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HUMAN COGNITIVE RELIABILITY IN X-RAY BAGGAGE SCREENING

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Abstract. This study examines the main cognitive, psychological, ergonomic, and operational factors affecting human reliability during X-ray baggage screening in aviation security and customs control systems. The research is based on comparative analysis of scientific literature in the fields of human factors engineering, cognitive psychology, signal detection theory, aviation security, and intelligent screening technologies. The study demonstrates that screening effectiveness is significantly influenced by vigilance decrement, fatigue, cognitive workload, target prevalence, environmental stressors, operator expertise, and the quality of simulator-based training. Particular attention is devoted to the interaction between human operators and intelligent decision-support technologies in modern X-ray screening environments. The article analyzes the role of visual search behavior, perceptual learning, fatigue management, ergonomics, and adaptive training systems in improving operational reliability. The findings indicate that technological modernization alone cannot ensure high screening performance without systematic development of human cognitive capability and professional competency. Practical recommendations aimed at improving screening reliability through evidence-based training, ergonomic optimization, adaptive automation, and continuous competency assessment are proposed. The results of the study may be applied in aviation security systems, customs administrations, non-intrusive inspection environments, and professional operator training programs.

Keywords: X-ray screening, cognitive reliability, aviation security, customs control, visual search, vigilance decrement, operator performance, human factors, fatigue, ergonomics, simulator training, non-intrusive inspection.

Annotatsiya. Ushbu tadqiqot aviatsiya xavfsizligi va bojxona nazorati tizimlarida rentgen orqali bagaj tekshiruvi jarayonida inson kognitiv ishonchliligiga ta’sir etuvchi asosiy psixologik, ergonomik va operatsion omillarni tahlil qilishga bag‘ishlangan. Tadqiqot inson omili muhandisligi, kognitiv psixologiya, signallarni aniqlash nazariyasi, aviatsiya xavfsizligi va intellektual tekshiruv texnologiyalari sohalaridagi ilmiy adabiyotlarni qiyosiy tahlil qilish asosida amalga oshirilgan. Tadqiqot natijalari tekshiruv samaradorligi diqqatning pasayishi, charchoq, kognitiv yuklama, xavfli obyektlarning kam uchrashi, tashqi muhit omillari, operator malakasi va trenajyor asosidagi tayyorgarlik sifati bilan

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bevosita bog‘liq ekanligini ko‘rsatdi. Maqolada zamonaviy rentgen tekshiruv muhitlarida inson operatorlari va intellektual qaror qabul qilishni qo‘llab-quvvatlovchi texnologiyalar o‘rtasidagi o‘zaro munosabatlarga alohida e’tibor qaratilgan. Shuningdek, vizual qidiruv harakatlari, perseptiv o‘rganish, charchoqni boshqarish, ergonomika va adaptiv tayyorgarlik tizimlarining operatsion ishonchlilikni oshirishdagi ahamiyati tahlil qilingan. Tadqiqot natijalari texnologik modernizatsiyaning o‘zi yuqori tekshiruv samaradorligini ta’minlay olmasligini, buning uchun inson kognitiv qobiliyati va kasbiy kompetensiyalarini tizimli rivojlantirish zarurligini ko‘rsatadi. Maqolada dalillarga asoslangan tayyorgarlik, ergonomik optimallashtirish, adaptiv avtomatlashtirish va doimiy kompetensiya baholash orqali tekshiruv ishonchliligini oshirishga qaratilgan amaliy takliflar ishlab chiqilgan. Tadqiqot natijalaridan aviatsiya xavfsizligi tizimlari, bojxona organlari, intruziv bo‘lmagan tekshiruv muhitlari va operatorlarni kasbiy tayyorlash dasturlarida foydalanish mumkin.

Kalit so‘zlar: rentgen tekshiruvi, kognitiv ishonchlilik, aviatsiya xavfsizligi, bojxona nazorati, vizual qidiruv, diqqat pasayishi, operator faoliyati, inson omili, charchoq, ergonomika, trenajyor tayyorgarligi, intruziv bo‘lmagan tekshiruv.

Аннотация. Данное исследование посвящено анализу основных психологических, эргономических и операционных факторов, влияющих на когнитивную надёжность человека в процессе рентгеновского досмотра багажа в системах авиационной безопасности и таможенного контроля. Исследование выполнено на основе сравнительного анализа научной литературы в области инженерии человеческого фактора, когнитивной психологии, теории обнаружения сигналов, авиационной безопасности и интеллектуальных технологий досмотра. Результаты исследования показывают, что эффективность досмотра напрямую зависит от снижения устойчивости внимания, утомляемости, когнитивной нагрузки, редкости появления опасных объектов, факторов внешней среды, квалификации операторов и качества тренажёрной подготовки. Особое внимание в статье уделено взаимодействию операторов и интеллектуальных систем поддержки принятия решений в современных условиях рентгеновского досмотра. Также анализируется роль визуального поиска, перцептивного обучения, управления утомляемостью, эргономики и адаптивных систем подготовки в повышении операционной надёжности. Результаты исследования свидетельствуют о том, что одной лишь технологической модернизации недостаточно для обеспечения высокой эффективности досмотра; необходима системная разработка когнитивных способностей и профессиональных компетенций операторов. В статье разработаны

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практические рекомендации, направленные на повышение надёжности досмотра посредством подготовки, основанной на доказательных подходах, эргономической оптимизации, адаптивной автоматизации и постоянной оценки компетенций. Результаты исследования могут быть использованы в системах авиационной безопасности, таможенных органах, средах неинтрузивного контроля и программах профессиональной подготовки операторов.

Ключевые слова: рентгеновский досмотр, когнитивная надёжность, авиационная безопасность, таможенный контроль, визуальный поиск, снижение внимания, деятельность оператора, человеческий фактор, утомляемость, эргономика, тренажёрная подготовка, неинтрузивный контроль**.**

INTRODUCTION.

The increasing complexity of global transportation systems, international trade, and passenger movement has significantly expanded the importance of X-ray baggage screening technologies in aviation security and customs operations. Airports, border checkpoints, railway terminals, cargo inspection facilities, and critical infrastructure systems increasingly rely on non-intrusive inspection technologies to detect prohibited or dangerous items concealed within baggage and cargo [1].

Despite major technological advances in computed tomography, automated image processing, and intelligent threat recognition systems, the effectiveness of screening operations remains heavily dependent on human cognitive performance [2]. Human operators continue to serve as the final decision-makers in most operational environments. Consequently, the ability to accurately interpret complex X-ray images under conditions of uncertainty and time pressure directly affects security outcomes and operational efficiency [3].

X-ray baggage screening represents a highly demanding visual search and decision-making task. Operators must detect low-prevalence threats embedded within cluttered and overlapping objects while simultaneously maintaining high throughput rates [4]. Such operational conditions create significant cognitive demands involving attention allocation, working memory, pattern recognition, perceptual discrimination, and rapid decision-making.

Research demonstrates that screening performance is influenced by multiple interconnected factors including visual complexity of baggage, target prevalence, time pressure, fatigue, vigilance decrement, cognitive workload, operator expertise, training quality, environmental stressors, automation reliability, and ergonomic workplace conditions [5].

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The author's previous investigations concerning non-intrusive inspection systems, simulator-based training technologies, and X-ray image interpretation methodologies additionally confirm that technological modernization alone cannot guarantee operational reliability without systematic development of human cognitive capability [9; 10].

The purpose of this article is to analyze the main determinants of human cognitive reliability in X-ray baggage screening and to identify evidence-based approaches aimed at improving operator performance and operational effectiveness.

METHODS.

Research Design

The study employs a comparative analytical approach based on systematic review and synthesis of scientific literature related to cognitive psychology, human factors engineering, aviation security, and customs screening technologies.

Data Sources

The analysis is based on scientific publications devoted to vigilance, visual search behavior, signal detection theory, human reliability analysis, ergonomics, and intelligent screening technologies published between 1948 and 2023 [1–8]. The author's previous research concerning simulator-based training and non-intrusive inspection technologies is also incorporated into the analysis [9; 10].

Analytical Framework

Human cognitive reliability is examined through five interconnected domains:

1. Visual search and perception;
2. Vigilance and sustained attention;
3. Fatigue, stress, and cognitive workload;
4. Human–technology interaction;
5. Training and ergonomics.

Within each domain, factors affecting detection sensitivity, operational stability, and decision-making reliability are analyzed.

RESULTS AND DISCUSSION.

Visual Search and Perceptual Challenges

X-ray baggage images substantially differ from natural visual scenes. Operators must interpret semi-transparent, overlapping, and distorted representations of objects. Threat items may appear differently depending on orientation, concealment methods, material composition, and surrounding objects.

Several characteristics significantly increase perceptual difficulty:

- superposition of objects;

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- varying object orientations;
- cluttered baggage structure;
- low-contrast regions;
- material density overlaps;
- unfamiliar object configurations.

Experienced operators demonstrate significantly higher detection sensitivity, faster response times, improved image interpretation capability, and reduced cognitive workload [8]. Expertise develops through repetitive exposure, feedback-based learning, and simulator-assisted training environments.

The author's earlier studies devoted to simulator-based operator preparation additionally demonstrated that adaptive educational technologies improve perceptual learning and long-term image interpretation stability [9].

Vigilance and Sustained Attention

One of the most significant challenges in baggage screening is vigilance decrement — the gradual decline in attention and detection performance during prolonged monitoring tasks.

Mackworth demonstrated that extended visual inspection tasks lead to declining vigilance and reduced operational effectiveness [4]. In screening environments, vigilance decrement may produce:

- reduced detection sensitivity;
- slower response accuracy;
- increased missed detections;
- reduced visual scanning efficiency.

Recent field studies involving airport screeners demonstrated that performance remains relatively stable under moderate workload conditions; however, prolonged screening duration combined with high task load increases error probability [1].

Low target prevalence represents another critical cognitive challenge. Threat items occur relatively infrequently in real operational environments. This creates psychological adaptation effects that increase the likelihood of missed detections [5].

Fatigue, Stress, and Cognitive Workload

Mental fatigue significantly reduces sustained attention, processing speed, visual discrimination capability, decision accuracy, and working memory capacity.

Fatigue accumulation may result from:

- prolonged monitoring;
- shift work;
- insufficient recovery periods;

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- circadian disruption;
- excessive workload.

High passenger throughput often creates operational time pressure. Studies demonstrate that increased time pressure produces a speed–accuracy tradeoff in which operators increase inspection speed while detection sensitivity decreases [3].

Operational screening environments additionally expose personnel to passenger interactions, queue pressure, environmental noise, and social confrontation. These factors substantially increase cognitive workload and negatively influence attention allocation and decision consistency.

Human–Technology Interaction

Modern screening systems increasingly incorporate:

- automated threat recognition technologies;
- intelligent image processing systems;
- object segmentation tools;
- adaptive visualization systems;
- computed tomography analysis.

Such technologies assist operators during image interpretation and may improve throughput, reduce workload, and enhance target detection capability [2]. However, excessive dependence on automation may create additional cognitive risks including automation bias, reduced vigilance, and decreased independent verification [6].

Consequently, modern operational concepts emphasize human-centered technological integration in which intelligent systems function primarily as decision-support mechanisms rather than independent operational authorities [7]. The author's previous investigations related to intelligent technologies in customs profiling similarly support the conclusion that technological systems should strengthen rather than replace professional operator decision-making [10].

Training and Competency Development

Simulator-based training represents one of the most effective approaches for improving X-ray image interpretation competency [8].

Computer-based training systems provide:

- large-scale image exposure;
- adaptive difficulty progression;
- immediate performance feedback;
- realistic threat projection;
- continuous competency assessment.

Effective training systems should develop:

- visual discrimination;

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- object recognition;
- spatial interpretation;
- decision confidence;
- stress resilience;
- attentional control.

The author's previous scientific investigations concerning simulator-based educational systems additionally demonstrated that competency-oriented training significantly improves operator preparedness in complex X-ray image interpretation environments [9].

Ergonomics and Workplace Design

Human factors engineering aims to optimize interaction between operators and screening technologies.

Poor ergonomic conditions may increase:

- visual fatigue;
- musculoskeletal strain;
- attentional decline;
- cognitive overload.

Environmental factors affecting cognitive reliability include:

- lighting conditions;
- workstation layout;
- environmental noise;
- seating posture;
- temperature conditions.

Controlled operational environments and ergonomically optimized screening centers may significantly reduce cognitive stressors and improve operational stability.

Organizational Reliability

Organizational culture strongly influences human reliability and operational effectiveness.

High-reliability organizations prioritize:

- continuous learning;
- transparent reporting systems;
- evidence-based procedures;
- non-punitive error analysis;
- continuous professional development.

Continuous performance monitoring systems may help identify fatigue indicators, declining performance trends, and training deficiencies before serious operational failures occur.

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International standardization of training requirements and image interpretation procedures additionally remains essential for reducing cognitive ambiguity and improving screening consistency.

Practical Recommendations

Based on the conducted analysis, the following practical recommendations are proposed:

1. Implement adaptive simulator-based training systems;
2. Integrate evidence-based fatigue management programs;
3. Expand the use of Threat Image Projection technologies;
4. Improve ergonomic design of screening workstations;
5. Introduce continuous professional development programs;
6. Standardize certification requirements for screening personnel;
7. Strengthen interdisciplinary cooperation between aviation security agencies and customs administrations;
8. Improve integration of intelligent decision-support technologies into screening operations.

Implementation of these measures may significantly reduce detection errors and improve operational reliability in non-intrusive inspection systems.

CONCLUSION.

Human cognitive reliability remains one of the most critical determinants of effectiveness in X-ray baggage screening systems. Although intelligent technologies and automated detection systems continue to evolve rapidly, human operators remain central to operational decision-making in aviation security and customs control environments.

The conducted analysis demonstrates that X-ray image interpretation represents a highly demanding cognitive activity involving perception, attention management, pattern recognition, decision-making, and sustained vigilance under operational stress.

Scientific evidence confirms that vigilance decrement, fatigue, excessive workload, time pressure, and poorly designed automation may significantly reduce screening effectiveness. Conversely, expertise development, adaptive training systems, ergonomic optimization, and competency-oriented educational approaches substantially improve operational reliability.

The author’s previous investigations concerning non-intrusive inspection technologies and simulator-based operator preparation additionally confirm that long-term operational effectiveness depends on systematic development of human cognitive capability alongside technological modernization [9; 10].

Future screening systems should therefore focus not on replacing human cognition but on strengthening professional operator performance through

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balanced integration of advanced technologies, ergonomic optimization, and evidence-based training systems.

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