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Human error and response to alarms in process safety

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Abstract
Human operators are required to respond to alarms in normal conditions, and also to find solutions to unexpected situations in real time. The aim of this study is to increase the knowledge of human responses to alarms in the context of occupational situations. It describes how humans contribute to accidents, and pays special attention to the assurance of process safety assurance, which is in part realized by timely reactions to system alarms. An experiment involving an operator´s reaction times to alarm signals was undertaken to investigate whether there are differential responses to visual as opposed to auditory alarms. The findings in the research show that visual alarm indicators are perceived faster than auditory signals. Furthermore, there was a significant negative correlation between the number of errors and reaction time, indicating an individual difference in error-proneness when reacting to visual alarms in a supervisory task.

Keywords: alarms, auditory signal; visual signal; human error; process safety; reaction time.

Error humano y reacción a alarmas en seguridad de procesos

Resumen
Operadores humanos responden a alarmas en condiciones normales y también en situaciones inesperadas y anormales en tiempo real. El objetivo de este estudio consiste en aumentar el conocimiento de las reacciones humanas a alarmas en el ámbito laboral. Describe como los humanos pueden contribuir a accidentes y presta atención a la seguridad del proceso que se efectúa en el tiempo de reacción a las alarmas de sistema. Este experimento fue ejecutado para investigar si hay diferencias en respuestas diferenciales a alarmas visuales comparándolas a alarmas auditivas. Los resultados indican que las alarmas visuales son percibidas de manera más eficiente que las alarmas auditivas. Incluso, se pudo ver una correlación negativa entre la cantidad de errores y el tiempo de reacción, lo que indica una diferencia individual en su disposición a errores cuando reaccionan a alarmas visuales en operaciones de supervisión.

Palabras Clave: alarmas; señales auditivas; señales visuales; error humano; seguridad de procesos; tiempo de reacción.

1. Introduction

Technological progress has contributed to more advanced human-machine systems. However, in complex systems, human error is still perceived as a cause or contributing factor to in approximately 90% of accidents. Most of these accidents could have been prevented by safety management measures [1]. This is particularly visible in the case of accidents in construction and manufacturing, in which errors are viewed as inappropriate human decisions that have a negative impact on the operation of technical systems. Thereby they impact system performance by reducing safety and effectiveness [2]. Management of human errors is commonly focused on training, motivation, hardware design, and management systems, all of which can lead to improved safety performance [3,4].

In this paper, the role of humans in system failures in an industrial setting is discussed, and the particular element of alarm perception and reaction is tested in an experiment. The

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study aims to illustrate the effect of different alarm signals on human operators' reaction times and identify alarms for which the response was defined according to a pre-defined code. Reaction time and the correctness of responses for compound reactions were assessed for auditory and visual signals in a laboratory simulation situation. The final part of the paper formulates recommendations for overall system performance in machinery and equipment design.

2. Human contribution to occupational accidents

Theories on the causes of occupational accidents have changed over the years. However, two basic perspectives on human error and human contribution to accidents can be identified [5,6]. The first approach, hereafter named the "old" approach began at the start of the 20th century. This approach states that "…*certain individuals are always more likely than others to sustain accidents, even though exposed to equal risk…*" [7, p.1]. The basic assumption in the 'old' approach was to see engineered systems as fundamentally safe, while unreliable humans were the primary threats to safety. According to this approach, the employer was not responsible for bad working conditions, and employees were accused of causing accidents [8]. The way to improve safety was to protect the systems through the training of operators, by keeping discipline, and through the application of procedures and through the selection of appropriate workers (e.g. by employing the less accident prone workers). In more recent times, this approach involved introducing automation in industrial processes [5]. It was not until the second half of the twentieth century that a system was seen as a factor that contributed to accidents. Employers were also required to provide safe working conditions for the first time. At the same time, it was realised that a person's accident proneness may differ from one period to another [7,9]. Moreover, research has shown that dismissing workers due to their accident proneness does not positively affect the ratio of occupational accidents [10]. The problem of accident proneness remains a widely discussed topic [11] and studies show that operators' accident proneness only refers to a small amount of accidents, for which the application of preventive safety barriers can reduce the involved risks [12].

Alternatively, according to the new approach, human error is no longer seen as a cause, but rather as a symptom of an underlying systemic weakness or failure. Hence, human error is not a cause in itself but it rather is something that must be explained. In contrast to the assumptions of the old approach, the new approach holds that safety is not intrinsic in systems as systems are created to fulfil multiple incompatible human goals simultaneously. Many of these goals can be conflicting, as is exemplified by the wish to improve safety and efficiency simultaneously (*e.g.* reducing relative number of errors while also increasing production). Human error is clearly associated with features of tools, tasks and operating environments. Therefore, human beings and their interaction with technology are important for creating safety and progress in terms of safety levels [5]. Thus, there is need for further investigation of human error and organizational deficiencies, design problems, and procedural shortcomings. Following on from this, it can be claimed that the new approach to human error shows a significant movement towards human factors and points to new ways of managing organizational safety.

Table 1.
Accident models: a review.

Author	Model	Accident causation
Heinrich (1931)	Domino theory	Ancestry and social environment, worker fault, unsafe act together with mechanical and physical hazard, accident, damage or injury
Bird & Germain (1985)	ILCI model	Lack of control: inadequate program, program standard, compliance to standard; basic causes: personal factors, job factors; immediate causes: substandard acts, substandard conditions; incident: contact with energy or substance; loss: people, property, environment, progress
Reason (1990)	Swiss cheese accident causation model	Fallible board decisions and policy, line management problems, psychological precursors of unsafe acts, unsafe acts, accident
Rasmussen (1997)	Risk management framework	Government, regulators associations, company, management, staff, work
Leveson (2004)	STAMP model	Inadequate control or enforcement of safety-related constraints, safety: control problem; accidents appear when component failures, external disturbances, dysfunctional interactions between system components are not adequately handled

Source: Adapted from [13-17].

As there are different approaches to the causes of occupational accidents, the literature review allowed us to make a distinction between different accident theories, as are summarised Table 1.

These models provide an insight into how and why accidents happen in organization. However, it should be stressed that there are only a few accident models that are based on human factors research [11]. They refer to different factors that appear in many forms; however, generally they reflect human and technical aspects, when a human being can be recognized as assurance of safety. It should also be mentioned that the technical system design can be controlled/designed to reduce the occurrence of human errors, whereas the control of environmental factors and manner of human operation of the system are somewhat less controllable. Predominantly, in large organizations and compound technologies, more than one sin gle liability can be distinguished [5,8,15,18].

3. Process safety performance

Over the last three decades, automation has changed the role of operators from manual control to supervision [10]. A great effort has been put into equipment design and interface, operation, operator selection and training and behavioral enforcement. These efforts have resulted in a drop of process safety accidents. There is still a need to operate complex systems with the recognition of operation breakdowns that occur as a result of human error [18]. It should be emphasized that the main category of human error is operating errors. For example, the following situations can result in operating errors [19]:

- lack of appropriate procedures
- task complexity and overload conditions
- poor personnel selection and training
- operator carelessness and lack of interest
- poor environmental conditions
- departure from the correct operating procedures

In order to monitor the performance of systems the operators have to do many tasks that can rely on [20]:

- monitoring sensor data from components (voltages, status of the capacitors, transmission lines, transformers, circuit breakers, etc.)
- monitoring the grid as a holistic system
- communicating information among several sub-systems
- responding to alarms

Alarm systems play a significant role in industrial production as they assure process quality and reliability. Industrial production requires human operators who observe, and, if necessary, intervene in process malfunction or abnormal system performance *i.e.* when the values of the system parameters exceed predefined tolerance limits, or approach critical levels [21,22]. However, nowadays a large number of notifications, which are configured inside such a system, lead to the operator receiving much more alerts than s/he can physically and cognitively perceive. Due to the material, energy and information flow in a plant, particular disturbances can cause multiple subsequent alarm messages, which may overload the operator with redundant alarms. This results in an “alarm flood”, when an operator is not able to react within a recommended response time and find the root cause of disturbances. Finally, the industrial applications of alarm systems become unreliable due to their complexity [23].

In order to increase knowledge of human reactions to unreliable signals, researchers refer to theories of learning and human cognition such as:

- Probability matching - the approximation of the perceived true alarm rate on the basis of the observed alarm responses
- Signal Detection Theory - signal detection and response is more rapid for historically reliable alarm systems
- Automation trust - the exhibited trust relates to behavioral patterns of system use and misuse

Regardless of what the operation task is, alarm reaction patters are unquestionably influenced by perceived alarm system reliability [24].

According to Lee and See [25] reliability of the alarm system is described as the percentage of critical events that are correctly identified by the alarm system. It is determined by the alarm’s sensitivity, setting of thresholds and defined probability of dangerous conditions [26]. The higher the alarm system's reliability is, the more that operators can rely on the alarm and the less monitoring the data is required. On the other hand, when reliability is low, the chance of the occurrence of false alarms or misses is higher and the relevant process data have to be monitored more frequently to be able to keep monitoring performance at a high level [27,28]. Unreliable systems can contribute to sensor failure or their inadequate performances, data processing limitations or output failure (i.e. electrical problems or component malfunction, etc.). All these states can lead to potentially hazardous situations as they cause more deviations in other parts of the plant [23].

4. Human reaction to alarms

Displays and controls have been used for a long time in human-machine interfaces. They range from simple to complex manufacturing systems and processes. There are also distinct sets of human factor principles for choosing frequency, duration, and intensity of signal presentation. In order to obtain attention and a response, the two most common modalities can be differentiated, which are visual and auditory signals.

In everyday life, most information is perceived with the eyes; however, in complex systems, where the object of the task is out of visual view, the use of auditory stimuli has become more common. Therefore, in industrial control visual and auditory signals are often presented together rather than as alternatives; however, they may also be separate or simultaneous, synchronous or asynchronous [29,30]. They can be used in hand and/or foot controlled communication devices. The foot controls are mainly designed for seated operators when there is a need to reduce the workload on the hands, or when free hands are required for tasks with greater levels of precision and skill. However, it should be emphasized that even in the case of equipment or systems that have foot controls (*i.e.* automobiles, airplanes), nearly all controls are assigned for hand control [31].

The literature studies revealed that the timing of auditory stimuli is generally longer than the timing of visual stimuli for the same signals presented separately. Furthermore, duration discrimination is more precise for auditory than for visual stimuli in simultaneous presentations [32]. It was also identified that the time perception relies on the prefrontal and parietal regions, and on the auditory and visual cortices. However, the neural mechanism responsible for these modalities remains unclear [33]. Moreover, in recognition of visual and auditory signals, the phenomenon called visual dominance [34] must be taken into account. Based on this, auditory signals may seem not to be responded to in simultaneous presentation with visual signals, which indicates that their use can be ineffective in control situations. Nevertheless, in many situations, it was recognized that they might stimulate situational awareness and thereby improve the effectiveness of visual displays. They are superior to visual signals for warning in monitoring tasks in which there is no need to observe a particular location all the time [35].

The level of urgency of alarms is correlated with the level of urgency of the indicated danger [36]. Furthermore, the perception of alarms is subject to their frequency, intensity, and repetition. For instance, a low frequency alarm, which is repeated slowly, shows low urgency, whereas a high frequency alarm repeated quickly implies high urgency [37]. In simulated conditions it was shown that the reduction of luminous intensity from 42 to 5 cd increases the reaction time by 84 ms [38]. In the case of auditory signals, increased signal intensity causes faster reaction time, whereas its high-intensity, which is synchronous with a visual signal, reduces choice reaction time [39]. Thus, the growth of the intensity of auditory signal weakens the visual supremacy. For synchronous auditory and visual tasks, sound source location does not have a facilitating effect. It was concluded that sound not only warns, but also has an overall alerting effect. Auditory signals are quite useful when the spatial-visual information is limited or chaotic. For instance, they can be applied in control console tasks in which they alert operators or request action. While listening to critical auditory messages, visual signals are monitored. To optimize their reaction rate and reduce their performance lag, a fore-period warning (at least 2s and no more than 4s) is required to draw attention to incoming signals. Both signals should be simultaneously presented from the same direction to ensure quick responses. Nevertheless, in the case of asynchronous signals, a short delay (200 ms) between them may give a negative result, giving a poor response speed and accuracy [29].

Base on the literature study, it was hypothesized that reaction times for visual alarms would be significantly shorter than reaction times for audible alarms. It was also postulated that audible alarms would have a higher percentage of errors than visual alarms.

5. Materials and methods

Eighty-seven second-year students from engineering management and safety engineering courses in Poznan University of Technology participated in the experiment. The sample consisted of 36 males and 51 females, with a mean age of 20.16 years (SD = 0.37). They did not report having hearing loss or color vision deficiency. In order to have free movements they were asked to wear casual and comfortable clothing. As the experiment was conducted during their laboratory classes, all the students were awarded a course credit.

At the beginning of the experiment the task was clearly explained, and then participants were allowed to practice until they became familiarized with it. Their individual training lasted for about 5 minutes. Afterwards, they experienced 3 visual and 1 auditory signals while operating the simulator (MCR-2001E). The experimental task was to react to 50 signals according to the previously defined code, which is shown in Table 2. When the experimental task started, a single auditory or visual target signal appeared on its own for each test trial. No feedback on the accuracy of responses was given to the participants.

Table 2.
Alarm sequence representation

Element number	Modality	Element number	Modality
1	visual	26	audible
2	audible	27-31	visual
3-5	visual	32	audible
6	audible	33-35	visual
7-9	visual	36	audible
10	audible	37-39	visual
11-22	visual	40	audible
23	audible	41-50	visual
24-25	visual		

Source: The authors.

Only reaction times for correct responses were recorded. Incorrect responses were given a reaction time of zero (0) and treated as a missing variable in the statistical analysis. Mean reaction time was calculated by summing up all the correct response times for each participant and then dividing this sum by the number of correct responses for visual and auditory alarms respectively.

IBM SPSS 22 was used for statistical analysis. All confidence intervals for *r* (Pearson correlation) were calculated using the bootstrap function in SPSS, and there were 1000 resamplings that had replacement.

6. Results and discussion

Visual alarms (*M* = 524.67 ms, 99% *CI* [506.39, 540.73]) had a significantly shorter reaction time than audible alarms (*M* = 579.27 ms, 99% *CI* [552.88, 608.64]) as measured by a paired samples *t*-test ($t_{(86)}$ = -6.336, M_{diff} = -54.61 ms, 99% *CI* of M_{diff} [-77.31, -31.90], *p* < .001). This is in accordance with the literature review and the stated expectations of this study.

Following this difference in mean reaction time, a difference in delayed (but correct) responses was expected. Delayed responses where defined as responses with more than 500 ms reaction time. Visual alarms had a much lower ratio of delayed responses (*M* = 42.78%, 99% *CI* [37.37%, 49.47%]) than audible alarms (*M* = 57.12%, 99% *CI* [49.01%, 65.57%]). This difference was statistically significant as measured by a paired samples *t*-test ($t_{(86)}$ = -4.869, M_{diff} = -14.33%, 99% *CI* of M_{diff} [-22.09%, -6.58%], *p* < .001).

Regarding the number of errors, a paired samples *t*-test showed that there was no difference in the ratio of errors for visual alarms (*M* = 11.30%, 99% *CI* [9.35%, 13.49%]) as compared to audible alarms (*M* = 10.49%, 99% *CI* [7.61%, 13.36%]). The difference was not significant ($t_{(86)}$ = 0.616, M_{diff} = -0.008%, 99% *CI* of M_{diff} [-0.027, 0.043], *p* = .54). This is not in accordance with the hypothesized difference that audible alarms would be more prone to errors.

When the relationship between the rate of errors and reaction time was further investigated, a statistically significant negative correlation was found between reaction time for visual alarms and the ratio of errors to correct responses ($r_{(87)}$= -.301, 95% *CI* [-.484, -.085]). This indicated that the participants who on average responded faster to visual alarms also tended to make a larger number of errors; therefore, this indicated an individual difference in error-proneness when reacting to visual alarms in a supervisory task.

For audible alarms, the same negative correlation between reaction times and ratio of errors was observed, but this relationship was not statistically significant ($r_{(87)}$=-0.95, 95% *CI* [-.223, .117]). The lack of a significant negative correlation in this study could be due to the relatively lower number of auditory alarms (8 in total) compared to visual alarms (42 in total).

This study employed a non-randomized convenience sample, hence limiting the ability to make causal inferences outside the current sample. However, our findings are still in accordance with the existing literature on this matter.

The limited number of audible alarms has restricted our ability to identify real differences in error rates when responding to audible alarms. This limitation can explain our lack of ability to statistically identify differences between error rates as well as the lack of a significant negative correlation between reaction time and error rates for audible alarms. This limitation can be amended in future studies by balancing the number of visual to audible alarms.

7. Conclusions

In any process industry, safety issues are of primary importance as any accident can have cataclysmic consequences for both people and the environment. Therefore, efforts must be made to prevent or limit the hazards of the plant. To achieve this aim, an increasing number of industrial quality and reliability systems is applied. In these systems, operators pay attention to present process states and predict their future states using information from alarm systems. Alarms are frequently performed via display terminals in which information is presented in a variety of formats. In this paper, particular attention has been paid to visual and audible signals. The results of the present study revealed that the participants could react faster to visual signals than audible ones when the signals are predefined according to a code. No difference was found in the reaction of errors compared with the total number of alarms.

These results aim to be helpful in formulating recommendations to work towards a more optimal design of control consoles when auditory and visual displays are presented. They may be also effective in improving system performance in machinery and equipment design.

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