UNIVERSAL DESIGN FOR AIRCRAFT SAFETY

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Abstract

This paper focuses on safety, specifically for accident prevention, through a human factors and aviation medicine approach, using Universal Design as a tool for analysis and product design. As this subject involves human-machine interface, some aspects of aircraft design methodology and operation in adverse conditions are also referenced.

1 General Introduction

The "Seven Principles of Universal Design" were developed in 1997 by a working group of architects, product designers, engineers and environmental design researchers in the North Carolina State University [13]. The main purpose of the Principles is to guide the design of urban environments, products and communications, and may be applied for evaluating existing designs, for guiding the design process and for educating both designers and consumers about the characteristics of more usable products. They are:

- Equitable Use;
- Flexibility in Use;
- Simple and Intuitive Use;
- Perceptible Information;
- Tolerance for Error;
- Low Physical Effort;
- Size and Space for Approach and Use.

1.1 Air transportation trends and challenges

Air transportation has become a very spread and safe way. As a consequence, many people who had never flown before came on board. On the operating side, crew training faced new challenges, not only because of the increasing demand, but also for the need to qualify crews for new aircraft models and operational requirements, including systems with unprecedented design complexity.

As a legacy of other seemingly unrelated business areas, Universal Design principles, geared toward people with different physical and cognitive abilities, appear as a practical way of thinking about improving safety in this scenario. As a side effect, an environment designed according to these principles shall become more attractive and easier to handle, even for users without any disabilities. These principles specially apply to the so-called "able-bodied" people in situations where they may be "not fully functional", including difficulties in seeing, hearing, moving or concentrating in some task, for example. Some common agents are: smoke in the cockpit, lighting, turbulence, fatigue, inclement weather etc. In an environment resilient to human error, people will be able to better understand the situation and operate correctly the controls in order to achieve their intention, since the lower mental and physical demands provided by such environment will provide a sufficient level of situational awareness and control.

1.2 Human aspects

The human brain is roughly divided in three zones. The Reptilian brain (the most primitive one), controls the body's vital functions such as heart rate, breathing, body temperature and balance. It is reliable, but tends to be somewhat rigid and compulsive.

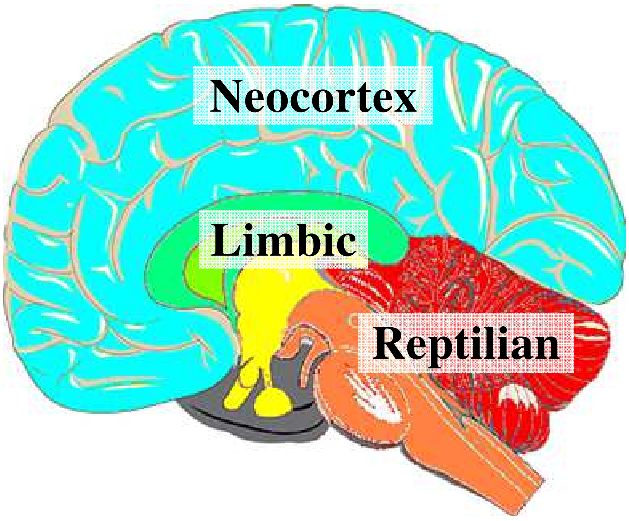


Fig. 1. Human brain zones.

The Limbic brain, which emerged in the first mammals, records memories of agreeable and disagreeable experiences, being responsible for what are called emotions in human beings. It is the seat of the value judgments made, often unconsciously, that exert such a strong influence on the behavior.

Finally, the Neocortex first assumed importance in primates and culminated in the human brain with its two large cerebral hemispheres that play such a dominant role. These hemispheres have been responsible for the development of human language, abstract thought, imagination and consciousness. It is flexible and has almost infinite learning abilities.

Although these layers are interconnected and work together, the problem arises when, when exposed to stress or fatigue, the brain tends to progressively revert to the primary core, which means that emotions will take the place of the rational consciousness, and finally the survival effort will take over all the others.

Some situations in which stress leads to a condition in which incremental demand is added to monitor one's own reactions may even cause a kind of breakdown. It is like being nervous about being nervous about something. So, in an environment where the necessary information about a situation is acquired more intuitively, and the means for taking control are undoubtedly understandable, the brain will work more efficiently to overcome the issues, even if part of the senses and/or the ways for necessary human action are compromised.

The central thought is that people, when exposed to stressful situations, tend to act more instinctively than rationally, in a common and even predictable way. So, why not prepare the human/machine interface to accommodate these reactions, reducing self-generated stress so that people feel more comfortable and self-confident about their actions, thus allowing a more rational collaboration from the neocortex to take place? Imagine a scenario where, in addition to all these external stressing factors such as lighting, noise, traffic, turbulence etc., the crew must deal with a somewhat tricky aircraft control logic, indistinctly shaped levers, colors, contrasts or sounds, or whatever would make that environment stressful for them, even if they are not aware about that... The same idea would apply to all crew members as well as to the passengers, as they all collaborate to achieve an adequate operational safety level (for instance, during the evacuation of an aircraft).

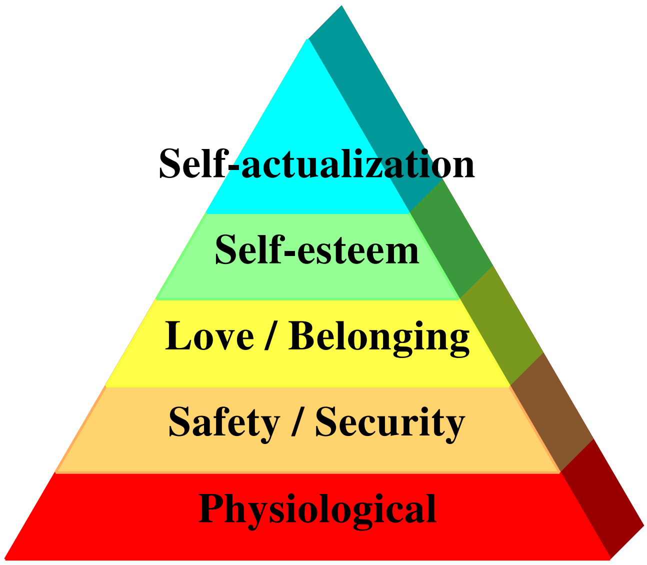


Fig. 2. Maslow's Hierarchy of Needs, adapted from [10].

Although there is some controversy about human needs, especially at the higher levels, the above figure helps to understand some human aspects, as demonstrated firstly by Abraham Maslow in 1943 [10]. Starting from the basic ones, they can be explained as follows:

- Physiologic: breathing, circulation, temperature, intake of food and fluids, elimination of wastes, movement.
- Safety / security: housing, community, climate.
- Love / belonging: relationships with others, communications with others, support systems, being part of community, feeling loved by others.
- Self-esteem: hope, joy, curiosity, happiness, accepting self.
- Self-actualization: thinking, learning, decision making, values, beliefs, fulfillment, helping others.

Assuming that lower needs must be met to allow other needs to be addressed, it is easy to see that the latter (thinking, learning, decision-making, required throughout the flight and especially to solve unexpected situations), will only have the opportunity to manifest themselves if the sense of security and the attendance to the most basic physiological needs are guaranteed.

1.3 Historical facts

Historically, several artifacts that follow Universal Design principles have already been developed. The shapes of the gear and the flap levers are one of the more iconic examples. The initial physical resemblance and proximity between them (as in Douglas DC-3 aircraft) led to several cases where one was actuated rather than the other, with unintended results.

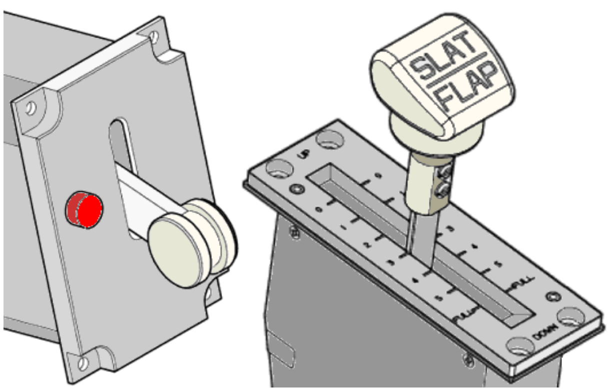


Fig. 3. Gear (at left) and Flap (at right) levers in a current aircraft design (Embraer E-Jets).

Nowadays, both levers reflect a physical similarity with the controlled element, allowing users to positively know that the correct lever is being handled. The Code of Federal Regulations (CFR) Part 25 – Airworthiness Standards: Transport Category Airplanes §25.777 Cockpit controls, says: "(a) Each cockpit control must be located to provide convenient operation and to prevent confusion and inadvertent operation."

Pushing to the limit, assuming a cabin environment was designed to be operated by a blind person, someone that is "temporarily blind" will face less difficulty to have a positive outcome. This blindness can originate from smoke, condensation, dust, intense or absent lighting, visual illusions, distraction or simply from the need to focus on other visual field. The latter is exactly what happens daily when pilots use either flaps or gears levers. The flap selection uses multiple inputs to confirm the desired action, in addition to vision: tactile (touch / force, proprioceptive / motion), sound (noise, click of the detent), acceleration (aircraft slows) etc. Thus, reinforcement using more than one sensory channel is paramount in this case. And it is correct to suppose that even a qualified pilot may be prone to pick up the wrong lever some day if the shape of both is similar.

So there is still a lot of room for improving the lives of the crew and the passengers by designing a whole environment that makes them feel more comfortable, even though they cannot tell specifically why some particular item feels more intuitive or attractive. The net result is that the user interface will be connected to their three brain layers, so they will understand, like and depend on it.

This article correlates the principles of Universal Design with some of the most well-known causes of human error in aviation, evaluating ideas for raising the overall level of operational safety.

Equipment, instructions, software, colors, shapes, sounds or any interfaces with the crew or passengers are implied. As has been said, the overall stress level is expected to be reduced, keeping the brain with all three layers working together, optimizing aspects of survivability, affinity and rationality, and thereby enhancing both the overall safety and the user experience.

2 Sources of human errors

There is no expectation of covering all sources of human error here. Only a few of them, which play a significant role in the purposes of this article, will be referenced.

2.1 Impairing conditions

Beginning with hypoxia, which is the lack of oxygen to the body areas where it is requested at a specific time, some stages are [11]:

Indifferent stage: Vision, especially night vision, will deteriorate even at altitudes less than 5,000 feet, without self-awareness of it.

Compensatory stage: The body and mind can be severely affected and in an increasing and subtle way. At 12,000 to 15,000 ft, the symptoms are drowsiness, poor judgment and frequent subtle errors in flying skills become apparent. More dangerous is a feeling of well-being and indifference (euphoria).

Disturbance stage: Headache, impaired peripheral vision, hyperventilation, marked fatigue, sleepiness, and specially euphoria.

Critical stage: Unconsciousness. This can happen within 3-5 minutes after someone failed to recognize that he/she was hypoxic.

The following are some of the most common symptoms which may impair safety:

- "Tunnel vision" and lack of visual focus.
- Weakness in muscles.
- Feeling very tired, fatigued, sleepy.
- Diminished sense of touch.
- Headache, dizziness.
- Muscular coordination decreased.
- Stammering, poor communication.
- Impaired judgment, slow thinking.
- Loss of self-criticism, overconfidence.
- Aggressiveness, depression.
- Reactions time decreased.
- Greatly reduced color discrimination.

In summary, the signs and symptoms of hypoxia are many and varied, and are unpredictable at any given time and altitude. As can be expected, alcohol and tobacco or any air pollutants also play a significant role in decreasing body's tolerance to hypoxia, as does the ambient temperature.

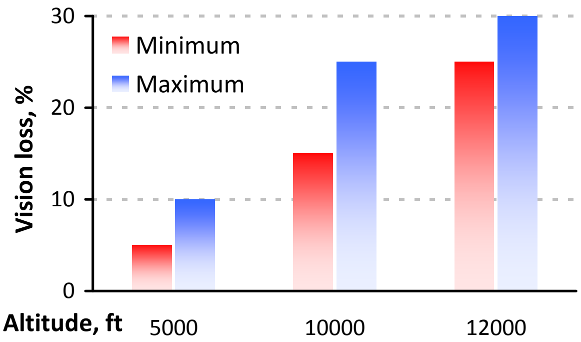


Fig. 4. Vision loss versus altitude as a symptom of hypoxia – adapted from [11].

Some experiments were done using a Cessna 172 aircraft with inexperienced and experienced pilots, requiring them to fly Instrument Landing Systems (ILS) approaches with various levels of blood alcohol [5]. Glide slope and localizer deviations, as well as procedural errors were recorded, for various Blood Alcohol Concentrations (BAC).

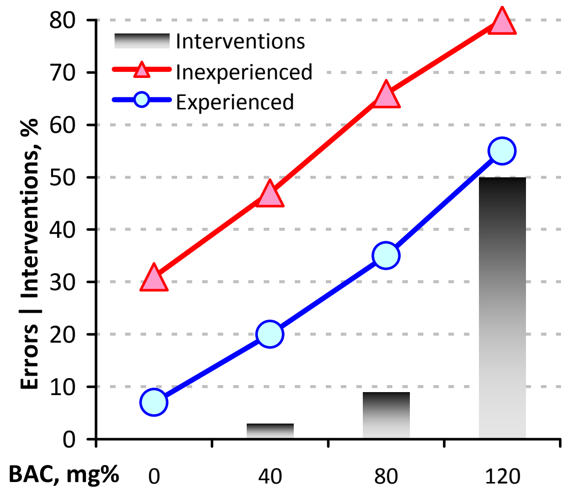


Fig. 5. Error frequency and Interventions when proceeding landing tests under influence of alcohol – adapted from [5].

In addition, it was necessary for the safety pilot to intervene and take over half of the times the BAC was at the maximum test value.

Some easy to find impairment factors are related to health issues, whether transient or not. A middle ear block, where the Eustachian tube is swollen by a cold or hay fever, can cause enough discomfort to impair the human senses. A sinus block may also lead to this. Even dental problems like abscesses can generate a disabling pain sensation during rapid decompression events, where joint pain may also be present.

Medications, even those that are "over-the-counter", used to solve health issues, may cause unwanted reactions, as many of which reduce users' perception or readiness (e.g., antihistamines have sedation as a side-effect).

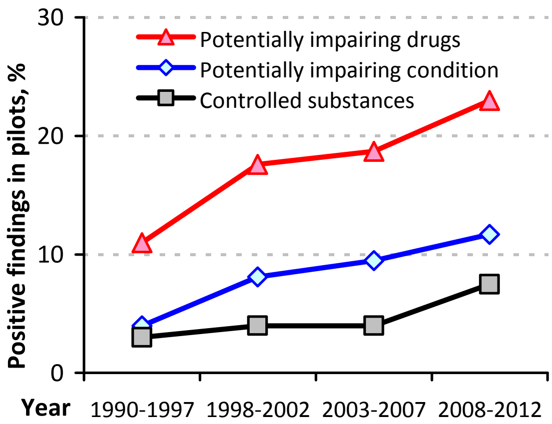


Fig. 6. Positive findings for potentially impairing drugs and conditions, and controlled substances – adapted from [9].

2.2 Characteristics of the human body

Even healthy individuals must deal with characteristics and limitations of the human body, which is similar to the operational envelope of an aircraft. And this envelope changes with age, usually reducing someone's ability. This is specially true with hearing, which affects more men than women.

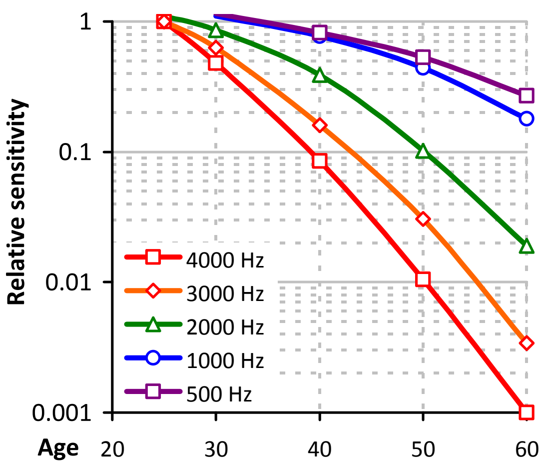


Fig. 7. Hearing loss with age (for man). All curves are plotted against the 25-year value for a 4000 Hz tone – adapted from [5].

From the figure above, sensitivity drops about one-hundredth of its value at 25 years for a 50-year man, and ten times more at age 60.

The vision also presents some tricks. In addition to the physical blind spots for daytime vision (one in each eye) that normally go unnoticed, there is also a central blind spot in night vision.

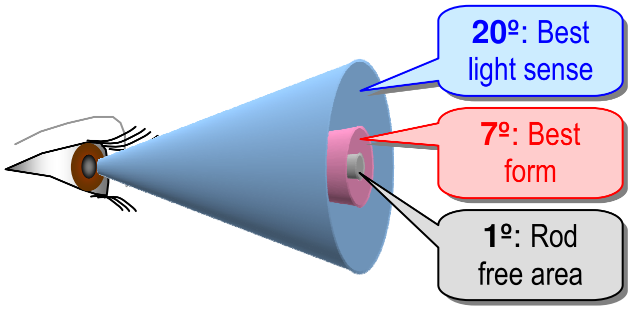


Fig. 8. Eye characteristics for night vision – adapted from [11].

This "rod free area" (due to the massive presence of cones) leads to a central blind spot in dim light. So, the best vision area during the day becomes the worst of them at night.

The most common way to overcome this issue is to use off-center vision, which makes subjects fall in the "7º zone" (for best form vision) or in the "20º zone" (best light sense). Dark adaptation, for instance, may take up to 30-45 minutes to complete (getting longer with increasing age) if no extreme condition was experienced before, such as looking at bright snow, water or sand, or strobe lights of an aircraft. Some harmful effects are cumulative and may persist for days after exposure.

Circadian rhythms, if not respected, may lead to fatigue, especially due to jet lag or poor sleeping hygiene.

Individuals working nights and rotating shifts rarely get optimal amounts of sleep. In fact, an early objective study showed that night shift workers get 1 to 4 hours less sleep than normal when they were working nights. Sleep loss is cumulative and by the end of the workweek, the sleep debt (sleep loss) may be significant enough to impair decision-making, initiative, integration of information, planning and plan execution, and vigilance. The effects of sleep loss are insidious and until severe, are not usually recognized by the sleep-deprived individual [6].

Hypoglycemia, from improper nutrition habits or inadequate meals time, may also develop fatigue. When blood glucose levels drop, so does cognition. And it is the higher cognitive functions, such as decision making and the ability to perceive risk, that go out first [7]. As with hypoxia, probably the most important symptom of fatigue is the feeling of indifference, expanding one's tolerances and limits for performance, which allows mistakes or substandard skills.

One obvious yet sometimes overlooked item is the difference among individuals. The differences between men and women are clear. But it is not just the physical dimensions of people within one ethnic group that may vary from generation to generation. Large differences between ethnic groups can be expected at the same time, either in the overall size or in body proportions, for example trunks and legs lengths. If the design was poor in terms of these items, the operation may be compromised specially during tasks performed under unfavorable conditions.

2.3 Training

As occurs to any human activity, training is necessary for dealing with complex tasks (in this case an aircraft full of people).

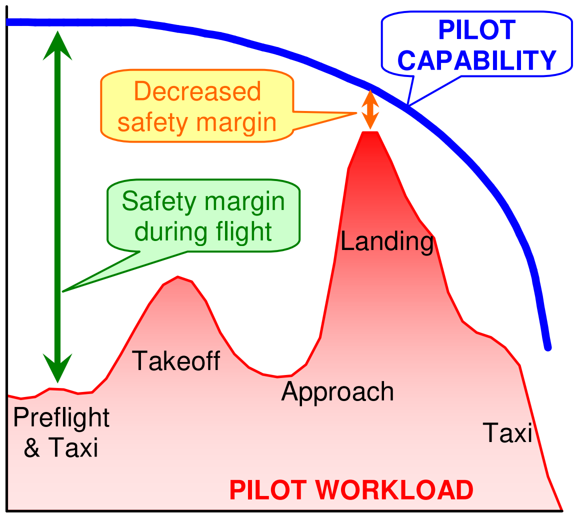


Fig. 9. Pilot capability and workload for the various flight phases – adapted from [12].

A skill is a pattern of organized and coordinated activity. It may be physical, social, linguistic or intellectual. As an alternative to training, it is possible to redesign the job or the job situation so as to present less challenge to the operator. The goal of modifying the job to suit the man, not the other way around, is a central activity in the technology of ergonomics and has frequently been neglected in incident and accident analysis and in subsequent recommendations [5].

In the case of the aircraft crew, it is correct to assume that although they may be extensively trained in the operation, several unexpected situations that demand their actions may arise. At least that is why they are there. Thus, great part of their learning (called "expertise") is got on-the-job. If all situations were well defined, an automatic system would be able to manage them.

We make assessments about the world, which updates our current understanding. This directs our actions in the world, which change what the world looks like, which, in turn, updates our understanding, and so forth [3]. But the new technology shifts the ways in which systems break down, adding new vulnerabilities that did not exist before.

2.4 Design issues

Over the last few decades, the skills needed to fly a commercial aircraft have changed considerably, mostly as a result of advances in control and display design and automation technology.

As a rough example, imagine that many of us have perhaps tried to pull a door with a handle on it, even though the label clearly says "push". This may happen merely because the handle design compels the user to pull it.

The introduction of the "glass cockpit" in the 1980s brought some unprecedented types of errors. The following table shows the percentage of pilots reporting having made common design-induced errors during the approach and landing phase while performing an autoland in a "glass cockpit" airliner, in 2005.

Error	%
Omitted to put the landing gear down until reminded	19.6%
Initially, dialed in an incorrect airspeed on the Flight Control Unit (FCU) by turning the knob in the wrong direction	39.1%
Adjusted the heading knob instead of the speed knob	78.3%
Entered the wrong altitude on the FCU and activated it	15.2%
Entered a heading on the FCU and failed to activate it at the appropriate time	34.8%
Failed to monitor the glide slope and found that the aircraft had not intercepted it	39.1%
Had an incorrect barometric air pressure set	45.7%
Set an altitude "out of the way" and then out of habit pulled the altitude knob	15.2%

Fig. 10. Reported design-induced errors – adapted from [1].

Fig. 11. Handsets at uncontained engine failure and subsequent fire – Chicago, IL Oct 28, 2016.

In above figure, flight attendants could not call the pilots before evacuation because at that time they simply were not able to operate the handset at center/right (which needs a numeric code to be dialed).

In the next picture, even though passengers always hear the words: "To start the flow of oxygen, pull the mask towards you. Place it firmly over your nose and mouth, secure the elastic band behind your head, and breathe normally", passengers are holding the masks over their mouths, but not their noses. Should not masks design prevent such misuse?

Fig. 12. Masks incorrectly worn during a decompression event – April 17, 2018.

3 Universal Design proposals

The philosophy is that the product must be correctly usable by people with a wide range of physical and/or cognitive abilities [13]:

- **Equitable Use**: The design is useful and marketable to people with diverse abilities;
- **Flexibility in Use**: The design accommodates a wide range of individual preferences and abilities;
- **Simple and Intuitive Use**: Use of the design is easy to understand, regardless of the user's experience, knowledge, language skills, or current concentration level;
- **Perceptible Information**: The design communicates necessary information effectively to the user, regardless of ambient conditions or the user's sensory abilities;
- **Tolerance for Error**: The design minimizes hazards and the adverse consequences of accidental or unintended actions;
- **Low Physical Effort**: The design can be used efficiently and comfortably and with a minimum of fatigue;
- **Size and Space for Approach and Use**: Appropriate size and space is provided for approach, reach, manipulation, and use regardless of user's body size, posture, or mobility.

These principles address only universally usable design, while the practice involves more than consideration for usability.

According to the US Census in 2010, 18.7% of the non-institutionalized civilian population had a disability. About 12.6% had severe disability, while nearly 4.4% needed assistance with one or more activities of daily living, or instrumental activities of daily living [2]. The numbers are similar for most countries, even worse for some of them.

Designing for disabled people is a real need. Moreover, if you design something to a deaf person, that solution would also apply to those who are in a noisy (or very quiet) place. Designing to a blind person would also caters to those who can not look directly at the product, or are in a very light (or dark) area. Designing to people who cannot control well their movements will also attend those with cold hands, wearing gloves or subject to vibrations when doing their job. Designing to people with reduced cognitive ability caters to tired, fatigued, under stress or drug influence, or even those which are attending an emergency.

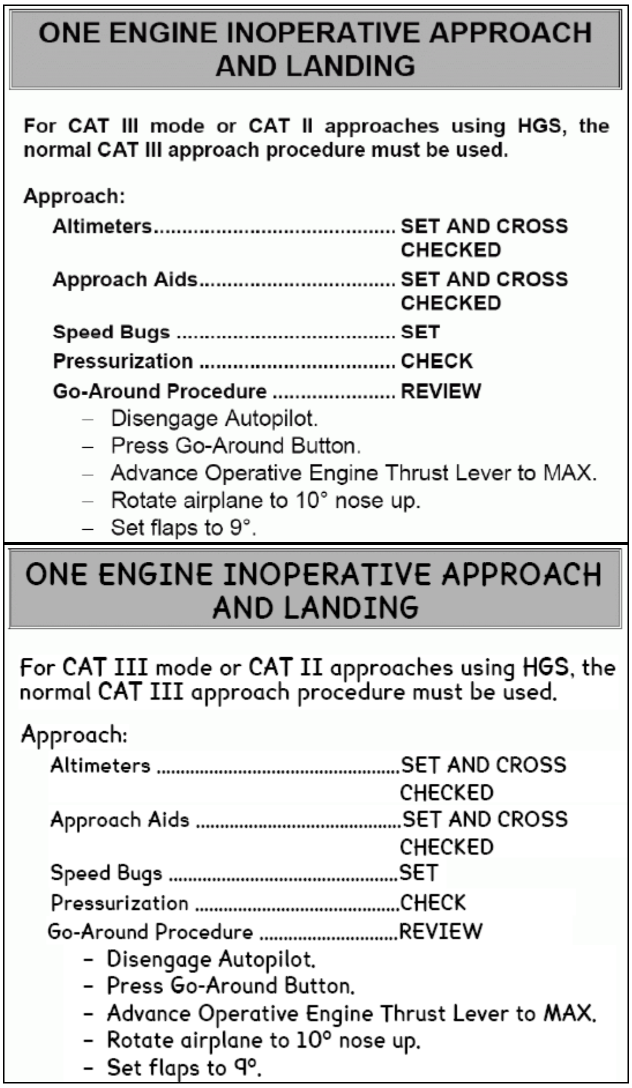
In many aspects, similar principles have already been integrated into aircraft design and are already required for certification. The proposal here is to take a step forward by using these principles to effectively drive the design, making aircraft operation even safer.

Follow some ideas and many questions intended to challenge the *status quo*.

Have you consider using Plain English in written documents, with fonts designed for dyslexic people? Remember that one in ten Americans is functionally illiterate, the primary cause being dyslexia [14]. Are we choosing the right font to write the manuals, signs, Quick Reference Handbooks (QRH), charts and on-board safety cards?

Have you ever heard in "What a wonderful world" song, that part "The bride bless the day, the dogs say goodnight" ("The bright blessed day, the dark sacred night")? Are there better ways to communicate clearly using voice?

In an environment where green and red colors have extremely opposite meanings, how to deal with color blindness, which affects around 8% of men?


ONE ENGINE INOPERATIVE APPROACH AND LANDING

For CAT III mode or CAT II approaches using HGS, the normal CAT III approach procedure must be used.

Approach:
Altimeters.. SET AND CROSS CHECKED
Approach Aids.................................. SET AND CROSS CHECKED
Speed Bugs .... SET
Pressurization .... CHECK
Go-Around Procedure .... REVIEW
– Disengage Autopilot.
– Press Go-Around Button.
– Advance Operative Engine Thrust Lever to MAX.
– Rotate airplane to 10° nose up.
– Set flaps to 9°.

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Fig. 13. Example for QRH: typical (upper) and proposal using font for dyslexia (bottom), which presents very dissimilar letters and numbers.

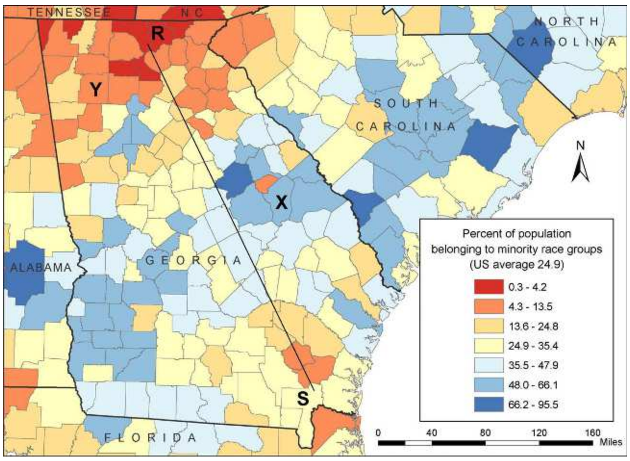

Fig. 14. Map suitable for color blind people [4].

There must be smarter ways to choose a color scheme for a display, deck or cabin.

Are all people onboard able to make the most of that expensive entertainment system? Moreover, they must be aware of the meaning of all emergency signs in case of any danger.

Can we use more aural checks for critical operations or conditions? Maybe full spoken sentences are more assertive than buzzers...

Is the aircraft fully prepared for elderly (or those "more experienced") crewmembers and passengers, most of them with sensory and/or motion impairments? Think on emergency exits being operated by “newly handicapped” people.

Imagine an environment (aircraft and people) able to positively communicate to the deaf (or “just-made-deaf”) people, both during normal cruising and during any emergency.

Are the facilities intelligible to illiterate people? And for the blind (or “newly blinded”) ones, maybe after being struck by a laser beam? Sometimes even stadium lights can be strong enough to affect pilots, like in Santa Clara, home of the San Francisco 49ers, which is in the flight path for one of the runways of San Jose Mineta International Airport.

Does some blinking lights cause flicker vertigo (an imbalance in brain-cell activity caused by exposure to low-frequency flickering or flashing of a relatively bright light) in you? Imagine yourself inside a helicopter under the sun (under the shadow of moving blades).

Do you know that exposure to high noise levels (over 90dB) may adversely affect tasks requiring vigilance, concentration, calculations, and judgments over time? As curiosity, a lawn mower can generate up to 90dB of pure noise, a food processor, 95dB, a rock band, 110dB, and a safety airbag, 170dB. Will you feel “a little deaf” just after a car crash?

Will the oxygen supply be accessible and understandable to people suffering from some degree of hypoxia, after a rapid decompression? Does this solution include people with arthritis, pneumonia, or a single cold? And do not forget the smokers and those who may have received a glass of Champaign when they embarked, or ordered some wine or beer on flight.

Have you really considered that, more and more, older people require products and services (like flying, for instance), and for a significant part of them it may be the first time? Everyone shall be aware of the relevant aspects of flight safety, including the beginners. And do you really know all of these safety items or gadgets inside that car you just rented (and make good use of them)? Try to ask the other members of your family as well, younger and older.

Are you in good shape? Maybe a few extra pounds, a back or tooth pain, a buzzing ear? Did you leave your pair of glasses in the checked luggage instead of bringing them with you? Being able to reach the outside of a crashed aircraft fast, even without glasses, may save your life.

Have you been sitting for more than two hours, maybe watching a good movie full of sound effects in surround? Are you well hydrated (and regularly go to the toilet)? Thrombosis can occur in situations that are typically encountered in air travel.

Do you sleep well while you're flying (or between flights, if you are a pilot)?

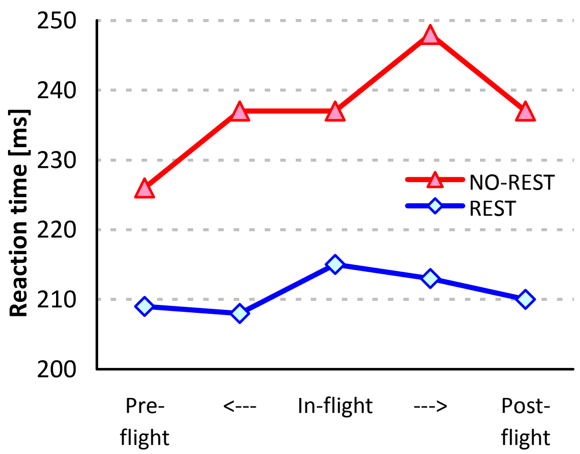

Fig. 15. Reaction time for pilots who have had a rest period or not (adapted from [8]).

There have been many studies showing that sleep-based fatigue results in lapsing and increased performance variability on short-duration reaction time (a performance measure) tasks involving sustained attention [8].

Have you heard about premenstrual syndrome (or do you have any symptoms of menopause / andropause)? Are you somewhat worried about your family, money or job? Will you arrive in time to take the next flight?

I hope you have been able to read and understand the whole text so far in this article, as not everyone could do the same.

In summary, you need to rely on human / machine interface design exactly when you are not operating as designed or desired.

Have all of these unveiled needs (not just those certification requirements) already been addressed when developing solutions for those incredible, fast and unstoppable cylindrical cabins stuffed with people, operating in harsh environment?

I believe that our task is not only to provide the minimum conditions necessary to prevent accidents, but rather to create an extremely pleasant environment to live and work, where safety is a natural consequence, most of the times even unnoticed by the users.

4 Conclusion

A product designed to be used by people with a wide range of physical and cognitive abilities will demonstrate its superiority under normal conditions and in emergencies. For both, reducing mental and physical stress to its use will lead to better awareness and ability to achieve the desired outcome.

Solutions that do not raise costs are possible, provided they are well-considered. Dealing with limitations and constraints is the daily activity of good engineers, and each one must keep in mind the unspoken needs of the customers and those which may arise during the product use, even during unpredictable situations. That is where excellence comes into play.

And for all people who will interact with these well designed items, even if they are not aware of the reasons, they will look more attractive, enjoyable and easier to use, during daily life (avoiding fatigue) or during emergencies (allowing greater assertiveness).

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