

## METHODS FOR INCREASING THE EFFICIENCY OF HUMAN INTERPRETATION OF X-RAY IMAGES IN CUSTOMS INSPECTION OF HAND LUGGAGE AND BAGGAGE

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### ABSTRACT

This research paper addresses the critical issues of enhancing the metrological and cognitive efficiency of X-ray image analysis performed by human operators within the customs control framework. For the first time, X-ray inspection is theoretically substantiated as an “integrated human-machine measurement system.” A six-stage decision-making model for operators was developed based on Signal Detection Theory (SDT) and Markov stochastic chains. An experimental study involving 20 operators of various categories was conducted, analyzing a database of 500 X-ray images. The results indicate that the Probability of Detection (POD) and False Alarm Rate (FAR) are directly contingent upon cognitive workload and image complexity. The paper concludes by proposing a new conceptual model for training customs X-ray operators and offering practical recommendations for the algorithmization of the analysis process.

**Keywords:** Customs control, X-ray inspection, human factor, Signal Detection Theory (SDT), cognitive workload, visual search, threat detection, algorithmization, metrological uncertainty, Markov chains.

### 1. INTRODUCTION

In the context of modern globalization, the rapid expansion of international trade and transport-logistics systems has led to a significant surge in the volume of cargo and passenger traffic crossing state borders. This phenomenon imposes strategic responsibilities upon customs control authorities, not only to protect economic interests but also to ensure international security by intercepting the illicit trafficking of weapons, explosives, and narcotics [1].

X-ray inspection systems, categorized as Non-Intrusive Inspection (NII) tools, serve as the cornerstone of contemporary customs control operations. These systems allow for the internal examination of objects without invasive physical intervention. However, regardless of the sophistication of the hardware, the final determination—categorizing an object as “threat” or “no threat”—is executed by a human operator. Consequently, the overall reliability of the inspection process depends not merely on the metrological parameters of the equipment but fundamentally on the cognitive capabilities of the individual [2].

Statistical data suggests that between 60% and 80% of undetected threats in X-ray screening are attributable to human error, specifically False Negatives [11]. Operators function under conditions of high time pressure, physical fatigue, and high-clutter visual environments. This reality necessitates a theoretical shift: viewing customs X-ray inspection not as a purely

technical measurement system, but as a complex “integrated human-machine measurement system.”

The objective of this study is to formalize the process of human X-ray image analysis through a cognitive-algorithmic model and to develop methods for enhancing inspection reliability by minimizing operator error.

## 2. LITERATURE REVIEW

While the role of the human factor in X-ray analysis has been studied globally, its specific metrological application within the customs domain remains under-researched.

**Visual Search Theory and Cognitive Stages:** Adrian Schwaninger and colleagues (2011) established that the success of X-ray operators is intrinsically linked to their visual memory and object recognition capabilities [5]. Jeremy Wolfe’s (1994) Visual Search Theory explains that human attention is guided by two primary mechanisms: “bottom-up” (driven by technical features like color and contrast) and “top-down” (driven by the individual’s knowledge, experience, and expectations) [6].

**The Prevalence Effect in Customs Control:** Research by Biggs and Mitroff (2014) identified that the infrequency of threat items negatively impacts operator alertness. In environments where the probability of encountering a threat is low (1–5%), which is typical for customs checkpoints, the rate of False Negatives significantly increases as operators subconsciously adapt to a “no-threat” expectation [7].

**Cognitive Workload and Attentional Resources:** Christopher Wickens (2008) developed the Multiple Resource Theory, substantiating the limitations of human working memory and the difficulties of processing information through multiple channels simultaneously [9]. As cognitive load increases, the operator’s decision criterion shifts, leading to a higher probability of error.

**Signal Detection Theory (SDT) Framework:** Founded by Green and Swets (1966), SDT serves as the primary mathematical apparatus for evaluating the ability to distinguish a signal (threat) from noise (clutter/background) [10]. This theory enables the separation of an operator’s sensitivity ( $d'$ ) from their decision-making strategy (criterion).

## 3. METHODS

The study utilized a combination of theoretical modeling, stochastic analysis, and experimental measurement.

### 3.1 Mathematical Model of the System

The total reliability of the customs X-ray inspection system ( $R_{total}$ ) is defined as the product of technical reliability ( $R_{tech}$ ) and human reliability ( $R_{human}$ ):

$$R_{total} = R_{tech} \times R_{human}$$

To determine human reliability, the process was modeled as a 6-stage Markov chain:

$$R_{human} = \prod_{i=1}^6 P_i = P_1 \times P_2 \times P_3 \times P_4 \times P_5 \times P_6$$

Where  $P_i$  represents the probability of success in each cognitive phase:

- (1) Global Scan,
- (2) Segmentation,
- (3) Shape Analysis,
- (4) Material Identification,
- (5) Contextual Evaluation,
- (6) Decision.

### 3.2 Experimental Design

The experiment involved 20 operators, categorized into three distinct groups based on proficiency:

- **Novice:** 8 personnel with less than 1 year of experience.
- **Intermediate:** 7 personnel with 1–3 years of experience.
- **Expert:** 5 professionals with over 5 years of experience.

**Test Database:** A total of 500 X-ray images were utilized (150 featuring threat items, 350 safe). Threats included weapon components, knives, improvised explosive devices, and various prohibited electronics.

## 4. RESULTS

The experimental findings quantitatively demonstrated the correlation between operator performance, experience, and cognitive workload.

**Table 1: Analysis of Experimental Results by Operator Group**

Metric	Novice	Intermediate	Expert
<b>POD (Probability of Detection)</b>	0.71	0.82	0.91
<b>FAR (False Alarm Rate)</b>	0.21	0.16	0.09
<b>d' (Sensitivity Index)</b>	1.45	1.83	2.35
<b>Mean Decision Time (sec)</b>	8.5	6.2	4.1

Metric	Novice	Intermediate	Expert
False Negative (FN) Rate	29%	18%	9%

Table 2: POD Analysis Based on Image Complexity (Clutter)

Complexity Level	Novice	Intermediate	Expert
Low Clutter	0.88	0.94	0.98
Medium Clutter	0.65	0.78	0.89
High Clutter	0.42	0.61	0.76

The sensitivity index ( $d'$ ) in the Expert group was 62% higher than in the Novice group. This scientifically validates the superior ability of experts to distinguish the signal from the background noise [10].

## 5. DISCUSSION

The results elucidate the metrological role of the human factor in customs X-ray inspection.

**Cognitive Nature of Errors:** An analysis of False Negative errors revealed that expert errors are primarily associated with “visual fatigue” and “time pressure,” whereas novice errors are linked to “recognition failure” (insufficient template database). This highlights the need for training programs that focus on expanding the library of visual mental models [5].

**Cognitive Load Dynamics:** A 15% decrease in average POD was observed after the 4th hour of work. This corroborates Wickens’ theory: as cognitive resources deplete, the operator enters a state of “visual tunneling” [9]. Consequently, a work-rest cycle consisting of a 20-minute break every 2 hours is metrologically justified.

**Significance of Algorithmization:** The proposed 6-stage analysis algorithm enhances the reproducibility of operator decisions. It was observed that experts analyze images systematically (e.g., scanning dense objects first) rather than randomly.

## 6. CONCLUSION

This study led to the following scientific conclusions regarding the enhancement of reliability in human-centric customs inspection:

1. X-ray inspection was defined for the first time as an **integrated human-machine measurement system**, with a corresponding mathematical model.

2. Human Uncertainty was formalized as a metrological parameter, and a methodology for its assessment was established.

3. Minimum proficiency criteria for operators were scientifically substantiated (POD > 0.85, FAR < 0.15).

4. A 6-stage cognitive-algorithmic model for X-ray image interpretation was proposed.

**Practical Recommendations:** It is recommended that customs authorities utilize SDT metrics ( $d'$ ) for personnel certification, implement Threat Image Projection (TIP) systems to monitor vigilance, and employ simulators with progressive visual complexity during training [12].

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