}} = 0.037$ , G-Gp = 0.037) and Tasks ( $F_{p\text{-value}} = 0.0001$ , G-Gp = 0.0014) were statistically significant.

Subjects perceived the temporal demand of inspecting parts containing only one types of defect to be higher than inspecting parts containing both type of defect (see Figure 18). According to a Newman-Keuls post hoc analysis, the subject perceived the temporal demand to be higher as the number of tasks to be performed increased (see Table 19 and Figure 18). Based on the mean score of the items in the subjective workload questionnaire (that showed no statistically significant differences) it can be stated that: 1) subjects perceived the mental and physical demand of all the experimental treatments to be minimum, and 2) subjects perceived that they were able to accomplish the experimental tasks satisfactorily with a minimum mental and physical effort.

Table 18. ANOVA summary table of temporal demand.

Source	df	SS	MS	F	p-value	G-Gp
<u>Between-Subjects</u>						
Subjects (S)	11	68.0167	6.1833			-----
<u>Within-Subject</u>						
Defect Type (DT)	1	3.2089	3.2089	5.61	0.037 *	0.037 *
DT x S	11	6.2944	0.5722			
Tasks (Tsk)	2	34.6558	17.3279	14.71	0.0001 *	0.0014 *
Tsk x S	22	25.9075	1.1776			
DT x Tsk	2	0.0469	0.0235	0.03	0.974	-----
DT x Tsk x S	22	19.9097	0.9050			
Total	71	158.04				

\* Statistically significant at  $\alpha=0.05$

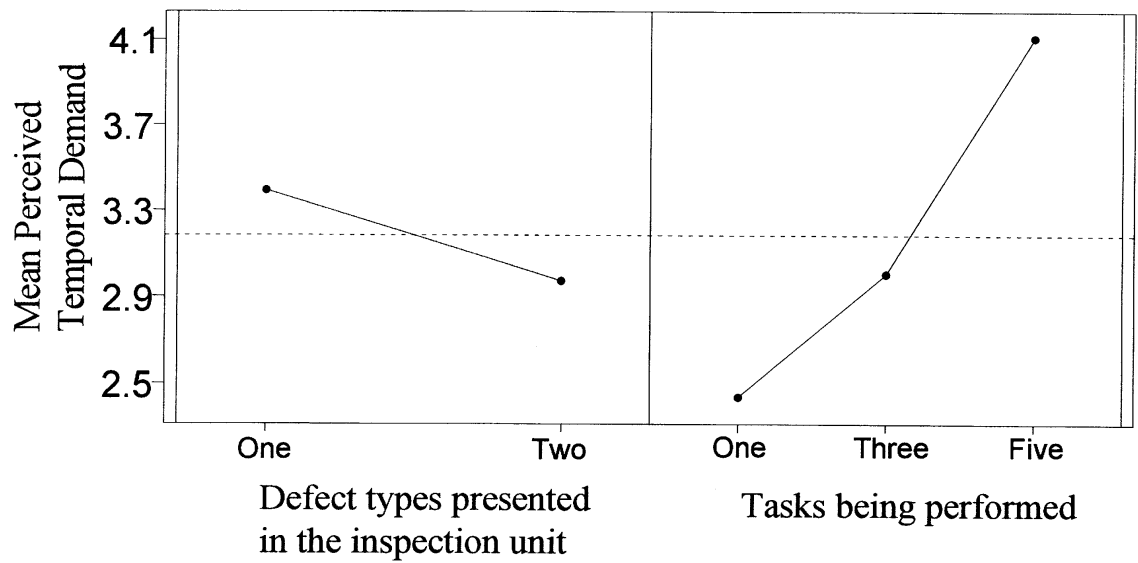


Figure 18. Mean plot of Defect Type and Tasks effects on the temporal demand.

Table 19. Newman-Keuls analysis of the effect of Tasks on the temporal demand.

Increasing Rank Order						
		1	2	3		
Treatment Means		Tsk <sub>5</sub> 2.438	Tsk <sub>3</sub> 3.004	Tsk <sub>1</sub> 4.108	r	CD <sub>0.05</sub>
Rank Order	1	-----	0.566 *	1.67 *	3	0.321
	2		-----	1.104 *	2	0.265

\* Statistically significant at  $\alpha=0.05$



## Chapter 4. DISCUSSION

The results obtained from this experiment support the assertion that the characterization of the operator's performance in the quality inspection task while conducting multitasking in an AMS is not strictly bounded by the classical decision theory paradigm. Processing resources and memory load concepts need to be considered in order to obtain a better understanding of the operator's performance in quality inspection. This position will be evident as the three hypotheses that motivated this research are evaluated.

### Hypothesis 1

Hypothesis 1 stated that the operator's decision making component of the quality inspection task in AMS would be significantly affected by the appearance of different types of defects in the units being produced. The nonsignificant differences on hit, false alarm, and the SDT metrics ( $d'$ ,  $\beta$ , and  $c$ ) as a function of Defect Type failed to support this hypothesis. This finding is consistent with those reported by Craig et al. (1977) and Craig (1979) in which they concluded that the added complexity of looking for more than one kind of signal (two types) has no adverse effect on vigilance task performance.

Even though the participants were instructed to use a neutral payoff they maintained a conservative response criterion (strict payoff) throughout the experiment. This resulted in the operator (consciously or unconsciously) trading off hits in order to avoid false alarms. The strongest evidence to support the subjects' conservative behavior is that their response bias (mean  $\beta = 19.06$ , mean  $c = 0.659$ ) exceeded the ideal criterion ( $\beta_i = 1.25$ ,  $c_N = 0$ ) despite the fact that their perceptual sensitivity (mean  $d' = 3.096$ ) was high. These results seem to suggest the ineffectiveness of using instructions as the only instrument to control the payoff adopted by the subjects.

The increase in load imposed by the inspection of more than one defect (two different types) in the same unit was not enough to reduce the monotony of the task nor to

improve the performance in terms of detection. Subjects perceived the inspection task to be boring. Most of them expressed a preference for performing additional tasks because, as some of them indicated in the comments section of the questionnaires or directly to the experimenter, “it helps to break the monotony of the quality inspection.” Subjects complained about the temporal uncertainty of the quality inspection task. They would have liked to control the pace of the task, or as some of them indicated, “I like performing additional tasks because it makes the quality inspection time pass quickly.” Apparently, the less they worked the more bored they felt. This can be supported by the fact that the perceived temporal demand of inspecting parts containing both defect types was significantly less than when inspecting parts containing only one defect type at a time. This is in spite of the fact that the average time to make a decision when both defects were presented in the parts was significantly greater than when only one type of defect was presented.

The finding that operator performance was not adversely affected by more than one defect type in the same part is important for the quality inspection task in real world AMS. However, it is important to realize that it is possible to have more than two defect types in units inspected in real manufacturing environments. Even if the maximum number of defect types per inspected unit is two, it should be taken into consideration that the average proportion of correct detection ( $\text{hit} = 0.776$ ), although consistent with what has been reported for 100% industrial quality inspection (Juran, 1974; Konz, Peterson, and Joshi, 1981; Schilling, 1982), may not be acceptable for a World Class Manufacturing organization.

## Hypothesis 2

Hypothesis 2 stated that the operator’s decision making component of the quality inspection task in AMS would be significantly affected by multitasking. The nonsignificant differences obtained on hit, false alarm, and the SDT metrics ( $d'$ ,  $\beta$ , and  $c$ ) as a function of Tasks failed to support this hypothesis. Once again (as in the Defect

Type factor) the operators maintained a conservative response bias despite having a high perceptual sensitivity, as the number of tasks performed ranged between one and five.

The additional load imposed by multitasking seems to have a significant reducing effect in the average time to make a decision about the inspected part. But, opposite to the effect of the Defect Type factor (where the perceived temporal demand decreased as the Defect Type increased), the perceived temporal demand significantly increased as the load imposed by multitasking increased. The effect of multitasking on the average time to make a decision about the inspected part is consistent with the inverted-U theory, the left side in particular (Wiener et al., 1984; Craig, 1984; Poulton, 1977). An increase in load imposed by multitasking improved the performance in terms of response time at the quality inspection task. Nevertheless, the increase in load of the Tasks factor alone was not enough to significantly affect the average proportion of correct detection.

The finding that the operator's decision making performance in the quality inspection task was not affected by multitasking (up to five tasks) supports the task allocation practices in AMS in which the operator plays a supervisory control role. A major implication of this finding is the need to assess and control the operator's payoff before the actual task is conducted (off-line). This could be beneficial to prevent operators from maintaining the wrong response criterion throughout the actual quality inspection task (on-line) while multitasking in AMS.

### Hypothesis 3

Hypothesis 3 stated that the operator's decision making component of the quality inspection task in AMS would be significantly affected by the interaction between multitasking and the number of different types of defects in the units being inspected. This hypothesis is primarily supported by the statistically significant difference in hits and the SDT metric for response bias  $c$ . The significant effect of the interaction on the average proportion of correct detection provides some support for both sides of the inverted-U function (McGrath, 1965; Wiener et al., 1984).

The increase in load imposed by multitasking of three tasks and the memorized criterion for the quality inspection task of parts containing two defect types at a time compared to just the inspection of parts containing two defect types at a time (no multitasking) caused a significant increase in average proportion of correct detection (from  $\text{hit} = 0.784$  to  $\text{hit} = 0.826$ ). The significant decrease in response bias (from  $c = 0.663$  to  $c = 0.476$ ) observed for this case suggest that as the number of tasks increased from one to three the subjects adopted a less conservative criterion. In terms of the average proportion of correct detection, this can also be interpreted as an example of the left-hand side of the inverted-U (the task performance level being improved by increasing the load). On the other hand, the load imposed by increasing the number of tasks from three to five and the memorized quality criterion for the quality inspection task of parts containing two defect types caused a significant drop in the average proportion of correct detection (from  $\text{hit} = 0.826$  to  $\text{hit} = 0.736$ ). As expected a significant increase in response bias (from  $c = 0.476$  to  $c = 0.826$ ) was observed for this case suggesting that as the number of tasks increased from three to five the subjects adopted a more conservative criterion. In terms of the average proportion of correct detection, this can also be interpreted as an example of the right-hand side of the inverted-U (the task performance level being degraded by overload).

For the case of the quality inspection of parts containing only one defect type at a time there was no significant change on the average proportion of correct detection ( $\text{hit} = 0.753$ ) nor on the response criterion when the number of tasks conducted by the operator increased from one to three. The only significant increase in average proportion of correct detection (from  $\text{hit} = 0.753$  to  $\text{hit} = 0.806$ ) occurred when the operator was conducting all five tasks. The significant decrease in response bias (from  $c = 0.734$  to  $c = 0.524$ ) observed for this case suggest that as the number of tasks increased from three to five the subjects adopted a less conservative criterion. Apparently an overload effect was not evident for the quality inspection of parts containing only one defect type because, as previously discussed, the memory load imposed by this particular condition seemed to be less than for the case of two defects at a time. This is supported by the fact that the

highest average proportion of correct detection for the inspection of parts with one defect type occurred when the operator was multitasking five tasks ( $\text{hit} = 0.806$ ) while the lowest average proportion of correct detection overall ( $\text{hit} = 0.736$ ) was observed when the operator was inspecting parts with both defect types and multitasking five tasks.

Although a conservative response bias ( $c > c_N$ ) was observed at all the levels of the interaction between Defect Type and Tasks there were statistically significant different degrees of conservative criterion. If the interaction has the same effect in an operator with a neutral payoff ( $c_N = 0$ ) it might be possible to observe the operator adopting a conservative criterion ( $c > c_N$ ) or a lax criterion ( $c < c_N$ ) as a function of an increase in load imposed by multitasking and the memorized criterion for the quality inspection.

The finding that the operator's decision making performance in quality inspection was significantly affected by the interaction between the Defect Type and Task factors demonstrates that the quality inspection task with working memory load demands a continuous supply of processing resources, and is susceptible to interference from concurrent tasks (Parasuraman 1979; Wickens, 1992). This supports the importance of adequate task allocation in AMS. Doing so will be instrumental to maximizing the utilization of the human operator while minimizing performance problems.

## **Chapter 5. Conclusions and Future Research**

This research was intended to gather information about factors contributing to the characterization of the operator's performance in the quality inspection task while multitasking in an AMS. The ineffectiveness of using instructions as the only instrument to control the payoff adopted by the subjects might be considered as an external validity limitation of this research. Given the strict payoff adopted by the subjects throughout the experiment, the findings previously discussed might be interpreted as valid primarily for operators with a conservative criterion.

Despite the limitations of a laboratory simulated AMS with subjects who were not necessarily experiencing the daily pressures typical of many manufacturing environments, the findings of this research are beneficial to the design of AMS. The major implication derived from these research findings is that a quality inspection task which depends on memorized criterion will create a mental load which needs to be considered when allocating multiple tasks to an operator in an AMS. The performance of the operator in the quality inspection task while multitasking in an AMS will be determined not only by the number of different types of defect that can be presented at a time in the inspected parts, but also by the mental processing resources required to meet the demand imposed by the multiple independent tasks and the memorized quality criterion. The best performance will be obtained when the additional tasks' load minimizes the monotony of the quality inspection task without interfering with the processing resources needed for the memorized quality criterion. However, it is worth mentioning that although the best performance in terms of average proportion of correct detection exceeded the commonly accepted 0.80 for 100% quality inspection (Juran, 1974; Konz, Peterson, and Joshi, 1981; Schilling, 1982), there is room for improvement.

Given the limitation of the study presented herein it is evident that more research on the effect of multitasking on quality inspection in AMS should be conducted using more effective methods, other than instructions, to control the operator's adopted payoff. Perhaps a payoff system that encourages the operator to adopt the criterion of interest

(lax, neutral, or strict) will increase the external validity of this type of research. Further research to determine the effect of different fraction of defectives, and knowledge of results in the operator's performance in the quality inspection task while multitasking in an AMS are necessary. The results of such research should be compared to the findings of this research, and those of more traditional laboratory research with simple vigilance tasks and no multitasking. Based on the experience from this research the use of SDT is recommended for future research oriented to determine the effect of multitasking on the decision making performance in complex monitoring tasks. In addition to be instrumental in the assessment of the operators' adopted payoff throughout this study, the SDT extensive research body was helpful for the interpretation of the results. Finally, a confirmation study is recommended to determine the generalizability of the results obtained in this laboratory experiment to real world AMS.

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## APPENDIX A

### **General Information: The Effects of Multitasking on Quality Inspection in AMS**

The purpose of the experiment in which you have been asked to participate is to determine if the human operator's performance in a quality inspection task is affected by multitasking (concurrently conducting multiple independent tasks) in Advanced Manufacturing Systems (AMS). The general information presented in this sheet is intended to help you decide whether you wish to participate in this experiment. If you do, you will be asked to fill out an informed consent form. At this point a screening procedure will be conducted to determine if your visual detection characteristics match those required for this experiment. First, your vision will be tested for acuity using a Baush & Lomb Vision Tester. If you meet the visual acuity criterion, a psychophysical test, known as the Forced Choice Procedure (detecting differences in images on a computer screen), will be conducted to determine your visual capability to detect quality defects. Before each test you will receive written instructions and an interactive demonstration. You will be compensated for your time whether or not you are selected as a participant. The screening procedure has an approximate duration of twenty minutes.

At this point, if you have been selected as a participant, your visual perception sensitivity characteristics will be determined via a psychophysical procedure known as the constant stimuli method (detecting differences in images on a computer screen). The constant stimuli method procedure has a duration of approximately one hour. After this procedure you will receive training and practice in the experimental rules and procedures, tasks and equipment, and the defect rejection criterion. The training and practice activities have an approximate duration of forty minutes. After satisfactorily completing the training and practice session, six experimental sessions of approximately two hours each will be scheduled for six different days. During the experimental sessions you will be instructed to perform as an operator in a laboratory controlled manufacturing cell performing up to five independent task:

- 1) quality inspection: compare a part presented on a computer screen to a memorized criterion and decide whether to accept or reject the part.
- 2) production scheduling: schedule a production order presented on a computer screen based on a scheduling criterion.
- 3) inventory control: conduct an inventory on a specific part and place an order for the quantity required to meet the part demand presented on a computer screen.
- 4) machine setup: enter the parameters of a setup needed to produce a part on a computer screen.
- 5) machine disturbance control: enter an alphanumeric code on a computer to solve a machine problem presented on a computer screen.

Written instructions and an interactive demonstration will be provided before each experimental session.

The monetary compensation is \$5 per hour. You will be paid in cash at the end of each session. Total time commitment will be 14 hours, consisting of 7 sessions of 2 hours each, with total pay up to \$70. Please ask the experimenter now if you have any questions based on this general description of the experiment. Otherwise, request and complete the informed consent form if you wish to participate in this research.

## **APPENDIX B**

### **VIRGINIA POLYTECHNIC INSTITUTE AND STATE UNIVERSITY**

#### **Informed Consent for Participants of Investigative Projects**

**Title of Project:** The Effects of Multitasking on Quality Inspection in AMS

**Investigator:** José A. Pesante-Santana

**Faculty Advisor:** Dr. Robert C. Williges

#### **I. The Purpose of this Research**

There are still a surprising number of parts in AMS that can only be inspected by means of human visual sensory detection. Even when the quality inspection search component has been automated, human operators must make a final decision on the acceptability of a manufactured part. In many cases, this judgment must be made on the basis of a comparison with a memorized criterion for acceptable parts. The purpose of this experiment is to determine if the human operator's performance in a quality inspection task is affected by multitasking (concurrently conducting multiple independent tasks) in AMS.

#### **II. Procedures**

This research is comprised of two phases: 1) the training and practice phase, 2) the experimental treatments phase. The training and practice phase will begin by determining some of your visual perception sensitivity characteristics via a psychophysical procedure, known as the constant stimuli method. You will receive written instructions and an interactive demonstration before this procedure. During the rest of this phase you will receive training (written instructions and an interactive demonstration) and practice in the experimental rules and procedures, tasks and equipment, and the defect rejection criterion. This session has an approximate duration of three hours. After satisfactorily completing the training and practice session, the second phase of the research will be scheduled. This phase consists of six experimental sessions of approximately two hours each (so total time commitment will be 14 hours, consisting of 7 sessions of 2 hours each). Written instructions and an interactive demonstration will be provided before each experimental session. Your participation in both phases of the research will be monitored from a video cube station outside the experimental room. However, it will not be videotaped.

During the second phase you will participate in six experimental treatments in a laboratory controlled manufacturing cell. The number of defects in the manufactured parts and the number of tasks to be conducted will be the two factors that will be varied

over the six treatments. There are up to five independent tasks to be conducted in the manufacturing cell:

- 1) quality inspection: compare a part presented on a computer screen to a memorized criterion and decide whether to accept or reject the part.
- 2) production scheduling: schedule a production order presented on a computer screen based on a scheduling criterion.
- 3) inventory control: conduct an inventory on a specific part and place an order for the quantity required to meet the part demand presented on a computer screen.
- 4) machine setup: enter the parameters of a setup needed to produce a part on a computer screen.
- 5) machine disturbance control: enter an alphanumeric code on a computer to solve a machine problem presented on a computer screen.

Of these tasks, quality inspection will be conducted at every experimental treatment. The six experimental treatments will be scheduled in six sessions (one experimental treatment per session).

### **III. Benefits of this Research**

Throughout the evolution of manufacturing, human sensory (visual) detection capabilities have been a vital, but often ignored, component of the quality inspection task. Despite all the significant technological developments in manufacturing, human sensory detection capabilities are still essential for the decision making component of the quality inspection task. Your participation in this research will provide significant information leading to a better understanding and characterization of the operator's performance in a quality inspection task while multitasking in AMS. The contribution of such characterization to present and future manufacturing systems is significant information that can be used for the design and allocation of the tasks in a way that maximizes the human operator's performance.

No promise or guarantee of benefits have been made to encourage you to participate. You may receive a summary of the research results when completed.

### **IV. Extent of Anonymity and Confidentiality**

The information collected in this experiment will be treated with confidentiality. At all times your name will be separated from your data and a coding scheme will be used to identify your data by subject number, gender, and treatment (e.g., S2-F-T3). The images provided by two video cameras inside the laboratory controlled manufacturing cell will be used to monitor your participation in the research. However, it will not be videotaped.

## **V. Compensation**

If you decide to participate in this research you will be paid \$5 per hour (cash) at the end of each session.

## **VI. Freedom to Withdraw**

You are free to withdraw from this study at any time without penalty. If you choose to withdraw, you will be compensated for the portion of time that you completed.

## **VII. Approval of Research**

This research has been approved, as required, by the Institutional Review Board for Research Involving Human Subjects at Virginia Polytechnic Institute and State University, and by the Department of Industrial and Systems Engineering.

## **VIII. Subject's Responsibilities**

I voluntarily agree to participate in this study and execute all the research tasks at every phase of the research (training, practice, and experimental treatments) to the best of my capabilities.

## IX. Subject's Permission

I have read and understand the Informed Consent and conditions of this project. I have had all my questions answered. I hereby acknowledge the above and give my voluntary consent for participation in this project.

If I participate, I may withdraw at any time without penalty. I agree to abide by the rules of this project.

---

Name

---

Signature

Date

Should I have questions about this research or its conduct, I may contact:

José A. Pesante-Santana  
Investigator

231-3193

Dr. Robert C. Williges  
Faculty Advisor

231-6270

H.T. Hurd  
Chair, IRB  
Research Division

231-5281

## **APPENDIX C**

### **The Forced Choice Procedure**

The two-alternative forced-choice (2AFC) procedure was used to derive a measure of each subject's sensitivity (visual capability to detect quality defects). This sensitivity measure was independent of the subject's criterion (Green and Swets, 1966). For this procedure each subject was given a series of 102 presentations. Each presentation contained twelve items of the same type (lines or dots) equally divided in two groups. The subject's task was to detect the group that contained one item with an intensity (length or diameter) different to the other parts in the group (defect). The position of the rejectable defect was counterbalanced to control the effect of space error. The order of the presentations was randomized.

The sensitivity value was obtained from the proportion of correct detection of the rejectable defect. In order to be selected for the experiment the subjects needed to score a proportion of correct detection of at least 0.80 for both type of defects. The criterion of 0.80 is consistent with what has been commonly accepted for industrial quality inspection (Juran, 1974; Konz, Peterson, and Joshi, 1981; Schilling, 1982).

Visual Basic 4.0 was used to generate the computer-based 2AFC procedure code. The procedure was conducted in a 486-DX computer with a high resolution monitor located in a standing work table.



## APPENDIX D

### Instructions for the Two Alternatives Forced Choice Procedure

Imagine that you are an industrial quality inspector in charge of a process in which you have to identify one of two batches containing a defective part (see Figure A). Each batch will consist of six items of equal length (in the case of lines) or equal diameter (in the case of circles). The batch containing an item different from the remaining five items should be identified as defective. All you need to do in order to identify the defective batch on each presentation is to click the DEFECTIVE button below the particular batch. You should continue the quality inspection task until the message End of Task appears on the screen.

The screenshot shows a software interface titled "Quality Inspection Station" in a black box at the top. Below the title is a large white rectangular area divided by a vertical black line. On the left side of the line, the text "Batch A" is centered above six horizontal black lines. On the right side, "Batch B" is centered above six horizontal black lines. At the bottom of the left column, there is a button with a dotted border and the word "DEFECTIVE" in bold. At the bottom of the right column, there is a button with a solid border and the word "DEFECTIVE" in bold. The entire interface is enclosed in a light blue border.

Figure A Screen image of the Forced Choice screening procedure.

## **APPENDIX E**

### **The Constant Stimuli Method Procedure to Determine Difference Threshold**

The constant stimuli method procedure was used to determine the difference threshold (DL, for the German “Differenz Limen”) or just noticeable difference that each subject could detect. To determine the DL, the stimuli (defect) of interest were presented in pairs, with one stimuli called the standard stimulus (St) and the other called the comparison stimulus (Co). Seven comparison stimuli were used with intensity above and below the St (an equal number of each). A total of 100 stimuli pair presentations were conducted for each stimuli used in the experiment. The order of Co and St on the pair was counterbalanced to control the effect of space error. Whether the subject judged the Co to be greater than St was recorded and plotted for each presentation.

A least square regression model was built using the seven stimuli and their respective proportion of “greater than” answers. As recommended by Gescheider (1985), the DL was obtained from the difference in intensity between the points where 25% of the time and 75% of the time the subject’s response was “greater than” (Appendix J). The psychometric function (ogive) obtained by plotting the seven stimuli (x-axis) and their respective proportion of “greater than” answers (y-axis) was used to supplement the estimation of the DL.

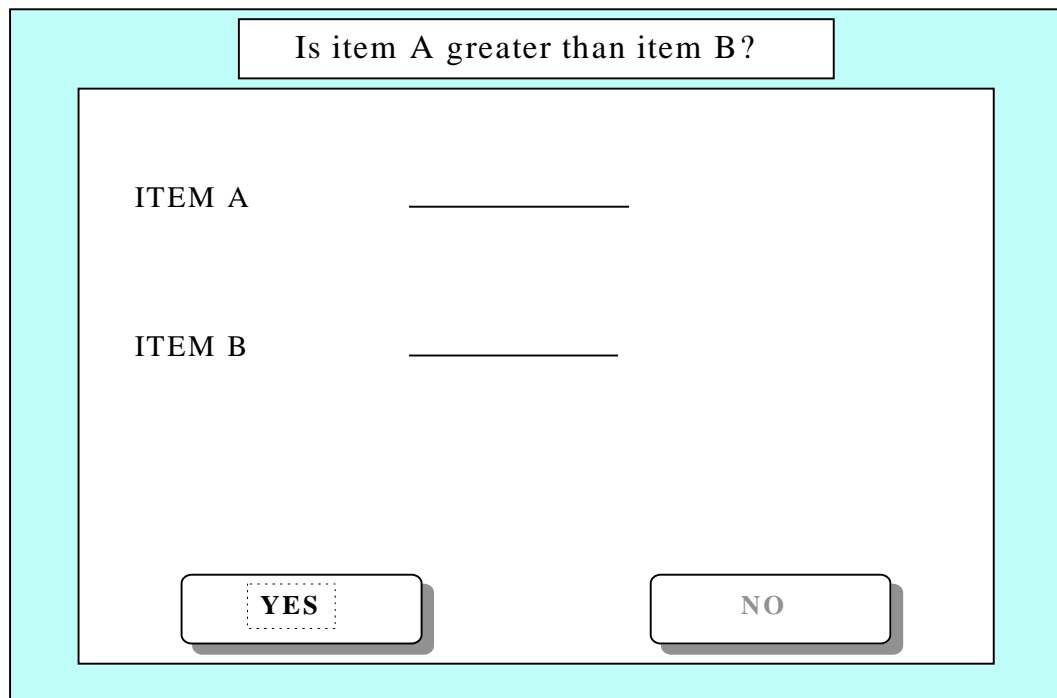
Visual Basic 4.0 was used to generate the computer-based 2AFC procedure code. The procedure was conducted in a 486-DX computer with a high resolution monitor located in a standing work table.

## APPENDIX F

### Instructions for the Constant Stimuli Method Procedure to Determine Difference

#### Threshold (DL)

Imagine that you are an industrial quality inspector in charge of a process in which you have to determine if one item is greater than another item (in terms of length for lines, or in terms of diameter for circles). All you need to do is to click the YES or the NO button below the items presented on the screen to indicate whether you perceive the item in question to be greater than the other item being presented in the computer screen (see Figure A). A bell sound will alert you to the arrival of a new set of items to be inspected on the computer screen. You should continue the quality inspection task until the message End of Task appears on the screen.



Is item A greater than item B?

ITEM A \_\_\_\_\_

ITEM B \_\_\_\_\_

**YES** **NO**

Figure A Screen image of the Constant Stimuli Method procedure for DL.

## APPENDIX G

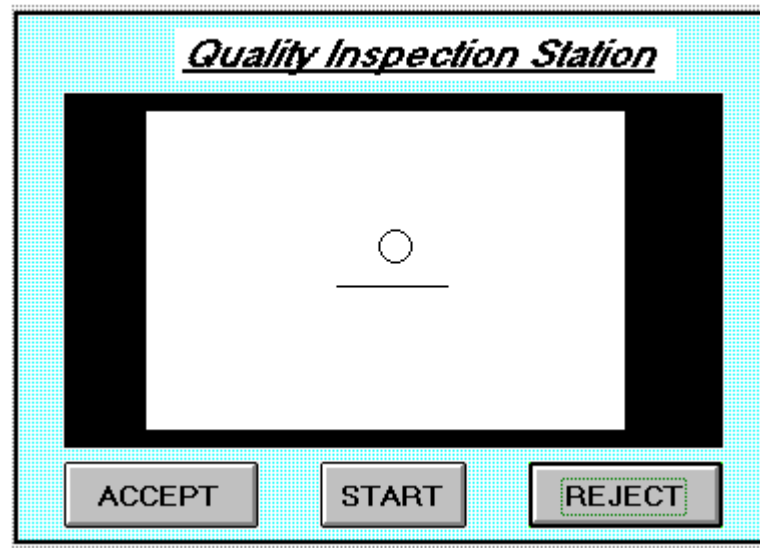
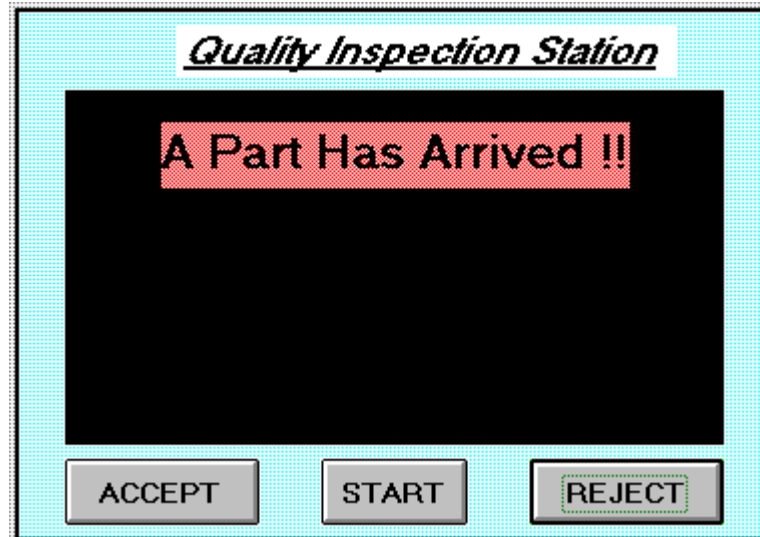
### Instructions for the Experimental Treatments

#### Instructions for the Quality Inspection Task

Imagine that you are an operator in an Advanced Manufacturing System (AMS). Your main function is to inspect the quality of the units presented on the computer monitor of the station. After hearing a ringing sound and seeing the red sign on the computer screen announcing the arrival of a new part to be inspected you are expected to conduct the following steps:

- 1) Click on the “Start” button once you are in front of the computer monitor and ready to begin the inspection.
- 2) If the unit has a defect compare its length (for the Scratch) or its diameter (for the Speck) to the memorized Quality Specifications.
  - a. If the unit’s dimension (length or diameter) just inspected exceeds the memorized quality criterion, then reject the unit (click the “Reject” button).
  - b. If the unit’s dimension (length or diameter) just inspected does not exceed the memorized quality criterion, then accept the unit (click the “Accept” button).
  - \* Defects will always be located at the center of the part.
  - \*\* Whenever both defects (Scratch and Speck) are present in the same unit compare both with their respective memorized quality criterion and reject the unit (click the “Reject” button) if at least one of the defect’s dimensions exceeds the criterion. Otherwise accept the unit (click the “Accept” button). In other words, only accept the unit if both defects are acceptable.
  - \*\*\* Notice that your decision will be right whenever you reject a rejectable unit or accept an acceptable one. Your decision will be erroneous whenever you accept a rejectable unit or reject an acceptable one
- 3) If there is no defect in the unit being inspected, then accept the unit (click the “Accept” button).
- 4) If there is no other task waiting for your intervention, then wait at the Quality Inspection Station until the next part arrives to be inspected.
- 5) Always finish the inspection of the unit presented in the computer monitor before you begin another task. Remember that if you do not enter your decision about the part you are inspecting within the allowable time (six seconds after the “Start” button was clicked), then the part will move on to another process without having been inspected.

- 6) If a part arrives to be inspected while you are conducting another task, it will stay in the quality station until you click the “Start” button. The six seconds allowed to inspect the part only begins after you click the “Start” button.



### Instructions for the Production Scheduling Task

Whenever you hear a “Scheduling” message you are expected to do the following:

- 1) Go to the Production Scheduling and Inventory Station as soon as possible (after finishing the task you may be conducting). Remember, do not leave the quality inspection without entering your decision of “Accept” or “Reject” for the part being inspected.
- 2) Enter the number in which the new production order (at the bottom of the screen) should be scheduled to be processed, using the following criterion:
  - a. A new order should be scheduled to be processed before any order with a later due date.
  - b. In the case of more than one order with the same due date, the one with the smallest quantity should be scheduled first.
- 3) After entering the scheduling number for the order, click the “OK” button.
- 4) Return to the Quality Control Station if there is no error in the transaction just completed and/or there is no other task (machine setup or disturbance control) waiting for your intervention.
- 5) If there is an error in the transaction just completed, repeat the task from step 2.

***Production Scheduling***

Processing Order	Part Number	Description	Quantity	Due Date
1	XY7425	Triton	30	March/13
2	UP3472	Jason	45	March/18
3	PQ8917	Emerald	45	March/27
4				

**New Order**

Part Number	Description	Quantity	Due Date
WK0475	Coquix	35	March/15

Input the Processing Order

### Instructions for the Inventory Task

Whenever you hear a “Inventory” message you are expected to do the following:

- 1) Go to the Production Scheduling and Inventory Station as soon as possible (after finishing the task you may be conducting). Remember, do not leave the quality inspection without entering your decision of “Accept” or “Reject” for the part being inspected.
- 2) Identify the specific part requested to be inventoried in the inventory control screen (at the bottom of the screen).
- 3) Count the number of parts in the correct bin and enter the quantity in the inventory control screen (“Available QTY” field).
- 4) Mentally calculate the quantity required to complete the order, enter the amount of units needed to complete the required order, and click the “OK” button.
- 5) Return to the Quality Control Station if there is no error in the transaction just completed and/or there is no other task (machine setup or disturbance control) waiting for your intervention.
- 6) If there is an error in the transaction just completed, repeat the task from step 2.

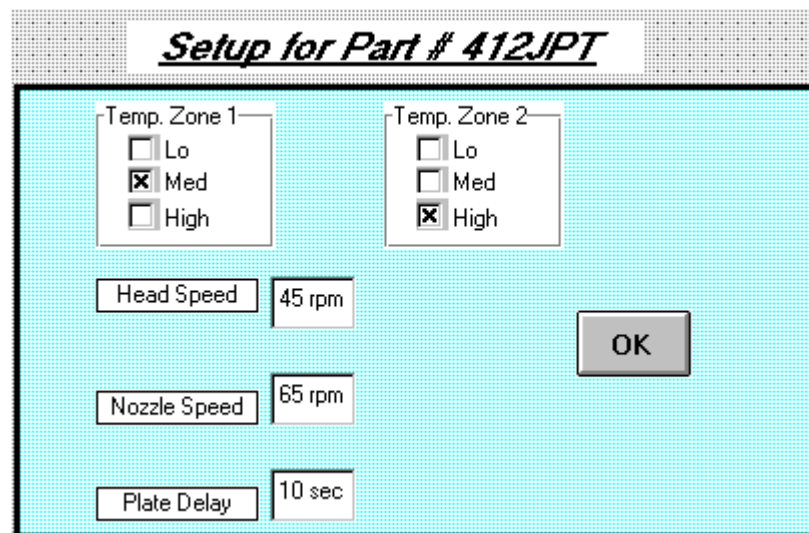
Part #	Description	Required QTY.	Available QTY.	QTY to be ordered
437425	Blue part	60	23	37
973472	Red part	25	22	3
568917	White part	45	<input type="text"/>	<input type="text"/>

OK

### Instructions for the Machine Setup Task

Whenever you hear a “Machine Setup” message you are expected to do the following:

- 1) Go to the Adjacent Process Station as soon as possible (after finishing the task you may be conducting). Remember, do not leave the quality inspection without entering your decision of “Accept” or “Reject” for the part being inspected.
- 2) Identify the specific part number for which the setup has to be entered and find the values for the setup in the setup card available at the station.
- 3) Enter the values for the setup requested in the setup screen.
- 4) After entering the setup click the “OK” button.
- 5) Return to the Quality Control Station if there is no error in the transaction just completed and/or there is no other task (production scheduling or inventory) waiting for your intervention.
- 6) If there is an error in the transaction just completed, repeat the task from step 2.



The image shows a computer screen titled "Setup for Part # 412JPT". The screen has a light blue background with a black border. It contains two columns of settings. The left column is for "Temp. Zone 1" and the right column is for "Temp. Zone 2". Each column has three radio button options: "Lo", "Med", and "High". In the "Temp. Zone 1" column, the "Med" option is selected. In the "Temp. Zone 2" column, the "High" option is selected. Below these columns are three input fields: "Head Speed" with a value of "45 rpm", "Nozzle Speed" with a value of "65 rpm", and "Plate Delay" with a value of "10 sec". To the right of these input fields is a large "OK" button.

Temp. Zone 1	Temp. Zone 2
<input type="checkbox"/> Lo	<input type="checkbox"/> Lo
<input checked="" type="checkbox"/> Med	<input type="checkbox"/> Med
<input type="checkbox"/> High	<input checked="" type="checkbox"/> High

Head Speed: 45 rpm

Nozzle Speed: 65 rpm

Plate Delay: 10 sec

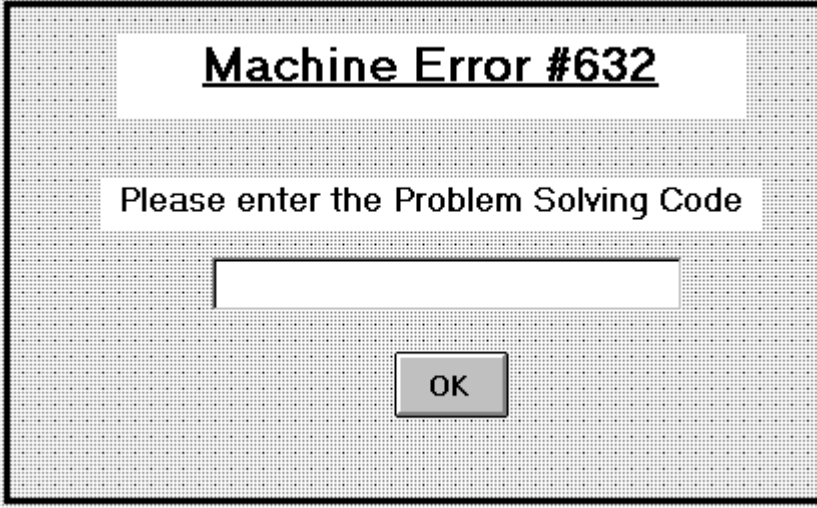
OK



### Instructions for the Machine Disturbance Control Task

Whenever you hear a “Machine Problem” message you are expected to do the following:

- 1) Go to the Adjacent Process Station as soon as possible (after finishing the task you may be conducting). Remember, do not leave the quality inspection without entering your decision of “Accept” or “Reject” for the part being inspected.
- 2) Identify the machine problem number and find the alphanumeric code (from the disturbance control codes card available at the station) needed to solve the machine problem.
- 3) Enter the alphanumeric code in the station and click the “OK” button.
- 4) Return to the Quality Control Station if there is no error in the transaction just completed and/or there is no other task (production scheduling or inventory) waiting for your intervention.
- 5) If there is an error in the transaction just completed, repeat the task from step 2.



A screenshot of a computer dialog box titled "Machine Error #632". The text "Please enter the Problem Solving Code" is displayed above a text input field. Below the input field is an "OK" button.

**Machine Error #632**

Please enter the Problem Solving Code

OK

## Overview of the Instructions for the Experiment

Imagine that you are an operator in an Advanced Manufacturing System (AMS). Although your main function is always to perform the quality inspection task as instructed in the training session, there might be occasions (experimental treatments) in which you will have to concurrently execute other tasks (such as production scheduling, inventory control, machine setup, and/or machine disturbance control) in addition to your main task. Even though quality inspection is your primary task, it is expected that you will perform any additional tasks to the best of your abilities (as trained and practiced in the training session). There will be only one experimental treatment per scheduled session. The following information will remind you of the main steps (previously learned and practiced in the training session) that you have to follow in the experiment.

- 1) There will be two types of defects (Scratch and Speck). Their presence will vary base on the experimental treatments. In some experimental treatments only one type of defect might appear on an inspection unit, while in other treatments both type of defects might appear on the same inspection unit. You will be informed before each session which one of the two possible cases will you be dealing with during the experimental treatment. In the inspection task a ringing sound will alert you to the arrival of a unit to be inspected. You will click the “Start” button to indicate the beginning of the inspection. Six seconds will be allowed for the inspection. You will click the “Reject” button to reject a unit that exceeds the memorized quality criterion (learned and practiced in the training session) or the “Accept” button to accept a unit that does not exceed the criterion. Your decision will be right whenever you reject a rejectable unit or accept an acceptable one. Your decision will be erroneous whenever you accept a rejectable unit or reject an acceptable one.
- 2) An “Inventory” or a “Scheduling” message from the production scheduling and inventory control station will let you know when you need to conduct a scheduling task or an inventory control task (in addition to the quality inspection task). If the scheduling screen appears on the station monitor with a new order, you will compare its quantity and due date with the other orders already in the system, then you will schedule it based on a scheduling criterion. According to this criterion the new order should be scheduled to be processed before any order with a later due date. In the case of more than one order with the same due date, the one with the smallest quantity should be scheduled first. After making your decision, you should input the processing order in the screen and click the “OK” button. For the inventory control task, you will identify the specific part requested to be inventoried in the inventory control screen. Then you will count the number of parts in the bin and enter the quantity in the inventory control application screen. You will place an order for any part which is below the quantity required for production and click the

“OK” button. Return to the quality control station if there is no other task (machine setup or disturbance control) waiting for your intervention.

- 3) A “Machine Problem” or a “Machine Setup” message from the adjacent process station will let you know when you need to conduct a machine setup task or a machine disturbance control task (in addition to the quality inspection, production scheduling, and inventory control tasks). For the setup task you will enter the parameters of a particular product (from the setup card available at the station) requested in the setup screen of the adjacent process station. For the disturbance control task you will read the displayed error message in the adjacent process station’s screen and enter a particular alphanumeric code (from the disturbance control codes card available at the station) to restart the process. Return to the quality control station if there is no other task (production scheduling or inventory) waiting for your intervention.
- 4) You are required to complete every task. The production scheduling and inventory tasks have the same importance as the machine setup and disturbance control tasks.
- 5) After each experimental treatment you will be asked to fill out a questionnaire.
- 6) After filling out the questionnaire you will be paid.

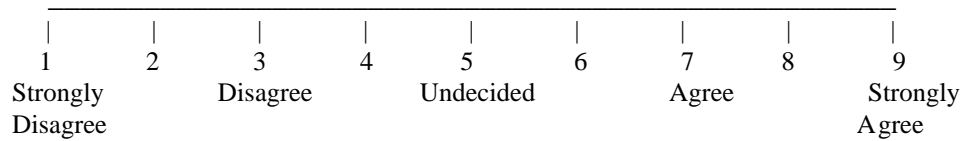
## APPENDIX H

### Likert-like Scale for Subjective Mental Workload

Please evaluate the experimental treatment you just completed by placing an (x) on the Likert-like scale provided for each statements. Place the (x) at the area that corresponds with your opinion of this statement. You may place your (x) between numbers.

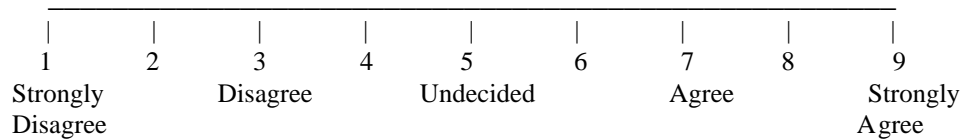
#### Example:

The sky is blue-green.

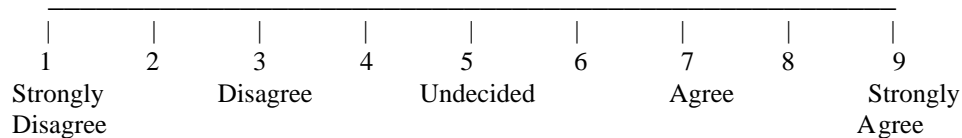


#### Mental Demand

1. The experimental treatment that I just completed was easy.

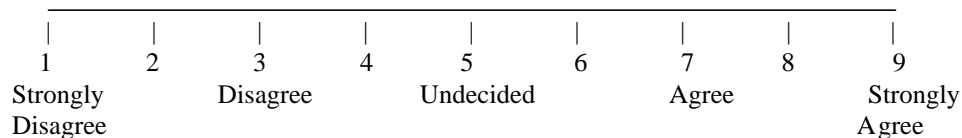


2. The experimental treatment that I just completed required too much thinking.



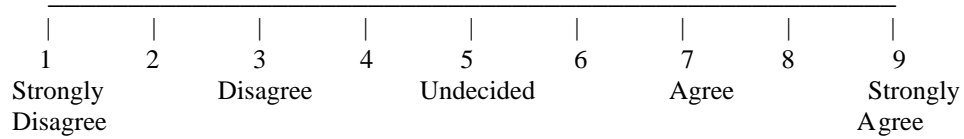
#### Physical Demand

3. The experimental treatment that I just completed required too much physical activity.



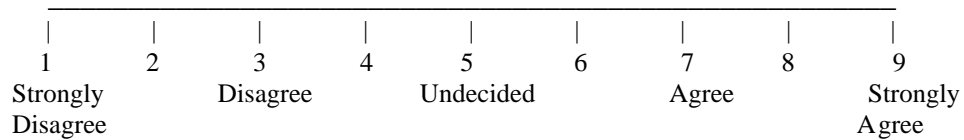
Physical Demand (cont.)

4. The experimental treatment that I just completed was not strenuous.

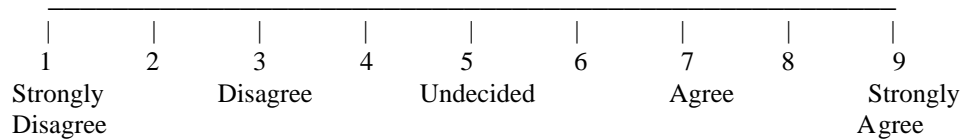


Temporal Demand

5. The experimental treatment that I just completed placed a significant amount of time pressure on me.

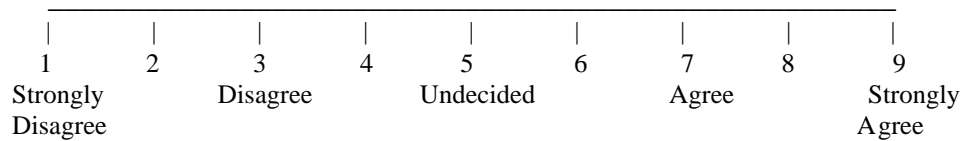


6. In the experimental treatment I just completed, the pace at which the tasks or task elements occurred was rapid and sometimes frantic.

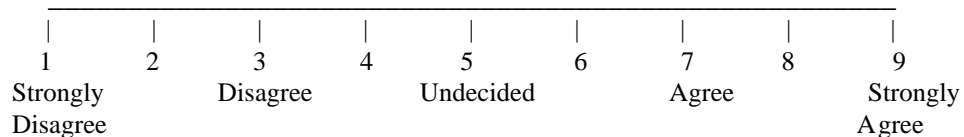


Performance

7. In the experimental treatment that I just completed, I think I was successful in accomplishing the goals set by the experimenter.

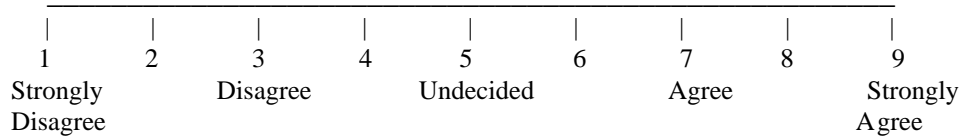


8. In the experimental treatment that I just completed, I am satisfied with my performance.

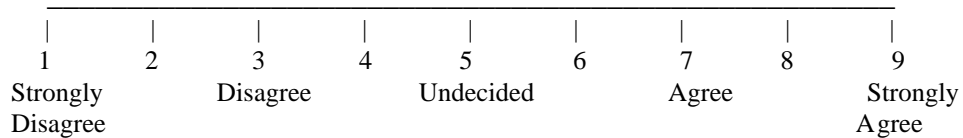


Effort

9. In the experimental treatment that I just completed, I was able to accomplish a satisfactory level of performance with minimum **mental** effort.

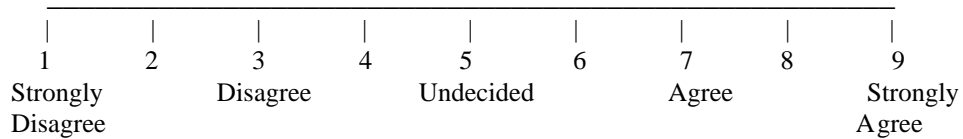


10. In the experimental treatment that I just completed, I was able to accomplish a satisfactory level of performance with a minimum **physical** effort.

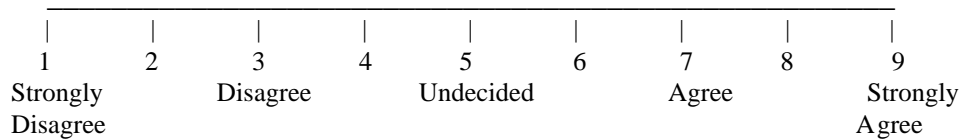


Frustration Level

11. While performing the experimental treatment that I just completed, I felt relaxed and complacent.



12. While performing the experimental treatment that I just completed, I felt insecure, discouraged, irritated, stressed, or annoyed.



Comments: \_\_\_\_\_  
\_\_\_\_\_  
\_\_\_\_\_  
\_\_\_\_\_  
\_\_\_\_\_

## Appendix I

### Computational Formulas

#### Variables definition

P\_Hit (H) = proportion of hits

P\_FA (FA) = proportion of false alarm

$z$  = standardized normal deviate associated with H or FA

N = noise

SN = signal-plus-noise

The ordinates for N and SN are calculated at  $z$

$p(N)$  = probability of noise

$p(SN)$  = probability of signal-plus-noise

#### Perceptual Sensitivity

$$d' = z_{FA} - z_H$$

#### Response Bias

$$\beta = \frac{\text{ordinate}(SN)}{\text{ordinate}(N)}$$

$$c = 0.5 (z_{FA} + z_H)$$

#### Ideal Beta

$$\beta_i = \frac{p(N)}{p(SN)}$$

## Experiment Data

Subj.	D_T	Tsk	P_Hit	P_FA	d'	$\beta$	c	Avg. Time (sec.)
1	1	1	0.5000	0.0117	2.2668	14.94	1.1334	1.67
1	1	3	0.4254	0.0017	2.7409	62.35	1.5585	1.12
1	1	5	0.6095	0.0083	2.6734	17.52	1.0587	1.11
1	2	1	0.6642	0.0017	3.3529	58.16	1.2525	1.39
1	2	3	0.5754	0.0017	3.1191	62.05	1.3694	1.36
1	2	5	0.5725	0.0017	3.1117	62.35	1.3731	1.26
2	1	1	0.6294	0.0050	2.9060	26.04	1.1227	1.70
2	1	3	0.9478	0.0183	3.7140	2.13	0.2331	1.09
2	1	5	0.8731	0.0083	3.5366	9.66	0.6271	1.11
2	2	1	0.9577	0.1128	2.9363	0.46	-0.2564	1.54
2	2	3	0.9328	0.0814	2.8926	0.90	-0.0506	1.82
2	2	5	0.8618	0.0717	2.5516	1.66	0.1874	1.72
3	1	1	0.8682	0.0548	2.7179	2.05	0.2410	1.07
3	1	3	0.8483	0.0483	2.6907	2.26	0.3161	1.18
3	1	5	0.9876	0.1578	3.2480	0.11	-0.6204	1.04
3	2	1	0.8725	0.0150	3.3083	4.37	0.5159	1.74
3	2	3	0.9876	0.1412	3.3194	0.12	-0.5847	1.33
3	2	5	0.9129	0.0714	2.8242	1.21	0.0533	1.48
4	1	1	0.5249	0.0050	2.6382	27.48	1.2566	0.90
4	1	3	0.6393	0.0017	3.2855	59.38	1.2862	1.17
4	1	5	0.7935	0.0083	3.2140	13.16	0.7884	1.07
4	2	1	0.8769	0.0450	2.8550	1.94	0.2678	2.02
4	2	3	0.8483	0.0050	3.6050	16.08	0.7733	1.34
4	2	5	0.7139	0.0050	3.1406	23.61	1.0055	1.36
5	1	1	0.7985	0.0116	3.1063	10.49	0.7169	0.83
5	1	3	0.6592	0.0017	3.3392	58.16	1.2593	0.84
5	1	5	0.9129	0.0615	2.9011	1.36	0.0917	1.09
5	2	1	0.7886	0.0050	3.3774	19.88	0.8871	1.19
5	2	3	0.8831	0.0150	3.3607	4.13	0.4897	1.01
5	2	5	0.8035	0.0017	3.7831	44.44	1.0374	0.91
6	1	1	0.8975	0.0150	3.4375	3.63	0.4513	1.51
6	1	3	0.8085	0.0183	2.9625	5.61	0.6089	1.19
6	1	5	0.7985	0.0017	3.7652	44.44	1.0463	1.23
6	2	1	0.6940	0.0017	3.4362	56.00	1.2108	1.26
6	2	3	0.8383	0.0017	3.9165	38.62	0.9707	1.14
6	2	5	0.6244	0.0017	3.2460	60.44	1.3059	1.43



Subj.	D T	Tsk	P_Hit	P_FA	d'	$\beta$	c	Avg_Time (sec.)
7	1	1	0.5398	0.0017	3.0289	63.00	1.4145	1.26
7	1	3	0.4900	0.0050	2.5507	27.50	1.3004	1.23
7	1	5	0.5452	0.0249	2.0752	8.18	0.9240	1.45
7	2	1	0.4502	0.0083	2.2702	18.07	1.2603	1.33
7	2	3	0.5746	0.1283	1.3225	1.86	0.4731	2.10
7	2	5	0.3209	0.0017	2.4638	56.76	1.6970	1.27
8	1	1	0.8333	0.0083	3.3627	11.56	0.7140	1.49
8	1	3	0.8075	0.0415	2.6022	3.15	0.4324	1.35
8	1	5	0.8930	0.0083	3.6380	8.58	0.5764	1.31
8	2	1	0.8930	0.0083	3.6380	8.58	0.5764	1.64
8	2	3	0.9425	0.0017	4.5051	18.90	0.6764	1.21
8	2	5	0.7289	0.0017	3.5384	52.48	1.1597	1.39
9	1	1	0.8333	0.0017	3.8962	40.17	0.9808	1.22
9	1	3	0.8085	0.0116	3.1425	10.16	0.6988	1.36
9	1	5	0.9179	0.0814	2.7868	1.00	0.0023	1.26
9	2	1	0.8184	0.1213	2.0777	1.31	0.1296	1.90
9	2	3	0.9726	0.0581	3.4913	0.57	-0.1747	1.31
9	2	5	0.9527	0.1213	2.8401	0.52	-0.2515	1.38
10	1	1	0.8284	0.0050	3.5236	17.46	0.8139	1.34
10	1	3	0.7587	0.0083	3.0975	14.20	0.8466	1.41
10	1	5	0.8417	0.0150	3.1715	5.03	0.5843	1.58
10	2	1	0.7075	0.0050	3.1219	23.61	1.0148	1.49
10	2	3	0.7312	0.0017	3.5454	52.48	1.1562	1.41
10	2	5	0.8085	0.0050	3.4482	18.72	0.8517	1.18
11	1	1	0.9876	0.0482	3.9070	0.26	-0.2909	1.61
11	1	3	0.9826	0.0748	3.5516	0.36	-0.3348	1.56
11	1	5	0.7935	0.0856	2.1869	1.77	0.2748	1.25
11	2	1	0.9527	0.0183	3.7618	2.13	0.2092	1.39
11	2	3	0.9475	0.0917	2.9514	0.63	-0.1453	1.54
11	2	5	0.9175	0.1717	2.3359	0.59	-0.2204	1.76
12	1	1	0.7985	0.0083	3.2317	12.79	0.7795	1.13
12	1	3	0.8582	0.0116	3.3423	8.34	0.5989	1.12
12	1	5	0.7040	0.0083	2.9313	15.88	0.9297	1.09
12	2	1	0.7338	0.0083	3.0197	15.10	0.8855	1.12
12	2	3	0.6759	0.0249	2.4179	7.39	0.7527	1.43
12	2	5	0.6095	0.0050	2.8538	26.46	1.1489	1.03

### Subjective Workload Questionnaire Scores

Subj.	D_T	Tsk	Mental Demand		Physical Demand		Temporal Demand	
			Item 1	Item 2	Item 3	Item 4	Item 5	Item 6
1	1	1	3.5	6.5	4.5	7.0	5.0	4.0
1	1	3	6.0	4.0	4.0	6.0	4.0	4.0
1	1	5	5.5	6.0	4.0	5.0	4.0	6.0
1	2	1	6.5	5.0	3.0	6.0	4.0	3.0
1	2	3	6.0	6.0	3.0	6.0	5.0	4.0
1	2	5	5.4	4.5	4.0	7.0	6.0	6.0
2	1	1	3.0	3.0	3.0	1.0	6.0	2.0
2	1	3	7.5	2.0	2.0	7.0	2.1	1.8
2	1	5	6.8	3.0	5.2	6.8	1.2	1.2
2	2	1	5.0	3.4	6.0	7.0	3.0	1.6
2	2	3	7.0	2.0	3.0	6.5	3.0	1.0
2	2	5	4.8	3.0	5.4	4.6	3.0	1.5
3	1	1	3.0	3.0	7.0	3.0	3.0	3.0
3	1	3	4.0	2.0	7.0	2.0	1.4	7.0
3	1	5	7.0	2.9	5.9	2.9	3.9	6.9
3	2	1	5.6	3.3	5.6	3.4	3.0	3.0
3	2	3	6.9	3.0	3.9	2.9	4.0	3.0
3	2	5	4.0	1.3	4.0	3.0	4.3	6.0
4	1	1	7.0	3.7	6.2	4.5	2.0	1.9
4	1	3	7.0	4.0	6.0	4.0	2.8	2.8
4	1	5	6.7	4.3	6.0	5.6	2.6	3.0
4	2	1	7.2	3.0	5.2	4.1	1.3	1.1
4	2	3	7.0	3.0	3.5	7.4	2.6	2.0
4	2	5	6.7	4.4	5.6	6.6	2.8	2.3
5	1	1	7.8	1.3	2.2	7.8	1.8	1.6
5	1	3	8.3	1.0	1.6	8.2	1.8	1.7
5	1	5	8.0	1.5	1.5	9.0	3.0	2.4
5	2	1	4.8	1.1	1.8	6.8	1.8	1.7
5	2	3	7.0	1.7	1.5	7.8	1.9	1.8
5	2	5	8.2	1.1	1.6	8.8	1.6	1.5
6	1	1	7.0	3.0	2.0	6.8	3.5	3.0
6	1	3	7.1	3.0	2.1	8.0	1.9	3.3
6	1	5	7.6	2.5	2.8	7.2	2.6	3.0
6	2	1	7.5	2.2	2.2	7.8	2.9	2.9
6	2	3	7.5	2.2	3.1	7.5	3.0	3.1
6	2	5	7.4	3.0	1.2	6.9	3.0	3.0
7	1	1	6.0	3.0	5.0	6.0	3.0	3.1
7	1	3	8.0	2.0	2.0	8.0	2.0	2.0
7	1	5	7.0	3.0	1.0	8.6	3.0	5.0
7	2	1	7.0	3.0	3.0	7.0	3.1	2.1
7	2	3	5.8	3.0	1.1	7.0	2.0	4.0
7	2	5	7.0	2.0	2.0	8.1	5.0	6.0

### Subjective Workload Questionnaire Scores

Subj.	D_T	Tsk	Mental Demand		Physical Demand		Temporal Demand	
			Item 1	Item 2	Item 3	Item 4	Item 5	Item 6
8	1	1	7.7	1.6	5.7	5.5	1.7	1.6
8	1	3	7.7	1.7	3.5	7.5	3.6	3.4
8	1	5	7.5	2.5	5.4	4.5	3.5	4.4
8	2	1	4.4	1.7	5.5	7.8	1.4	1.5
8	2	3	7.6	1.6	5.6	5.5	2.6	2.4
8	2	5	6.7	4.4	3.5	7.4	5.6	5.5
9	1	1	8.3	2.8	2.2	7.8	1.6	2.2
9	1	3	7.4	3.5	1.3	3.4	3.8	3.6
9	1	5	6.7	3.8	3.6	4.8	2.3	3.7
9	2	1	7.6	2.5	1.6	3.4	2.6	2.3
9	2	3	7.5	2.3	2.6	2.7	3.6	2.2
9	2	5	7.7	2.3	2.2	6.8	3.8	3.6
10	1	1	6.0	3.0	3.0	5.0	4.0	3.0
10	1	3	3.0	4.0	4.0	4.0	4.0	3.0
10	1	5	2.7	3.0	3.0	3.0	6.3	5.6
10	2	1	4.0	1.0	1.0	4.0	2.0	2.0
10	2	3	4.0	3.0	3.0	3.0	4.0	3.0
10	2	5	5.0	3.4	3.6	4.0	4.2	5.0
11	1	1	7.0	3.0	3.0	7.0	3.0	3.0
11	1	3	7.0	3.0	3.0	7.0	3.0	3.0
11	1	5	7.0	3.0	3.0	7.0	3.0	3.0
11	2	1	7.0	3.0	3.0	7.0	3.0	3.0
11	2	3	7.0	3.0	3.0	7.0	3.0	3.0
11	2	5	7.0	3.0	1.0	7.0	3.0	3.0
12	1	1	9.0	2.0	2.5	2.0	3.9	3.0
12	1	3	7.0	6.5	4.0	4.0	3.0	3.0
12	1	5	6.0	6.6	4.1	6.5	7.0	8.0
12	2	1	8.0	4.0	3.0	2.0	7.0	2.9
12	2	3	7.0	4.1	3.0	4.1	8.0	4.0
12	2	5	7.1	7.0	6.1	8.0	3.5	3.0

### Subjective Workload Questionnaire Scores

Subj.	D_T	Tsk	Performance		Effort		Frustration Level	
			Item 7	Item 8	Item 9	Item 10	Item 11	Item 12
1	1	1	3.0	3.0	3.0	6.9	4.0	5.0
1	1	3	7.0	8.0	6.0	7.0	7.0	3.4
1	1	5	7.0	4.5	4.5	5.4	4.0	5.0
1	2	1	7.0	6.0	4.0	7.0	6.0	5.5
1	2	3	7.0	7.0	6.0	7.0	7.0	5.0
1	2	5	5.0	5.0	4.0	6.0	4.0	6.0
2	1	1	5.0	3.0	4.0	7.0	3.0	6.5
2	1	3	8.0	8.0	7.0	6.0	7.0	2.3
2	1	5	8.0	8.0	7.0	7.0	7.0	3.0
2	2	1	3.0	2.0	3.0	7.0	4.0	5.0
2	2	3	8.0	7.0	6.5	6.5	7.0	3.0
2	2	5	7.0	7.0	5.5	6.0	7.0	4.0
3	1	1	7.0	8.9	4.0	3.0	7.0	3.0
3	1	3	7.0	7.0	2.9	3.8	7.2	1.0
3	1	5	7.0	8.8	4.0	3.0	7.0	3.0
3	2	1	6.8	7.4	5.5	4.5	8.0	1.7
3	2	3	7.0	9.0	7.0	4.0	4.0	5.3
3	2	5	7.0	7.0	5.6	4.2	6.0	2.0
4	1	1	6.6	6.4	7.2	5.5	7.0	2.2
4	1	3	7.6	8.0	6.0	7.9	7.0	1.9
4	1	5	6.2	6.5	4.4	5.4	7.0	2.0
4	2	1	7.6	7.2	8.0	8.5	8.0	2.0
4	2	3	7.0	6.8	7.2	6.1	6.6	1.4
4	2	5	7.0	7.0	5.6	5.6	6.8	2.0
5	1	1	7.8	7.0	7.8	8.2	7.1	3.2
5	1	3	8.8	8.9	8.6	8.5	8.3	1.3
5	1	5	8.0	7.0	9.0	7.0	7.0	1.6
5	2	1	8.0	7.0	8.6	8.0	7.0	1.3
5	2	3	7.7	8.0	8.0	7.6	7.9	1.6
5	2	5	9.0	8.8	8.2	8.4	9.0	1.7
6	1	1	7.0	6.2	6.8	8.0	7.0	3.0
6	1	3	7.3	6.8	6.9	7.0	6.8	3.1
6	1	5	7.5	6.8	7.2	7.2	7.2	1.8
6	2	1	8.0	6.8	7.0	7.2	7.1	2.1
6	2	3	7.7	7.1	7.0	6.8	7.5	2.7
6	2	5	8.0	7.0	6.5	7.4	6.6	3.4
7	1	1	8.0	8.0	8.0	8.0	7.0	2.0
7	1	3	8.0	8.0	8.0	8.1	7.1	2.0
7	1	5	8.0	7.0	7.0	8.0	7.0	3.0
7	2	1	8.0	8.0	6.0	8.0	7.0	2.0
7	2	3	7.0	6.0	7.0	8.0	5.0	2.0
7	2	5	8.0	8.0	7.9	7.9	8.0	2.0

### Subjective Workload Questionnaire Scores

Subj.	D_T	Tsk	Performance		Effort		Frustration Level	
			Item 7	Item 8	Item 9	Item 10	Item 11	Item 12
8	1	1	7.5	7.5	7.4	5.6	6.5	2.5
8	1	3	5.5	4.5	6.6	7.7	7.7	2.6
8	1	5	6.5	2.5	8.2	4.5	7.4	2.6
8	2	1	7.7	7.6	7.5	5.4	8.5	2.5
8	2	3	6.3	1.6	7.5	4.4	7.4	6.7
8	2	5	5.5	6.3	7.6	6.5	6.3	3.6
9	1	1	7.7	7.9	7.3	7.6	7.8	3.6
9	1	3	6.8	6.4	5.5	7.3	7.6	2.6
9	1	5	5.3	5.4	6.4	6.5	3.6	3.3
9	2	1	4.6	4.8	3.8	4.8	7.3	3.7
9	2	3	7.8	7.6	7.8	7.8	6.7	2.2
9	2	5	7.7	7.7	6.7	7.8	5.5	2.2
10	1	1	6.1	6.0	6.0	6.0	7.0	4.0
10	1	3	4.4	3.6	3.6	4.2	6.0	3.6
10	1	5	7.0	7.0	6.0	7.0	7.3	1.1
10	2	1	7.0	7.0	4.0	5.0	7.0	1.0
10	2	3	7.0	7.0	5.1	4.5	7.0	3.1
10	2	5	6.4	6.6	6.3	6.4	6.0	3.0
11	1	1	7.0	7.0	7.0	7.0	7.0	3.0
11	1	3	7.0	7.0	7.0	7.0	7.0	3.0
11	1	5	5.0	3.0	7.0	7.0	7.0	3.0
11	2	1	7.0	7.0	7.0	7.0	7.0	3.0
11	2	3	7.0	7.0	7.0	7.0	7.0	3.0
11	2	5	5.0	5.0	7.0	9.0	7.0	3.0
12	1	1	8.0	8.0	8.0	8.0	6.6	4.0
12	1	3	8.0	8.0	6.0	6.0	4.0	6.0
12	1	5	7.0	7.0	6.0	6.0	4.0	4.0
12	2	1	8.0	8.0	8.0	7.0	6.6	4.0
12	2	3	7.0	7.7	8.0	6.6	2.5	2.7
12	2	5	8.0	8.0	6.6	7.0	8.6	2.5

## **Appendix J**

### **Calculated DL for the Scratch and Specks Defects**

The DL, ogive curve, and least squared model of each subject was calculated for both Scratch (Line) and Speck (Black Speck) defects using the Constant stimuli method described on Appendix E. The stimuli intensity and the DL are expressed in terms of the Visual Basic unit of measure called *twip* (1/20 of a printer's point, or its relation to the monitor pixels).

### Subject 1

Line

Const\_A

Intensity

P(grtr)

Z-score

-3

0.639583

0.00495

-2.57925

-2

0.659722

0.014851

-2.17402

-1

0.679861

0.064356

-1.5192

0

0.7

0.183168

-0.90336

1

0.720139

0.470297

-0.07452

2

0.740278

0.787129

0.796498

3

0.760417

0.935644

1.519197

DL(1sd)=

0.038622

DL(.5sd)=

0.018257

PSE=

0.720198

Constant Stimuli - Difference Threshold

Proportion of "greater" Responses

1

0.9

0.8

0.7

0.6

0.5

0.4

0.3

0.2

0.1

0

Value of Comparison Stimulus

0.6396

0.6597

0.6799

0.700

0.7201

0.7403

0.7604

SUMMARY OUTPUT

Regression Statistics

Multiple R

0.995034

R Square

0.990092

Adjusted R Square

0.98811

Standard Error

0.166395

Observations

7

ANOVA

df

SS

MS

F

Significance F

Regression

1

13.83372

13.83372

499.6421

3.33E-06

Residual

5

0.138436

0.027687

Total

6

13.97216

Coefficients

Standard Error

t Stat

P-value

Lower 95%

Upper 95%

Lower 95.00%

Upper 95.000%

Intercept

-25.1366

1.094816

-22.9597

2.92E-06

-27.9509

-22.3223

-26.6044

13.35513402

X Variable

34.90238

1.561441

22.35268

3.33E-06

30.88857

38.91618

-19.5737

37.45704615

BLCK SPK

Const\_A

Intensity

P(grtr)

Z-score

-3

0.150694

0.00495

-2.57925

-2

0.160417

0.00495

-2.57925

-1

0.170139

0.014851

-2.17402

0

0.179861

0.044554

-1.70012

1

0.189583

0.430693

-0.17461

2

0.199306

0.866337

1.10924

3

0.209028

0.975248

1.964218

DL(1sd)=

0.01595

DL(.5sd)=

0.00754

PSE=

0.190229

Constant Stimuli - Difference Threshold

Proportion of "greater" Responses

1

0.9

0.8

0.7

0.6

0.5

0.4

0.3

0.2

0.1

0

Value of Comparison Stimulus

0.1507

0.1604

0.1701

0.1799

0.1896

0.1993

0.2090

SUMMARY OUTPUT

Regression Statistics

Multiple R

0.956418

R Square

0.914736

Adjusted R Square

0.897683

Standard Error

0.593647

Observations

7

ANOVA

df

SS

MS

F

Significance F

Regression

1

18.90405

18.90405

53.64115

0.000744

Residual

5

1.762085

0.352417

Total

6

20.66614

Coefficients

Standard Error

t Stat

P-value

Lower 95%

Upper 95%

Lower 95.00%

Upper 95.000%

Intercept

-16.0772

2.087586

-7.70133

0.000589

-21.4435

-10.7109

-25.3851

3.543113993

X Variable

84.51483

11.53942

7.324012

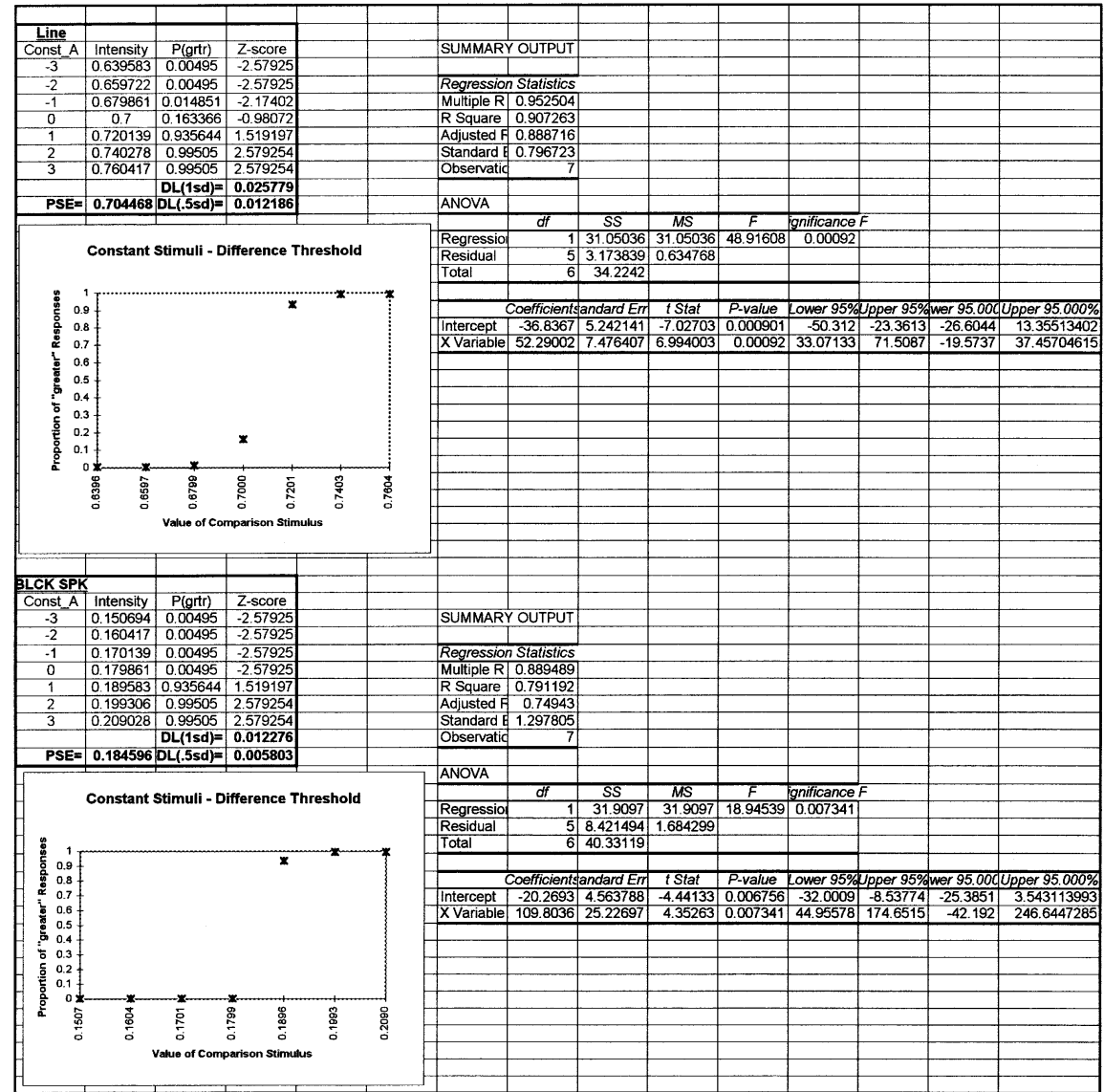
0.000744

54.85186

114.1778

-42.192

246.6447285





### Subject 3

Line			
Const	A	Intensity	P(grtr)
-3		0.639583	0.024752
-2		0.659722	0.00495
-1		0.679861	0.064356
0		0.7	0.193069
1		0.720139	0.430693
2		0.740278	0.648515
3		0.760417	0.816832
		<b>DL(1sd)=</b>	<b>0.047901</b>
		<b>DL(.5sd)=</b>	<b>0.022643</b>
<b>PSE= 0.729541</b>			

**Constant Stimuli - Difference Threshold**

df	SS	MS	F	Significance F
Regression	1	8.993127	8.993127	61.52276
Residual	5	0.730878	0.146176	0.000541
Total	6	9.724005		

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%	Lower 95.00%	Upper 95.00%
Intercept	-20.5301	2.515583	-8.16116	0.000449	-26.9966	-14.0636	-26.6044	13.35513402
X Variable	28.14109	3.587756	7.843645	0.000541	18.91848	37.36369	-19.5737	37.45704615

Const	A	Intensity	P(grtr)	Z-score
-3		0.150694	0.00495	-2.57925
-2		0.160417	0.00495	-2.57925
-1		0.170139	0.00495	-2.57925
0		0.179861	0.00495	-2.57925
1		0.189583	0.222772	-0.76286
2		0.199306	0.99505	2.579254
3		0.209028	0.99505	2.579254
		<b>DL(1sd)=</b>	<b>0.013291</b>	
		<b>DL(.5sd)=</b>	<b>0.006283</b>	
<b>PSE= 0.188202</b>				

**Constant Stimuli - Difference Threshold**

df	SS	MS	F	Significance F
Regression	1	27.22333	27.22333	16.46905
Residual	5	8.264998	1.653	0.009746
Total	6	35.48833		

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%	Lower 95.00%	Upper 95.00%
Intercept	-19.0875	4.521185	-4.2218	0.008313	-30.7096	-7.46547	-25.3851	3.543113993
X Variable	101.4206	24.99147	4.058207	0.009746	37.17805	165.6631	-42.192	246.6447285

### Subject 4

Line

Const

A

Intensity

P(grtr)

Z-score

-3

0.639583

0.014851

-2.17402

-2

0.659722

0.00495

-2.57925

-1

0.679861

0.014851

-2.17402

0

0.7

0.163366

-0.98072

1

0.720139

0.440594

-0.14946

2

0.740278

0.876238

1.156382

3

0.760417

0.955446

1.700118

DL(1sd)=

0.035994

PSE=

0.719839

DL(.5sd)=

0.017014

Constant Stimuli - Difference Threshold

Proportion of "greater" Responses

1

0.9

0.8

0.7

0.6

0.5

0.4

0.3

0.2

0.1

0

0.6396

0.6597

0.6799

0.700

0.7201

0.7403

0.7604

SUMMARY OUTPUT

Regression Statistics

Multiple R

0.955316

R Square

0.912628

Adjusted R Square

0.895154

Standard Error

0.552245

Observations

7

ANOVA

df

SS

MS

F

Significance F

Regression

1

15.92786

15.92786

52.2268

0.000791

Residual

5

1.524875

0.304975

Total

6

17.45274

Coefficients

Standard Error

t Stat

P-value

Lower 95%

Upper 95%

Lower 95.00%

Upper 95.000%

Intercept

-26.9587

3.633568

-7.41936

0.000701

-36.2991

-17.6184

-26.6044

13.35513402

X Variable

37.45107

5.18224

7.226811

0.000791

24.12972

50.77242

-19.5737

37.45704615

BLCK SPK

Const

A

Intensity

P(grtr)

Z-score

-3

0.150694

0.024752

-1.96422

-2

0.160417

0.00495

-2.57925

-1

0.170139

0.024752

-1.96422

0

0.179861

0.10396

-1.2593

1

0.189583

0.688119

0.490525

2

0.199306

0.99505

2.579254

3

0.209028

0.985149

2.17402

DL(1sd)=

0.01457

PSE=

0.183757

DL(.5sd)=

0.006887

Constant Stimuli - Difference Threshold

Proportion of "greater" Responses

1

0.9

0.8

0.7

0.6

0.5

0.4

0.3

0.2

0.1

0

0.1507

0.1604

0.1701

0.1799

0.1896

0.1993

0.2090

SUMMARY OUTPUT

Regression Statistics

Multiple R

0.921764

R Square

0.849649

Adjusted R Square

0.819579

Standard Error

0.895441

Observations

7

ANOVA

df

SS

MS

F

Significance F

Regression

1

22.65565

22.65565

28.25547

0.003152

Residual

5

4.009074

0.801815

Total

6

26.66473

Coefficients

Standard Error

t Stat

P-value

Lower 95%

Upper 95%

Lower 95.00%

Upper 95.000%

Intercept

-17.0015

3.148857

-5.39927

0.002944

-25.0959

-8.90714

-25.3851

3.543113993

X Variable

92.52173

17.40574

5.315588

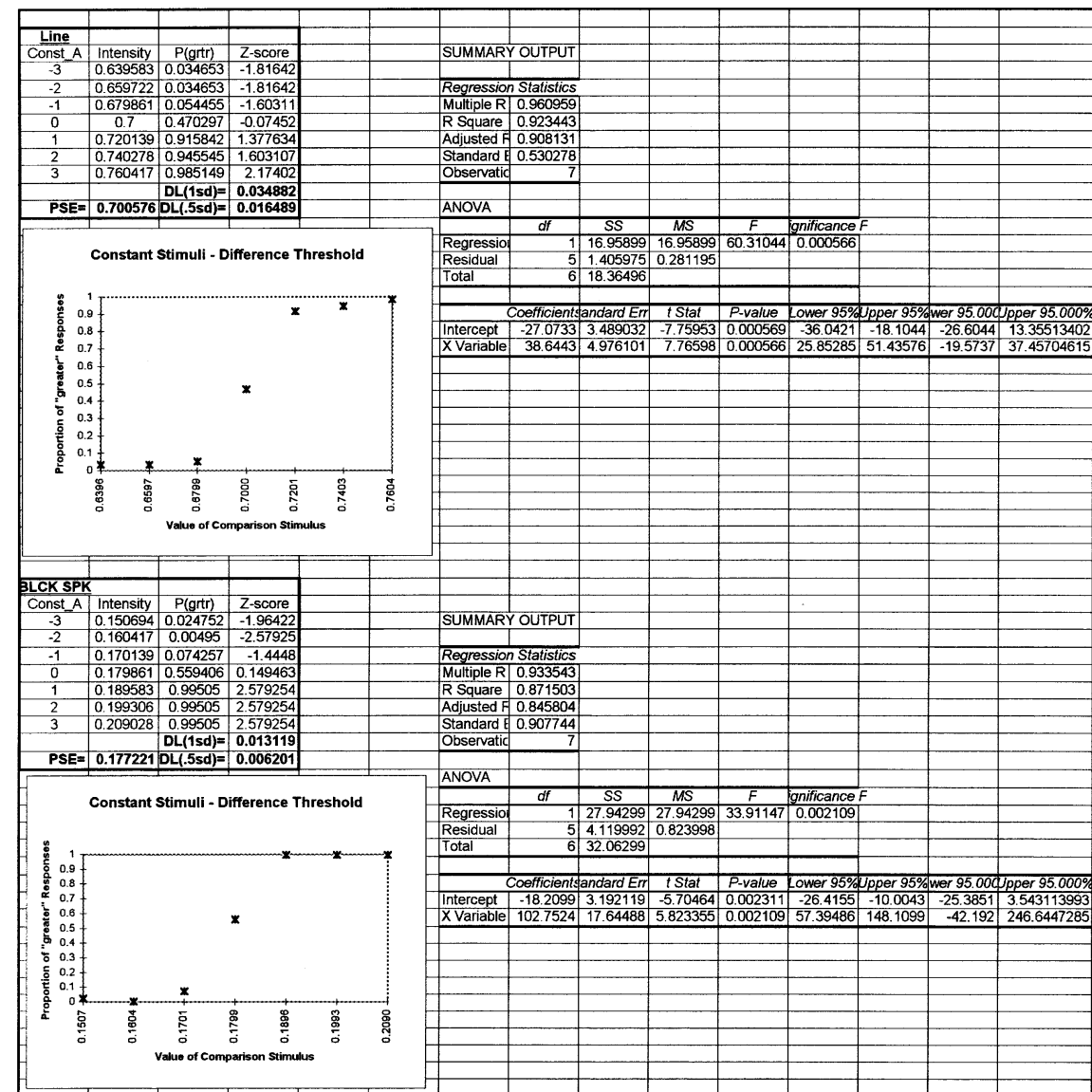
0.003152

47.77893

137.2645

-42.192

246.6447285



## Subject 6

Line

Const A

Intensity

P(grtr)

Z-score

-3

0.639583

0.00495

-2.57925

-2

0.659722

0.00495

-2.57925

-1

0.679861

0.00495

-2.57925

0

0.7

0.074257

-1.4448

1

0.720139

0.519802

0.049656

2

0.740278

0.876238

1.156382

3

0.760417

0.975248

1.964218

DL(1sd)=

0.032031

PSE=

0.720409

DL(.5sd)=

0.015141

Constant Stimuli - Difference Threshold

Proportion of "greater" Responses

1

0.9

0.8

0.7

0.6

0.5

0.4

0.3

0.2

0.1

0

0.6396

0.6597

0.6799

0.7000

0.7201

0.7403

0.7604

Value of Comparison Stimulus

SUMMARY OUTPUT

Regression Statistics

Multiple R

0.954422

R Square

0.910921

Adjusted R Square

0.893105

Standard Error

0.627179

Observations

7

ANOVA

df

SS

MS

F

Significance F

Regression

1

20.11219

20.11219

51.13001

0.000831

Residual

5

1.966769

0.393354

Total

6

22.07896

Coefficients

Standard Error

t Stat

P-value

Lower 95%

Upper 95%

Lower 95.00%

Upper 95.000%

Intercept

-30.3176

4.126606

-7.34685

0.000733

-40.9253

-19.7098

-26.6044

13.35513402

X Variable

42.08382

5.885417

7.150525

0.000831

26.9549

57.21274

-19.5737

37.45704615

BLCK SPK

Const A

Intensity

P(grtr)

Z-score

-3

0.150694

0.00495

-2.57925

-2

0.160417

0.00495

-2.57925

-1

0.170139

0.00495

-2.57925

0

0.179861

0.034653

-1.81642

1

0.189583

0.876238

1.156382

2

0.199306

0.965347

1.816416

3

0.209028

0.985149

2.17402

DL(1sd)=

0.013699

PSE=

0.18626

DL(.5sd)=

0.006476

Constant Stimuli - Difference Threshold

Proportion of "greater" Responses

1

0.9

0.8

0.7

0.6

0.5

0.4

0.3

0.2

0.1

0

0.1507

0.1604

0.1701

0.1799

0.1896

0.1993

0.2090

Value of Comparison Stimulus

SUMMARY OUTPUT

Regression Statistics

Multiple R

0.926629

R Square

0.858642

Adjusted R Square

0.83037

Standard Error

0.918567

Observations

7

ANOVA

df

SS

MS

F

Significance F

Regression

1

25.62616

25.62616

30.37116

0.002691

Residual

5

4.218831

0.843766

Total

6

29.84499

Coefficients

Standard Error

t Stat

P-value

Lower 95%

Upper 95%

Lower 95.00%

Upper 95.000%

Intercept

-18.328

3.230182

-5.674

0.002367

-26.6315

-10.0246

-25.3851

3.543113993

X Variable

98.40048

17.85527

5.511004

0.002691

52.50211

144.2988

-42.192

246.6447285

### Subject 7

Line	Intensity	P(grtr)	Z-score
Const A			
-3	0.639583	0.00495	-2.57925
-2	0.659722	0.014851	-2.17402
-1	0.679861	0.024752	-1.96422
0	0.7	0.252475	-0.66672
1	0.720139	0.579208	0.199868
2	0.740278	0.846535	1.021683
3	0.760417	0.905941	1.316166
DL(1sd)=		0.037552	
PSE=		0.719287	DL(.5sd)= 0.017751

**Constant Stimuli - Difference Threshold**

SUMMARY OUTPUT					
<i>Regression Statistics</i>					
Multiple R	0.983049				
R Square	0.966386				
Adjusted R	0.959663				
Standard E	0.319059				
Observat	7				
<i>ANOVA</i>					
	df	SS	MS	F	Significance F
Regression	1	14.63316	14.63316	143.7459	7.12E-05
Residual	5	0.508994	0.101799		
Total	6	15.14216			
<i>Coefficients</i>					
	Standard Err	t Stat	P-value	Lower 95%	Upper 95%
Intercept	-25.82	2.099291	-12.2994	6.29E-05	-31.2164
X Variable	35.8967	2.994035	11.98941	7.12E-05	28.2003

Line	Intensity	P(grtr)	Z-score
Const A			
-3	0.150694	0.00495	-2.57925
-2	0.160417	0.024752	-1.96422
-1	0.170139	0.00495	-2.57925
0	0.179861	0.10396	-1.2593
1	0.189583	0.549505	0.124411
2	0.199306	0.905941	1.316166
3	0.209028	0.985149	2.17402
DL(1sd)=		0.015599	
PSE=		0.187742	DL(.5sd)= 0.007374

**Constant Stimuli - Difference Threshold**

SUMMARY OUTPUT					
<i>Regression Statistics</i>					
Multiple R	0.94833				
R Square	0.899329				
Adjusted R	0.879195				
Standard E	0.665187				
Observat	7				
<i>ANOVA</i>					
	df	SS	MS	F	Significance F
Regression	1	19.76395	19.76395	44.6669	0.001134
Residual	5	2.212371	0.442474		
Total	6	21.97632			
<i>Coefficients</i>					
	Standard Err	t Stat	P-value	Lower 95%	Upper 95%
Intercept	-16.2239	2.339159	-6.93577	0.000956	-22.2369
X Variable	86.41563	12.93003	6.68333	0.001134	53.17799

Line	Intensity	P(grtr)	Z-score
Const A			
-3	0.639583	0.00495	-2.57925
-2	0.659722	0.00495	-2.57925
-1	0.679861	0.024752	-1.96422
0	0.7	0.232673	-0.73007
1	0.720139	0.648515	0.381315
2	0.740278	0.975248	1.964218
3	0.760417	0.99505	2.579254
PSE= 0.708766		DL(1sd)= 0.028249	
		DL(.5sd)= 0.013353	

Constant Stimuli - Difference Threshold

Line	Intensity	P(grtr)	Z-score
Const A			
-3	0.150694	0.014851	-2.17402
-2	0.160417	0.00495	-2.57925
-1	0.170139	0.00495	-2.57925
0	0.179861	0.00495	-2.57925
1	0.189583	0.99505	2.579254
2	0.199306	0.99505	2.579254
3	0.209028	0.99505	2.579254
PSE= 0.182704		DL(1sd)= 0.012341	
		DL(.5sd)= 0.005833	

Constant Stimuli - Difference Threshold

SUMMARY OUTPUT						
Regression Statistics						
Multiple R	0.97633					
R Square	0.95322					
Adjusted R	0.943864					
Standard Error	0.50379					
Observations	7					
ANOVA						
	df	SS	MS	F	Significance F	
Regression	1	25.85859	25.85859	101.8838	0.000163	
Residual	5	1.269024	0.253805			
Total	6	27.12761				
Coefficients						
	Standard Error	t Stat	P-value	Lower 95%	Upper 95%	
Intercept	-33.8213	3.314753	-10.2033	0.000155	-42.3422	-25.3005
X Variable	47.71862	4.727541	10.09375	0.000163	35.56611	59.87113

SUMMARY OUTPUT						
Regression Statistics						
Multiple R	0.847487					
R Square	0.718235					
Adjusted R	0.661881					
Standard Error	1.574054					
Observations	7					
ANOVA						
	df	SS	MS	F	Significance F	
Regression	1	31.57825	31.57825	12.74526	0.016043	
Residual	5	12.38824	2.477647			
Total	6	43.96648				
Coefficients						
	Standard Error	t Stat	P-value	Lower 95%	Upper 95%	
Intercept	-19.9571	5.535229	-3.60548	0.015454	-34.1859	-5.72841
X Variable	109.2319	30.59674	3.57005	0.016043	30.58059	187.8832

## Subject 9

Line	Intensity	P(grtr)	Z-score
Const A			
-3	0.639583	0.00495	-2.57925
-2	0.659722	0.00495	-2.57925
-1	0.679861	0.00495	-2.57925
0	0.7	0.054455	-1.60311
1	0.720139	0.262376	-0.63604
2	0.740278	0.579208	0.199868
3	0.760417	0.836634	0.980717
DL(1sd)=		0.041808	
PSE=		0.738974	
DL(.5sd)=		0.019763	

Constant Stimuli - Difference Threshold

Intensity	P(grtr)	Z-score
-3	0.639583	-2.57925
-2	0.659722	-2.57925
-1	0.679861	-2.57925
0	0.7	-1.60311
1	0.720139	-0.63604
2	0.740278	0.199868
3	0.760417	0.980717

df	SS	MS	F	Significance F	
Regression	1	11.8058	11.8058	54.93654	0.000704
Residual	5	1.074495	0.214899		
Total	6	12.8803			

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%	Lower 95.00%	Upper 95.00%
Intercept	-23.8266	3.05013	-7.81167	0.000551	-31.6672	-15.986	-26.6044	13.35513402
X Variable	32.24284	4.350133	7.411919	0.000704	21.06048	43.42519	-19.5737	37.45704615

Line	Intensity	P(grtr)	Z-score
Const A			
-3	0.150694	0.00495	-2.57925
-2	0.160417	0.00495	-2.57925
-1	0.170139	0.054455	-1.60311
0	0.179861	0.034653	-1.81642
1	0.189583	0.688119	0.490525
2	0.199306	0.806931	0.866642
3	0.209028	0.985149	2.17402
DL(1sd)=		0.015786	
PSE=		0.188304	
DL(.5sd)=		0.007462	

Constant Stimuli - Difference Threshold

Intensity	P(grtr)	Z-score
-3	0.150694	-2.57925
-2	0.160417	-2.57925
-1	0.170139	-1.60311
0	0.179861	-1.81642
1	0.189583	0.490525
2	0.199306	0.866642
3	0.209028	2.17402

df	SS	MS	F	Significance F	
Regression	1	19.29791	19.29791	49.33269	0.000903
Residual	5	1.955895	0.391179		
Total	6	21.2538			

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%	Lower 95.00%	Upper 95.00%
Intercept	-16.0794	2.199397	-7.31084	0.00075	-21.7332	-10.4257	-25.3851	3.543113993
X Variable	85.3907	12.15747	7.023723	0.000903	54.13898	116.6424	-42.192	246.6447285

Line

Const

A

Intensity

P(grtr)

Z-score

-3

0.63958

0.00495

-2.57925

-2

0.65972

0.00495

-2.57925

-1

0.67986

0.01485

-2.17402

0

0.7

0.30198

-0.51871

1

0.72014

0.70792

0.54732

2

0.74028

0.96535

1.81642

3

0.76042

0.98515

2.17402

DL(1sd)=

0.02949

PSE=

0.71036

DL(.5sd)=

0.01394

Constant Stimuli - Difference Threshold

Proportion of "greater" Responses

1

0.9

0.8

0.7

0.6

0.5

0.4

0.3

0.2

0.1

0

0.6396

0.6597

0.6798

0.7000

0.7201

0.7403

0.7604

BLCK SPK

Const

A

Intensity

P(grtr)

Z-score

-3

0.15069

0.00495

-2.57925

-2

0.16042

0.00495

-2.57925

-1

0.17014

0.00495

-2.57925

0

0.17986

0.08416

-1.37763

1

0.18958

0.87624

1.15638

2

0.19931

0.98515

2.17402

3

0.20903

0.99505

2.57925

DL(1sd)=

0.01278

PSE=

0.1842

DL(.5sd)=

0.00604

Constant Stimuli - Difference Threshold

Proportion of "greater" Responses

1

0.9

0.8

0.7

0.6

0.5

0.4

0.3

0.2

0.1

0

0.1507

0.1604

0.1701

0.1799

0.1896

0.1993

0.2090

SUMMARY OUTPUT

Regression Statistics

Multiple R

0.97299

R Square

0.94672

Adjusted R

0.93606

Standard Error

0.51675

Observations

7

ANOVA

df

SS

MS

F

Significance F

Regression

1

23.7222

23.7222

88.837

0.00023

Residual

5

1.33515

0.26703

Total

6

25.0574

Coefficients

Standard Error

t Stat

P-value

Lower 95%

Upper 95%

Lower 95.00%

Upper 95.00%

Intercept

-32.4668

3.40002

-9.549

0.00021

-41.2068

-23.7268

-26.6044

13.3551

X Variable

45.7049

4.84915

9.42534

0.00023

33.2398

58.1701

-19.5737

37.457

SUMMARY OUTPUT

Regression Statistics

Multiple R

0.94326

R Square

0.88975

Adjusted R

0.8677

Standard Error

0.85437

Observations

7

ANOVA

df

SS

MS

F

Significance F

Regression

1

29.4538

29.4538

40.3506

0.00143

Residual

5

3.64974

0.72995

Total

6

33.1036

Coefficients

Standard Error

t Stat

P-value

Lower 95%

Upper 95%

Lower 95.00%

Upper 95.00%

Intercept

-19.4322

3.00443

-6.46784

0.00132

-27.1553

-11.709

-25.3851

3.54311

X Variable

105.494

16.6074

6.35221

0.00143

62.803

148.184

-42.192

246.645





Line

Const. A

Intensity

P(grtr)

Z-score

-3

0.639583

0.00495

-2.57925

-2

0.659722

0.00495

-2.57925

-1

0.679861

0.00495

-2.57925

0

0.7

0.024752

-1.96422

1

0.720139

0.163366

-0.98072

2

0.740278

0.737624

0.636037

3

0.760417

0.945545

1.603107

PSE=

0.733056

DL(1sd)=

0.036942

DL(.5sd)=

0.017462

Constant Stimuli - Difference Threshold

Proportion of "greater" Responses

1

0.9

0.8

0.7

0.6

0.5

0.4

0.3

0.2

0.1

0

0.6396

0.6597

0.6799

0.7000

0.7201

0.7403

0.7604

BLCK SPK

Const. A

Intensity

P(grtr)

Z-score

-3

0.150694

0.00495

-2.57925

-2

0.160417

0.00495

-2.57925

-1

0.170139

0.00495

-2.57925

0

0.179861

0.00495

-2.57925

1

0.189583

0.222772

-0.76286

2

0.199306

0.925743

1.444796

3

0.209028

0.975248

1.964218

PSE=

0.192558

DL(1sd)=

0.015619

DL(.5sd)=

0.007383

Constant Stimuli - Difference Threshold

Proportion of "greater" Responses

1

0.9

0.8

0.7

0.6

0.5

0.4

0.3

0.2

0.1

0

0.1507

0.1604

0.1701

0.1799

0.1896

0.1993

0.2090

SUMMARY OUTPUT

*Regression Statistics*

Multiple R

0.927756

R Square

0.86073

Adjusted R

0.832877

Standard Error

0.699513

Observations

7

*ANOVA*

df

SS

MS

F

Significance F

Regression

1

15.12072

15.12072

30.90161

0.002591

Residual

5

2.446591

0.489318

Total

6

17.56731

*Coefficients*

Standard Error

t Stat

P-value

Lower 95%

Upper 95%

Lower 95.00%

Upper 95.000%

Intercept

-26.7491

4.602533

-5.81182

0.002128

-38.5803

-14.9179

-26.6044

13.35513402

X Variable

36.48982

6.56419

5.558922

0.002591

19.61606

53.36358

-19.5737

37.45704615

SUMMARY OUTPUT

*Regression Statistics*

Multiple R

0.892827

R Square

0.797141

Adjusted R

0.756569

Standard Error

1.001705

Observations

7

*ANOVA*

df

SS

MS

F

Significance F

Regression

1

19.71466

19.71466

19.64762

0.006812

Residual

5

5.017063

1.003413

Total

6

24.73173

*Coefficients*

Standard Error

t Stat

P-value

Lower 95%

Upper 95%

Lower 95.00%

Upper 95.000%

Intercept

-16.6193

3.522538

-4.71798

0.005252

-25.6742

-7.5643

-25.3851

3.543113993

X Variable

86.30782

19.47131

4.432563

0.006812

36.2553

136.3603

-42.192

246.6447285

## **VITA**

José A. Pesante Santana received a Ph.D. degree in Industrial and Systems Engineering from the Virginia Polytechnic Institute and State University, an M.S.I.E. degree from the Georgia Institute of Technology, and a B.S.I.E. degree from the University of Puerto Rico at Mayagüez. He has worked as a Manufacturing Development Engineer for Hewlett-Packard and as a Quality Engineer for Baxter Healthcare Corporation. His primary research interests are in the areas of statistical process control and human factors in manufacturing. He is an active member of Alpha Pi Mu, Institute of Industrial Engineering, and Human Factors and Ergonomic Society.