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# The Effects of Multitasking on Quality Inspection in Advanced Manufacturing Systems

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## Abstract

Although the industrial quality inspection task has been extensively studied, the effect of multitasking on the performance of the operator in a hybrid inspection system is still unknown. The experiment described in this article compared the quality inspection performance for participants performing a single task, 3 multiple tasks, and 5 multiple tasks. The results of this research indicate that the performance of the operator in the quality inspection task while multitasking in an advanced manufacturing system will be determined by the interaction between the number of different types of defects that can be presented at the same time in the inspected parts and multitasking. The best performance will be obtained when the load created by additional tasks minimizes the monotony of the quality inspection task without interfering with the processing resources needed for the memorized quality criteria.

## 1. Introduction

The development of numerically controlled machines, group technology, cellular manufacturing, and Just-In-Time production systems have revolutionized the way products are designed and manufactured. These technological and strategic advances 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 multifunctional work force of the high-tech or Advanced Manufacturing System (AMS). Dedicated quality inspectors have been replaced by operators who, in addition to the inspection task, perform many other duties such as job scheduling, inventory management, machine setup, and problem solving. The effects of performing other tasks on the accuracy and reliability of quality inspection have not been well addressed in the literature. The laboratory research described in this article examines both the advantages and disadvantages of having inspectors perform multiple work tasks while attempting to perform quality inspection.

## 2. Background

The notion that the quality inspection task performed by humans is prone to error has been widely accepted. Juran stated that human inspectors typically find about 80% of the defects (Juran & Gryna, 1980). Despite the contributions of human factors 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).

Quality inspection tasks have been characterized as having search and decision-making subtasks (Drury & Sinclair, 1983). It has been demonstrated 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 (Drury & Sinclair, 1983; Hou, Lin, & Drury, 1993). This computer-search/human-decision making system is known as a Hybrid Inspection System (HIS). The idea behind HIS is to capitalize on the speed and precision of machines to scan the inspection unit, and on the decision-making ability of humans. HIS has become a common element of AMS, specifically in high-precision processes such as surface mounted technology used in printed circuit boards assembly.

The human decision-making component of the visual inspection task has been extensively studied using the Signal Detection Theory (SDT) paradigm. This theory evaluates operator performance using two independent parameters: (a) the sensitivity or detectability index for a given signal ($d'$), and (b) the decision criterion or response bias ($\beta$ or $c$) (Green & Swets, 1966; Macmillan & Creelman, 1991; Swets, 1977). 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. Three significant findings often reported in these studies are: (a) $d'$ remains constant over time (Smith & Barany, 1970;Williges, 1969), (b) $\beta$ will shift over time as the observer performance changes (Drury & Addison, 1973; Smith & Barany, 1970;Williges, 1969), and (c) decision-making performance is affected by a payoff matrix, knowledge of results, and signal ratios (fraction of defective) (Fox & Halsegrave, 1969;Williges, 1971, 1973;Williges & North, 1972). More recently, it was reported that quality inspection tasks that impose a sustained load on working memory (to recall what the quality acceptability criterion looks like) will demand sustained mental processing resources (Parasuraman, 1979; Wickens, 1992). Such demand may fatigue the operator and otherwise affect performance in the quality inspection task.

Multitasking (often referred to as timesharing) has been extensively studied from a mental workload and human performance perspective. However, relatively few studies have been conducted in the manufacturing domain (Wickens, 1992). In general, a performance decrement is usually reported as the number of tasks increases. Different mental models have been used to explain the performance decrement in terms of multiple task competition for limited critical cognitive resources (Wickens, 1992). The role of human operators in AMS has been characterized as a supervisory control task (Bi & Salvendy, 1994; Sheridan, 1994). As described by Sheridan, "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" (Sheridan, 1994). 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." Production scheduling, inventory management, and problem solving have been among the supervisory control responsibilities commonly assigned to human operators in AMS (Ammons et al., 1988; Bi & Salvendy, 1994; Suri & Whitney, 1984).

## 3. Research Objectives

There are still a surprisingly large number of parts in AMS that can be inspected only 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 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. Specifically, this research attempted to measure the changes in human quality inspection performance due to the number of tasks being performed simultaneously (multitasking) and the different types of defects in the units being produced. As with a majority of the research described above, an SDT model is used to evaluate inspection performance.

## 4. Method

### 4.1. Participants

Twelve participants (9 male, 3 female) with no previous quality inspection task experience, 20/20 vision, and an acceptable proportion of correct responses ( $p[c] > 0.80$) in the Forced-Choice Procedure, as described by Gescheider (1985), were selected from among a pool of college students. The participants received individualized training and practice in the experimental rules and procedures, tasks and equipment, and the defect rejection criteria. The Method of Constant Stimuli, as described by Gescheider (1985), was used to determine each subject's Absolute Threshold (RL for the German *Reiz Limen*) and Difference Threshold (DL for the German *Differenz Limen*). The RL and DL were used to generate the defects' intensity consistent with the Just Noticeable Difference (JND) that each subject could detect.

### 4.2. Apparatus

A real-time, interactive simulation of an AMS cell was the scenario for the experimental tasks. It consisted of three main stations: (a) quality inspection station, (b) production scheduling and inventory control station, and (c) adjacent process station. Each station was represented by a personal computer. This representation is consistent with the human– machine interface in AMS. In addition to the stations, there was a working table with bins containing dummy parts. Two video cameras were used to record and transmit images of what was taking place in the laboratory-controlledAMS cell to the experimenter area (see Figure 1).

### 4.3. Experimental Design

A 2 × 3 within-subject factorial Balanced Latin Square design was used. Defect type and task were the independent variables used in the experiment as shown in Table 1.

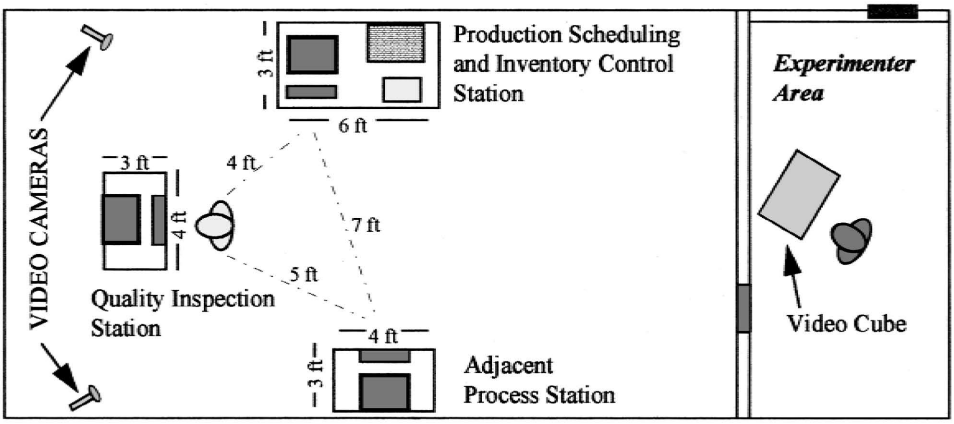

**Figure 1.** Laboratory layout for the experiment including the experimenter area and simulated AMS cell.

The two types of defects used were: (a) Speck = a small circular spot, and (b) Scratch = a narrow, shallow straight line. Only one of these defects was presented in the faulty units produced during a treatment when the defect type level was *single*. Both defects were presented in the faulty units produced during a treatment when the defect type level was *both*. The experimental unit was a square white plate (see Figure 2).

The task 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 task 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 task factor. At the *five* tasks level of the task factor, the operator concurrently conducted a machine setup task and a problem-solving task (machine disturbance control) in addition to the quality inspection, production scheduling, and inventory control tasks previously mentioned. The reason for using two levels of multitasking (three tasks and five tasks) was to increase the mental processing resources demand and to reduce the monotony of the job. The tasks were presented in a random order.

For 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 6 sec allowed), the operator clicked the "Re-

**Table 1.** Experimental Conditions

| Treatment | Defect Type | Tasks |
|---|---|---|
| 1 | Single | One Task |
| 2 | Both | Three Tasks |
| 3 | Single | Five Tasks |
| 4 | Both | One Task |
| 5 | Single | Three Tasks |
| 6 | Both | Five Tasks |

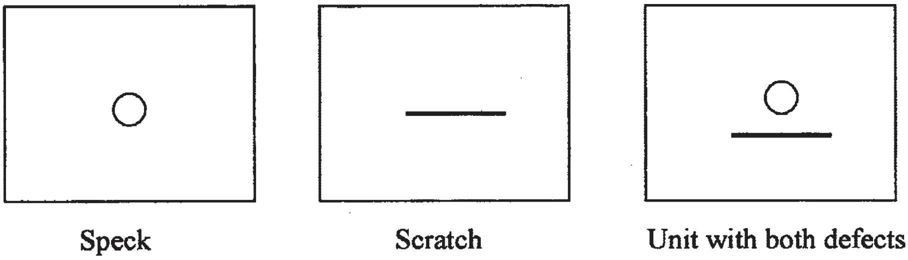

**Figure 2.** Experimental unit and defect types.

ject" 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. 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. 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 dummy parts in the bin and entered the quantity in the inventory control application of the production scheduling and inventories control station. 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.

For the machine setup and disturbance control tasks, 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. 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 an alphanumeric code (available at the station from a disturbance control codes card) to restart the process.

### *4.4. Procedure*

The experiment consisted of six experimental treatments as presented in Table 1. The average duration of each treatment ranged between 50 min and 120 min. 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 mm for the speck diameter and 26 mm for the scratch length. The 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 sec. The participants 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, participants conducted the other tasks at a performance level of at least 90.

The proportion of correct detection (rejection of unacceptable units, hit) and the proportion of incorrect detection (rejection of acceptable units, false alarm) were recorded for each experimental treatment. In addition, the SDT metrics of the inspector's sensitivity ($d'$) and the decision-making criterion or response bias ($c$) were calculated using the observed hit and false alarm rates. The measure of response bias $c$ was used instead of the more traditional measure $\beta$ because it has been shown to be independent of the inspector's sensitivity ($d'$) (Gescheider, 1985).

## 5. Results

The analysis of variance (ANOVA) of the dependent variable hit is presented in Table 2. Based on the unadjusted $F$ ($p = 0.0251$) the effect of the interaction between Defect Type and Tasks was statistically significant.

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. 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 participants conducted five tasks and both defects were present in the inspected parts, the hit rate was lower than when five tasks were performed but only one type of defect was present in the inspected parts. The effect of the interaction between Defect Type and Tasks is shown in Figure 3.

The ANOVA of the dependent variable false alarm indicated that for the $p$-values of the unadjusted $F$ there were no statistically significant effects ($\alpha = 0.05$). Similarly,

**Table 2.** ANOVA Summary Table for the Dependent Measure Proportion of Hit

| Source | *df* | *SS* | *MS* | *F* | *p* value |
|---|---|---|---|---|---|
| *Between Subjects* | | | | | |
| Subject (S) | 11 | 1.225 | 0.111 | | |
| *Within Subjects* | | | | | |
| Defect Type (DT) | 1 | 0.002 | 0.003 | 0.19 | 0.668 |
| DT × S | 11 | 0.127 | 0.012 | | |
| Tasks (Tsk) | 2 | 0.006 | 0.003 | 0.55 | 0.583 |
| Tsk × S | 22 | 0.123 | 0.006 | | |
| DT × Tsk | 2 | 0.065 | 0.032 | 4.38 | 0.025* |
| DT × Tsk × S | 22 | 0.164 | 0.007 | | |
| Total | 71 | 1.712 | | | |

* Statistically significant at $\alpha = 0.05$.

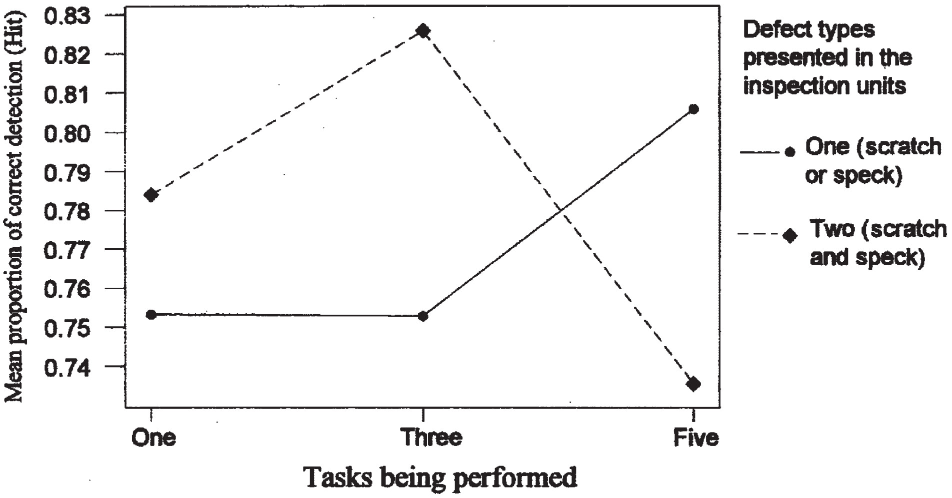

**Figure 3.** Mean plot of the interaction of defect type and task on the dependent measure hit.

the participants' perceptual sensitivity (mean $d' = 3.096$) remained constant throughout the experiment ($\alpha = 0.05$).

The ANOVA of the dependent variable *c* is presented in Table 3. Based on the unadjusted *F* ($p = 0.0448$) the effect of the interaction between Defect Type and Tasks was statistically significant.

Based on 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. The criterion or response bias when both defects were present in the inspected parts and the subject conducted one or

**Table 3.** ANOVA Summary Table for the Dependent Measure *c*

| Source | *df* | *SS* | *MS* | *F* | *p* value |
|---|---|---|---|---|---|
| *Between Subjects* | | | | | |
| Subjects (S) | 11 | 13.212 | 1.201 | | |
| *Within Subject* | | | | | |
| Defect Type (DT) | 1 | 0.028 | 0.028 | 0.14 | 0.718 |
| DT × S | 11 | 2.217 | 0.202 | | |
| Tasks (Tsk) | 2 | 0.163 | 0.081 | 0.88 | 0.429 |
| Tsk × S | 22 | 2.031 | 0.092 | | |
| DT × Tsk | 2 | 0.843 | 0.422 | 3.59 | 0.045* |
| DT × Tsk × S | 22 | 2.584 | 0.118 | | |
| Total | 71 | 21.078 | | | |

* Statistically significant at $\alpha = 0.05$.

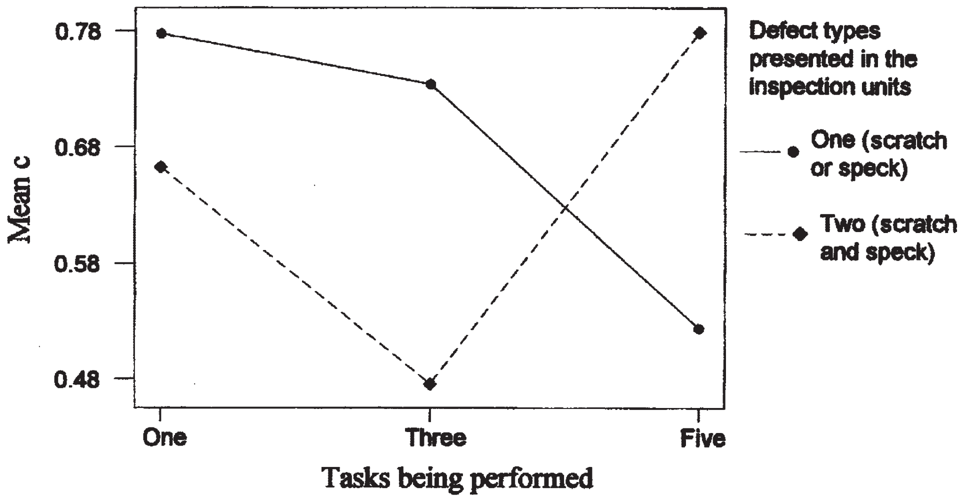

**Figure 4.** Mean plot of the interaction of defect type and task on the dependent measure *c*.

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 participants 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 effect of the interaction between Defect Type and Tasks is shown in Figure 4. 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 participants.

## 6. 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. Mental 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. It was initially hypothesized 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 ($d'$ and $c$) as a function of Defect Type failed to support this hypothesis. This finding is consistent with those reported by Craig and Colquhoun (1975) 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 participants' 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 participants.

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. Participants 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 questionnaires or directly to the experimenter, "it helps to break the monotony of the quality inspection." Participants 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."

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 (hit = 0.776), although consistent with what has been reported for 100% industrial quality inspection (Juran & Gryna, 1980; Konz, Peterson, & Joshi, 1981), may not be acceptable for a world-class manufacturing organization.

Multitasking was also expected to substantially affect the operator's decision-making component of the quality inspection task in AMS. The nonsignificant differences obtained on hit, false alarm, and the SDT metrics ($d'$ and $c$) as a function of the task manipulation 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 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.

An interaction effect between the number of different types of defects in the units being inspected and multitasking was demonstrated in 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, Curry, & Faustina, 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 hit = 0.784 to hit = 0.826). The significant decrease in response bias (from $c$ = 0.663 to $c$ = 0.476) observed for this case suggests that as the number of tasks increased from one to three, the participants 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 hit = 0.826 to 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 participants 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 of the average proportion of correct detection (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 hit = 0.753 to 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 suggests that as the number of tasks increased from three to five, the participants 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 (hit = 0.806) while the lowest average proportion of correct detection overall (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 ($c_N$ 5 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 mental 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.

## 7. Conclusions

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 participants might be considered as an external validity limitation of this research. Given the strict payoff adopted by the participants 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 participants 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 that depends on a memorized criterion will create a mental load that 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 mental 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 & Gryna, 1980; Konz et al., 1981), there is room for improvement.

## 8. Future Research

Given the limitations of the current study, 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 decisionmaking performance in complex monitoring tasks. 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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