THE EFFECT OF ATC AUTOMATED SYSTEMS' INTERFACES TO THE PROBABILITY OF ERRORS

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Annotation: *This article explores the critical impact of the automated system interfaces on error probability within Air Traffic Control. The study analyzes how interface design influences human cognitive processes, including perception, memory and decision-making. The findings emphasize that optimizing the interface is essential for maintaining safety standards in modern digital aviation environments.*

Key words: *Air Traffic Control (ATC), Human-Machine Interface (HMI). Automated Systems (AS), interaction, human factor, automation bias, transparency mechanisms, masking effect, multimodal system, cognitive ergonomics.*

Introduction

Modern Air Traffic Control (ATC) has transitioned its safety focus from mechanical durability to the cognitive efficiency of the Human-Machine Interface (HMI). Although Air Traffic Control (ATC) continues to digitalize, humans remain the definitive decision-making authority. The interface is more than a screen; it is a complex cognitive environment where technical data meets human perception and memory. As high-level automation like NextGen and Indra is implemented, the risk of failure shifts from manual slips to cognitive misinterpretations. This study examines how interface design—specifically visual hierarchy and multimodal feedback—affects error probability within the context of cognitive ergonomics.

Problems

To begin, let us consider a fundamental theoretical model of how a human-machine system function. This system is predicated on the integral interconnection between a single operator (pilot or controller), the aircraft, and the external environment. The operational process is executed through three primary functional stages within the human body: In the initial stage, the operator receives information from the aircraft and the environment through visual, auditory, and sensory signals. In the second stage, this data is analyzed using attention, memory, and perception to reach a specific decision. In the final stage, physical actions are executed via control elements like buttons and interfaces based on the decision made. Throughout this complex cycle, the human body experiences stress and fatigue. In such states, the probability of an ATC professional committing an error increases, regardless of their level of knowledge or experience. During their shifts, air traffic controllers make a large number of decisions, many of them quickly and at cognitive levels that do not always enter full conscious awareness. To better understand how these decisions are made, Jens Rasmussen’s widely recognized Skill–Rule–Knowledge (SRK) framework provides a useful theoretical perspective. Early in 1979, J. Rasmussen developed the scheme (fig. 1) that provides a useful framework for identifying the types of error likely to occur in different operational situations, or within different aspects of the same task where different types of information processing demands on the individual may occur. The human decision-making process can be divided into three levels: skill-based, rule-based, and knowledge-based. Decisions at the skill-based level are automatic and reflexive, carried out quickly and without conscious thought. Rule-based decisions are made consciously by following standard procedures, although with experience they can also be executed quickly and easily. Knowledge-based decisions, on the other hand, require evaluating alternatives and assessing situations in non-routine circumstances. In the context of ATC interfaces, these cognitive levels are directly influenced by how information is presented. Errors at the Skill-based level often occur due to 'visual noise' or clutter in systems like Euroscope, where a controller might miss a routine signal despite their experience. Rule-based errors are frequently triggered by 'automation bias'—a common issue in highly integrated systems like Indra—where the operator follows system-generated cues without verifying raw data. Finally, Knowledge-based errors arise when an interface fails to provide sufficient transparency during non-routine emergencies, causing the controller to fall out-of-the-loop and lose situational awareness.

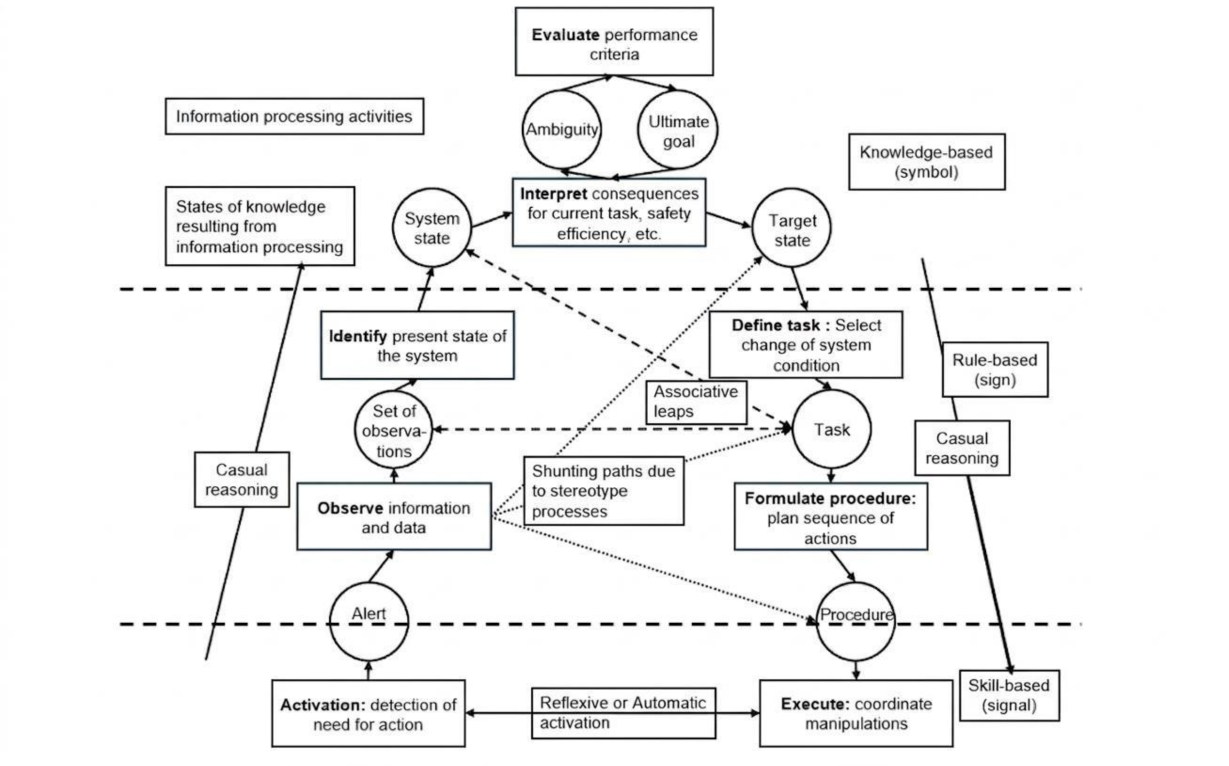
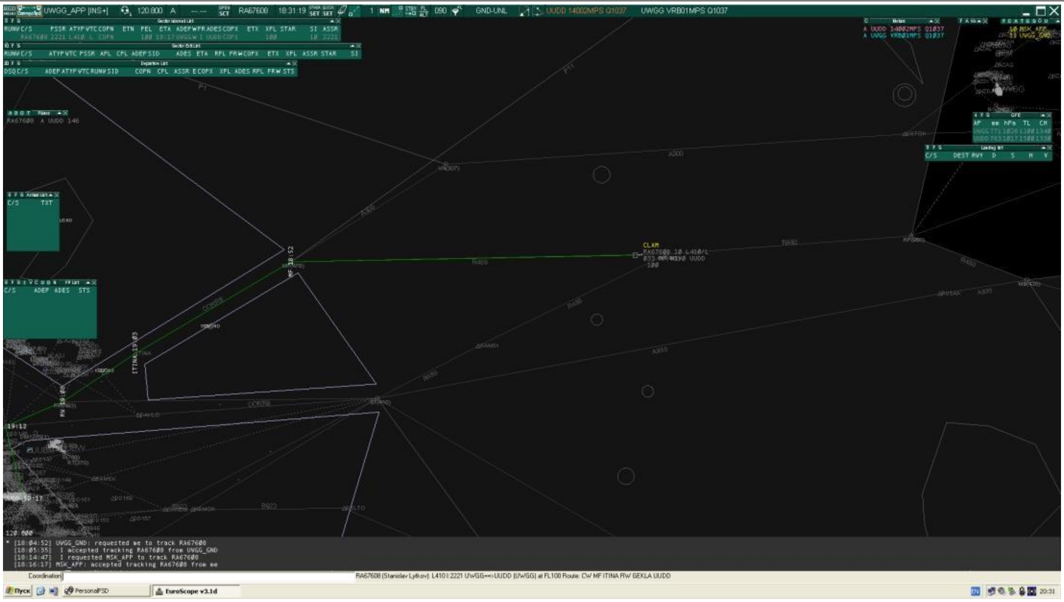


Fig. 1. J. Rasmussen’s framework.

From a systems perspective, analyses of human behavior primarily focus on knowledge-based decisions, since these cannot be directly generated by automated algorithms or fixed lookup tables. Therefore, in complex and unusual situations, human reasoning and analytical ability play a decisive role. Modern avionic displays are engineered to provide functionally integrated, real-time data to flight crews, however, research by Nikolic, Orr, and Sarter (2004) indicates that traditional visual encoding—specifically the use of color and motion to capture attention—is often ineffective within the high-density information environments of a "glass cockpit." Their findings suggest that flashing notifications do not inherently possess the presumed attention-drawing capability when embedded in dynamic, multicolor, and data-rich displays, likely due to visual saturation or attentional tunneling. Consequently, multimodal interfaces have emerged as a promising alternative for distributing cognitive load across different sensory channels, yet the availability of viable secondary modalities remains limited. While auditory displays are standard in systems like the Traffic Collision Avoidance System (TCAS) and the Ground Proximity Warning System (GPWS), they are susceptible to the masking effect, where an increase in concurrent signals renders individual alerts indistinguishable. Tactile sensors have also shown potential for conveying critical messages, but Ferris and Sarter (2008) caution that the integration of tactile cues can actually induce slower response times if the spatial location of the cue is not precisely aligned with the visual task, highlighting the complexity of cross-modal interference in flight deck design. A comparable principle governs Air Traffic Control (ATC) environments, where the human-machine interface functions as the critical nexus for safety-dependent decision-making. Much like pilots experiencing sensory saturation, controllers must manage increasingly sophisticated automated platforms such as Euroscope, Indra, or Alfa, each presenting distinct ergonomic and cognitive challenges. For example, the open architecture of Euroscope, while highly customizable, often precipitates information clutter that replicates the visual saturation seen in modern cockpits, thereby neutralizing the salience of critical alerts. In a similar vein, the high levels of integration in Indra systems, though designed for data streamlining, may foster automation bias and complacency, potentially causing controllers to overlook raw data anomalies in favor of system-generated cues. This issue is exacerbated by the "interaction noise" characteristic of the Alfa system, where complex menu nesting during peak traffic volumes forces a detrimental shift in visual fixation from the primary radar to the interface itself, increasing the probability of manual input errors. These vulnerabilities underscore a systemic flaw in contemporary ATC design: as data density scales, the efficacy of traditional visual and auditory stimuli degrades due to cognitive tunneling and the masking effect. Consequently, the evolution toward intelligent, multimodal ATC interfaces is a functional necessity rather than a mere technological refinement, essential for ensuring that high-priority data is not only rendered on screen but is also cognitively perceived and translated into timely operational action.

As an example, let’s take interfaces of couple of different ATC systems – Euroscope, Indra and Tompson (fig. 2).



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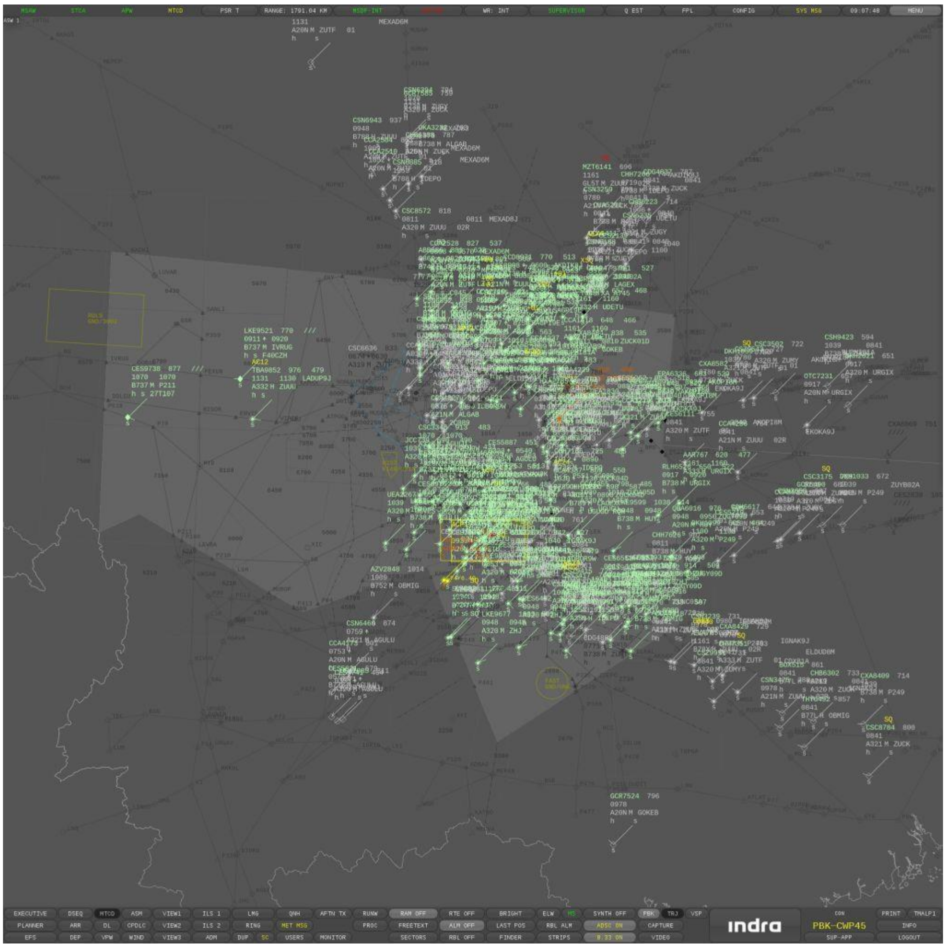

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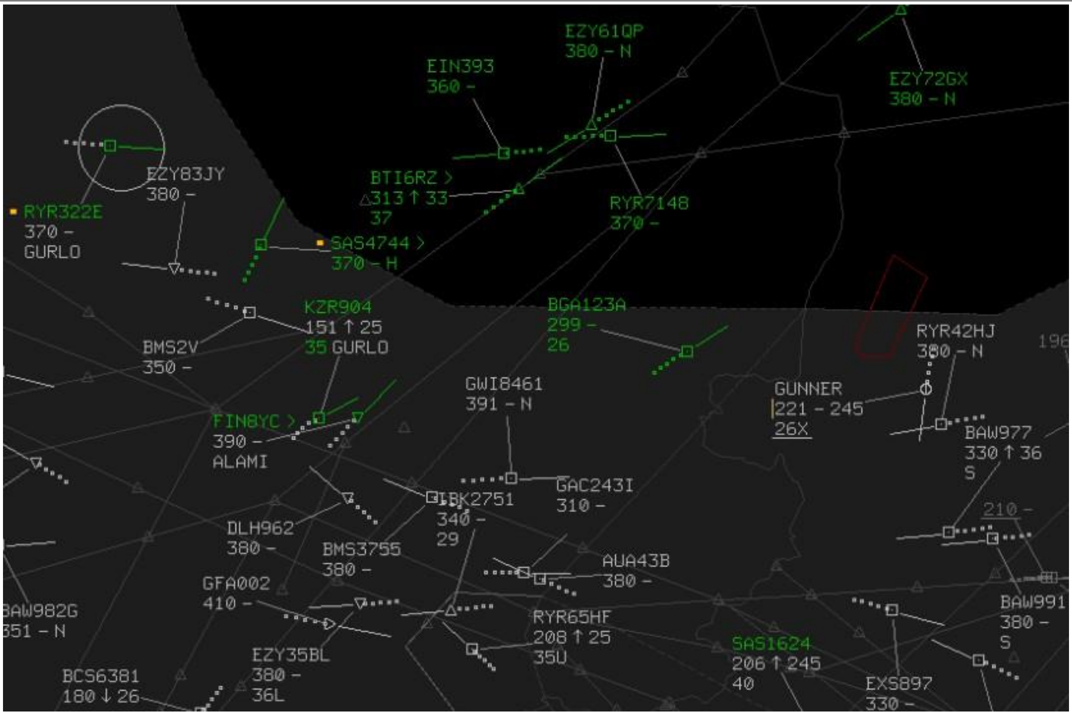

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Fig. 2. Main interfaces of Euroscope (a), Indra (b) and Thomson Eurocat 2000 (c) systems.

Solution

In recent years, efforts to model the complex aspects of cognition and intelligence have been increasing. In the context of modern air traffic management, the selection of an interface significantly dictates the probability of human-machine interaction errors, with Thomson Eurocat, Euroscope, and Indra representing distinct developmental philosophies. Thomson Eurocat serves as a foundational, stable platform that offers high reliability through a simplified visual hierarchy, however, its relative lack of advanced automation often shifts a higher cognitive workload onto the controller for manual calculations and projections. Conversely, Euroscope's open architecture allows for extreme customization, yet this flexibility frequently introduces "interaction noise" and significant information clutter, which can lead to a failure in detecting critical visual alerts due to the saturation of the controller's visual field. Among these, the Indra system represents the most sophisticated and globally prevalent model, making it a critical subject for studying contemporary error probabilities in highly automated environments. While Indra successfully streamlines vast amounts of data, its high degree of functional integration carries the specific risk of "automation bias" and complacency, where the controller may become an over-reliant observer of system-generated cues rather than an active processor of raw data anomalies. This shift in the controller's role—from active navigator to system monitor—can lead to "out-of-the-loop" phenomena, where the effectiveness of traditional auditory and visual stimuli is diminished by the sheer density of the automated interface. Therefore, for a scientific inquiry into the evolution of safety-critical errors, the Indra model is an essential inclusion as it illustrates how advanced automation, while reducing manual task load, creates new cognitive bottlenecks and subtle error vectors that are not as prevalent in more traditional or purely customizable systems like Thomson or Euroscope. To mathematically model these human-centered optimizations, it is necessary to move beyond 'crisp' logic. Since human communication and error are often nuanced, the integration of Fuzzy Logic into ATC interfaces allows for a more adaptive interaction mechanism, better reflecting the 'mental models' used by controllers in high-stress environments. The activities of artificial intelligence are primarily aimed at performing tasks considered intelligent, rather than fully replicating human brain function. At the same time, computer science has given rise to "cognitive science," which for some researchers means modeling human thought using computers, even though there is debate about whether the animal brain is comparable to a computer. Most current cognitive modeling work uses a rule-based approach, relying on structured programming principles rather than simple mathematical equations. The concept of mental models has become widespread, often built on precise (crisp) rules, though fuzzy logic allows variables to overlap, similar to how word meanings overlap in human communication. Aviation provides a relevant example: a computer-based mental model such as AIR MIDAS represents the information requirements, decision-making, communication, and motor processes of flight crews responding to controller instructions. Stochastic interruptions can be introduced into the model to predict decision-making, workload, and responses to clearances.When it comes to risk as well as safety,the third category of system models focuses on analyzing reliability.This is particularly crucial in aviation systems operated by humans, since individuals can make errors and technical equipment may malfunction, potentially resulting in severe outcomes. Reliability is nearly equivalent to safety, and maintaining safety has consistently been a central aim of human factors, especially within the aviation industry.In general, the effectiveness of air traffic control systems is strongly influenced by the interaction between ATC interface design and human cognitive performance, which plays a significant role in shaping the risk of operational error. According to models of human-machine collaboration and Rasmussen's SRK theory, air traffic controllers operate in several cognitive modes of decision-making, each of which requires specific types of information presentation and processing. The results of the study show that interface design is not just a technical feature, but also a key organizational element that directly affects cognitive load, situational awareness, and the effectiveness of operator responses. The movement toward safer aviation operations requires a transition from interfaces that simply present large amounts of data to those designed with cognitive ergonomics in mind. Research by Nikolic, Orr, and Mica R. Endsley Sarter (2004) highlights the shortcomings of conventional visual encoding and the information saturation commonly associated with the "glass cockpit." Traditional systems such as Thomson Eurocat employ simplified hierarchical structures that often increase the controller's manual workload. Conversely, highly customizable platforms like Euroscope can unintentionally create interaction noise because excessive visual customization leads to cluttered displays.

In modern air traffic control systems, interface design must evolve from a mere information display tool into a human-centered cognitive support system to effectively reduce operational errors. A comparative analysis of leading platforms shows that while Thomson Eurocat provides a stable and low-complexity environment, its inflexible visual hierarchy can increase manual workload. Conversely, the open architecture of Euroscope introduces excessive "chromatic noise" and visual clutter due to user-configurable elements. The Indra system, distinguished by its advanced integration of automated tools, poses risks of "automation bias" and sensory overload if not properly optimized. To enhance the Indra model, implementing a dynamic visual hierarchy is crucial. Utilizing desaturated gray (HEX #808080) or calm blue (HEX #2C3E50) for standard flight labels significantly reduces the visual saturation noted by Nikolic, Orr, and Sarter (2004). Research indicates that in Indra’s high-density, multi-color environments, traditional flashing and bright colors lose effectiveness due to the "masking effect". Therefore, high-intensity safety red (HEX #FF0000) should be reserved strictly for active Short-Term Conflict Alerts (STCA), while cautionary amber (HEX #FFBF00) is designated for medium-term alerts. This approach fosters a "knowledge-based" response within Rasmussen’s SRK model. Unlike Eurocat’s static design or Euroscope’s disorganized visual environment, an optimized Indra interface should implement shape-coding redundancy. For instance, changing circular radar symbols to bold triangles during alert states maintains information visibility even under "color fatigue". Since chromatic sensitivity may decrease under high cognitive load, this approach ensures reliable information perception. Additionally, using cyan (HEX #00FFFF) exclusively for selected targets creates high luminance contrast against dark radar backgrounds, helping direct controller attention while mitigating the risk of "attentional tunneling." To address the "out-of-the-loop" problem common in highly automated systems, the Indra interface must incorporate transparency protocols that explain the logic behind automated recommendations. This transforms controllers from passive observers into active decision-makers. This complex approach also involves reducing "interaction noise" by simplifying menu structures and introducing 3D spatial audio alerts to minimize response latencies, as noted by Ferris and Sarter (2008). Such measures ensure an optimal balance between technological automation and human cognitive efficiency within the Indra system. Within the framework of system mental models, the use of fuzzy logic allows for replacing the rigid "crisp" rules of legacy systems with a more natural and adaptive interaction mechanism. This strengthens the harmony between the interface and the user, accounting for the unpredictable nature of the aviation environment. Consequently, safety-critical information is not just displayed on a screen but is cognitively processed and transformed into rapid operational actions

Conclusion

In conclusion, the research demonstrates that the likelihood of operational errors in air traffic control is closely related to how automated system interfaces, structure and providing controllers with information. As automation becomes more advanced, systems must be designed in a way that supports the operator's cognitive activity rather than replacing it. Interfaces that overload the visual field or hide the internal logic of automated processes may reduce the controller's active involvement and increase the risk of misinterpretation or delayed responses.

The findings indicate that interface design should correspond to different levels of human decision behavior, ensuring that information is organized according to the controller's operational situation and cognitive demands. Making the internal mechanisms of automated alerts more understandable can help operators maintain awareness of system behavior and remain actively engaged in monitoring traffic conditions. In addition, decision-support structures that allow flexible interpretation of complex situations can better represent the variability and uncertainty present in real air traffic environments.

Another important improvement involves reducing excessive visual density by distributing information through several sensory channels. Combining screen-based data with carefully positioned sound cues and physical feedback mechanisms can help controllers detect important changes more quickly while lowering perceptual overload. Simplifying navigation within the interface and dynamically adjusting the amount of visible information according to traffic intensity can also decrease unnecessary interactions and improve the clarity of the operational display.

Overall, enhancing automated air traffic control systems requires a balanced approach that combines technological capability with an understanding of human cognitive performance. Interfaces designed with this perspective can strengthen situational awareness, support faster and more accurate decisions, and ultimately decrease the probability of errors due to negative effect of human factors, and human-machine relations in highly automated aviation environments. Ultimately, reducing error probability requires a shift from 'Information Representation' to 'Cognitive Support'. The transition toward desaturated color palettes, shape-coding redundancy, and explainable automation logic—as proposed in the Indra optimization model—is essential for ensuring that high-density data is not just seen, but correctly perceived and acted upon.

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