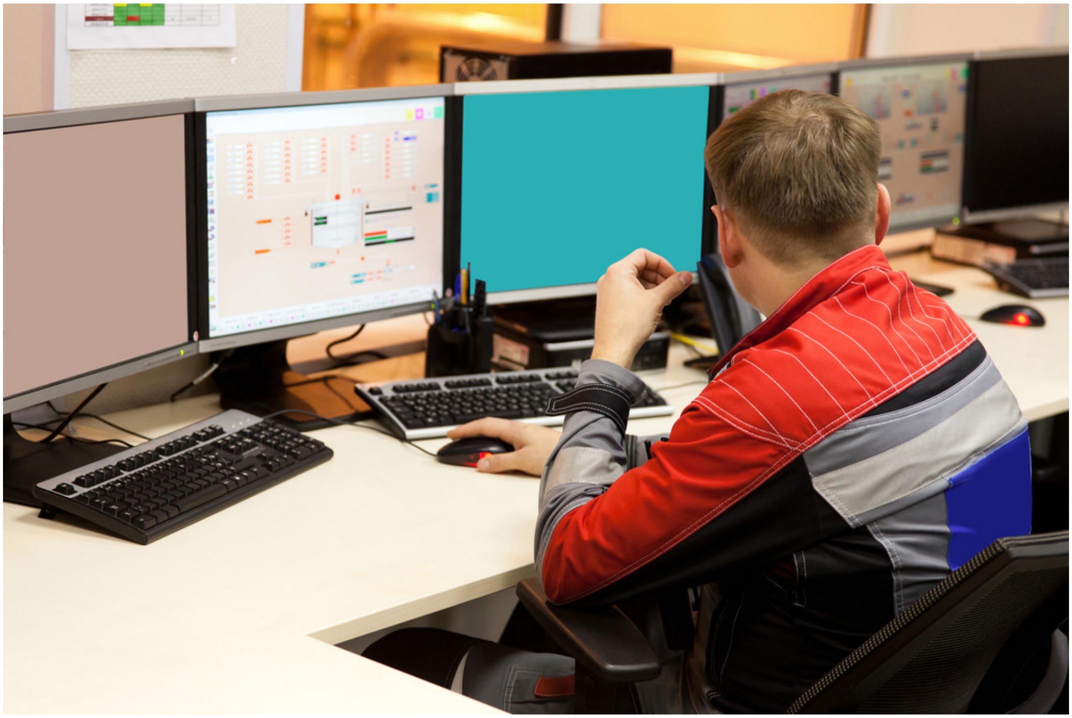
CHAPTER 5

Cognitive Ergonomics



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THIS CHAPTER PROVIDES:

- Descriptions of how the human brain and our perceptive abilities work and respond to stimuli and mental workload.
- Some guidelines for good cognitive design of instructions, interfaces and cognitive assembly supports like fixtures.

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WHY DO I NEED TO KNOW THIS AS AN ENGINEER?

Cognitive aspects of a workplace concern the sensory signals that give our brains the clues and cues to understand a task or to solve a problem. Your task as an engineer is to create the best possible conditions for workers to correctly interpret the task and task status, in order to avoid danger, errors, confusion, irritation and mental overload. This is obviously a very powerful design area, which can make or break a worker's ability to understand what to do in the workplace. In other words, we are moving focus from the physical to the mental in this chapter. Many cognitive aspects have to do with our interpretation of sensory stimuli (vision, hearing, touch, smell and taste), our capability to recognize patterns, our understanding of instructions and our ability to associate symbols with meaning. The brain is constantly handling cognitive processes (even during sleep!) and often needs to be well-rested and nourished to work optimally. However, it is not uncommon that work is performed in a state of fatigue, which adds limitations to our cognition, attention, perception, memory and mental models.

With some basic knowledge of good cognitive design principles, a production engineer can minimise unnecessary mental workload and help an operator perform their work tasks more efficiently and with fewer errors and misinterpretations. This theoretical knowledge can contribute to the design of workplaces, instructions, machines, tools and activities that communicate better to the worker how to achieve their goals. This chapter also brings up some examples of currently existing cognitive support solutions used in modern production.

WHICH ROLES BENEFIT FROM THIS KNOWLEDGE?

The *system performance improver* who understands human cognitive abilities and limitations will be able to specify requirements for appropriate equipment, instructions and human-machine interfaces that can aid workers in doing tasks efficiently and correctly.

The *purchaser* will be able to better understand the value of investing in human-machine systems that transmit information and instructions as quickly and intuitively as possible. For both these roles, there is an economic argument that workers with good cognitive support commit fewer errors, leading to better product quality and less waste and scrap – but this may need to be proven with a business case and translated into a prospect of higher quality and/or productivity to convince a purchaser.

The *work environment / safety specialist* can use this knowledge to pinpoint safety hazards and risks for error that can be traced to signals and information being missed or misinterpreted, due to sensory distraction or insufficient cognitive support.

5.1. What cognitive limitations exist in the workplace?

Human workers are still preferred in many assemblies over robots because of their superior ability to respond to variations in assembly instructions and quickly take decisions to address deviations from the normal process flow. However, the fact that the human is a thinking, learning, processing being that is constantly changing, also poses some consistency problems for performance. Sometimes, even on the basis of plenty of experience, humans can misinterpret information, make mistakes or make ill-advised choices, like deciding to take shortcuts in a process, which has in the past resulted in dire consequences such as costly, unnecessary mistakes, or even fatal consequences for health and safety.

One extreme example is the partial nuclear meltdown of the Three Mile Island power plant in Pennsylvania, USA, in 1979. (United States Nuclear Regulatory Commission, 2013). This emergency is attributed to operator error and several human factors errors that caused the plant operators to misunderstand the process, ignore status alerts, miss alarm signals and shut down the wrong functions. The bad cognitive ergonomics of the plant schematics (instructions), machine interfaces and alarm signal system led to partial core meltdown, radioactive contamination and enormous public distrust and backlash against the nuclear energy sector. Following this and similar accidents in other countries, the nuclear sector has globally invested large and lasting efforts in improving human factors aspects of its technology, knowledge among its personnel, and tightly controlled safety aspects (United States Nuclear Regulatory Commission, 2013). It is today one of the most advanced industrial sectors regarding human factors, with an emphasis on cognitive ergonomics.

In more production-related cases, the same assembly line and operators may be used to produce multiple variants of a product, where the fundamental elements are the same but subtle differences exist. This can often cause confusion or errors, leading operators to assemble parts incorrectly. This in turn causes defects and quality issues further down the line, resulting in unnecessary costs and rework. Many have attempted to address this issue with varying degrees of success through the use of various different methods, which will be outlined later in this chapter.

5.2. Human capabilities and limitations

Up to this point, this book has mainly focused on the human locomotive system and ways to improve physical well-being and performance. In this chapter, we focus on the abilities and limitations of the human mind and senses, which work together to process and interpret information from our environment and formulate goals for action – this is what constitutes a human's cognitive abilities (Figure 5.1).

Our mental capacity changes with age (both improving and declining, depending on training and genetic factors), and our cognitive abilities are a combination of skills, experience, pattern recognition, attention, memory, ability to focus, expectations, associations, generalization and the ability to sort information into categories. Of course, our physical well-being can have a significant impact on these abilities. If we try to perform mentally intensive work tasks when we are tired, over-stimulated, stressed, emotionally or chemically affected, alarmed, distressed or hungry, our brain may transfer from a mode of high-functioning thought (planning, reasoning, evaluating) to survival mode[1] (instinctive, quick actions to evade danger or discomfort), which may at worst result in negative effects ranging from small mistakes to fatal accidents. In particular, human abilities are drastically limited by being in a state of fatigue. Fatigue can contribute to mistakes and accidents, especially for tasks requiring sustained vigilance (such as observing a monotonous process that may change suddenly). This works both ways – poorly designed cognitive supports and tasks that routinely cause mental overload can also contribute to chronic fatigue, leading to demotivation, ill health and absenteeism.

Figure 5.1: The human brain interprets information from the external environment.

A cognitively well-designed work system can lessen the impact of fatigue by minimizing the ability to perform incorrect or dangerous actions. The more demanding the task or the more stressful the situation, the more important carefully designed cues become.

5.3. The senses

Commonly, it is said that humans have five senses, which are (listed from most to least dominant): vision, hearing, touch, smell and taste. The senses convey information about our surroundings and the internal state of our own bodies, by receiving stimuli through different receptors and sending them via the nerves to the brain for processing. While the latter two senses are seldom intentionally used for communicating information (and are therefore not described here in depth), a combination of visual, auditory and tactile cues (e.g. vibrations) make up the majority of signals that are transmitted to humans in a workplace setting. Additionally, humans are said to have a sense of balance and muscle sense[2], both of which can be used to interpret our surroundings and act accordingly (for example the sensation of gravity telling us which way is up – however, this sense can be confused by contradicting signals from our other dominating senses).

Vision

Vision is the most dominant sense that humans use. Our field of vision in total extends about 170 degrees horizontally; the outer rim (peripheral) of that field is good at detecting movement but not detailed information. Therefore, we are dependent on viewing detailed information in our central field of vision.

Light is a form of electromagnetic radiation (see Chapter 12), whose different wavelengths are interpreted by human eyes as different colours. The visual photoreceptors in the eyes are called the *rods* and *cones*. The cones are very sensitive to small differences in shape and colour, but require good lighting to function, while the rods are much more numerous and more sensitive to seeing in dim light, but they cannot distinguish colour. Our sense of vision is connected with our perception, which is actively looking for patterns and structures that our mental bank can recognize as meaningful. Several parameters affect sensory processing of light (Table 5.1).

As we age, our visual abilities tend to deteriorate from the approximate age of 40, especially our capacity to detect low contrast, small symbols and weak stimuli. This makes good task lighting and clear visual cues (with sufficient size and time duration) extra important when designing tasks, interfaces and environments for a whole work population (Bohgard, 2009 p.p. 346–350). Table 5.2 includes some design principles for visual information.

Table 5.1: Parameters that influence vision (adapted from Bohgard, 2009 pp. 351–352).

CONTRAST	Contrast sensitivity is our ability to distinguish between light and dark, allowing us to see lines, text, shapes and contours of objects. High contrast means that there is a large difference between black and white in the field of view, while low contrast means more subtle differences on a grey scale. Our contrast sensitivity decreases as we age, meaning that it becomes more important that readable information should have enough differentiation between black and white.
COLOUR	Colour is the result of how our brains interpret and distinguish different wavelengths of light. The receptors that dominate colour vision are the cones, which are centrally located in the eye's retina. Different people have different abilities to distinguish and interpret different colours, depending on age, education, culture and genetic preconditions (such as colour blindness).
DARK-ADAPTED VISION	Depending on the number of rods (the more numerous and sensitive receptors) in the eyes, our ability to see in the dark varies, with some people experiencing a brief period of inability to see. Also, in dark environments, our ability to see different colours decreases.
DEPTH PERCEPTION	This is the ability to distinguish how far away different objects are relative to each other. Our ability to perceive depth is dependent on binocular (two-eyed) stereo vision and on previous experience and is decreased in the dark.
MOVEMENT DETECTION	The human eye is very good at detecting movement (a remnant of our descent from stone-age hunter-gatherers), which can sometimes be used as a deliberate way to attract attention to details or changes of status in a process. This is extensively used in software, for example progress bars and flashing advertisements on web pages.
GLARE	Glare is irrelevant high-intensity light that does not contribute to better illumination, but instead irritates and overwhelms our sense of vision, leading to temporary inability to see.

Table 5.2: Key design factors for presenting visual information (adapted from Bohgard, 2009 p.p. 351–352).

INTENSITY	Particularly for displays and signs, the amount of light entering the human eye must not cause glare, nor must it be too dimly lit for the eye to perceive contrast and colour.
CHOICE OF COLOUR	It is wise to be restrictive with colour-coding critical information, or to provide a redundant backup system for interpreting the colours correctly. For example, colour-blind people who cannot distinguish red and green colours close together can still interpret traffic lights correctly because the colours are separated and follow a consistent rule of where they are positioned.
STRENGTH OF LIGHTING	Different tasks require different lighting strengths to be sufficient. For example, high-precision detail work demands much higher light compared to general office work lighting. Recommended lighting levels for different types of work are available (more on this in Chapter 12).
CONTRAST	Sufficient contrast – i.e. difference in object luminance – is important for humans to be able to distinguish symbols from their background, especially regarding written information and alarm signals.
ANGLE OF VISION	Consider where in the human's field of vision information must be placed to be perceived, the appropriate distance away from the eyes, and the angle that the neck must adopt to see well. This should be designed in parallel with illumination of the object being viewed.

Hearing

Human hearing, like vision, is tightly coupled to our cognitive pattern recognition skills, which helps us distinguish many nuances of sound – most of us can correctly identify the direction a sound comes from, the volume, the pitch (allowing recognition of melodies) and even when certain signals concern us or not, such as when hearing our name spoken in a noisy environment or being able to filter out sounds that carry no meaning for us (in some cases known as selective hearing). Sound is a particularly effective complement to vision when we are overloaded by visual stimuli. Sound can be used to bring attention to changes in process status, to warn of danger, to indicate distance (such as warning systems for backing a vehicle) or to confirm correct actions.

Since sound is a form of vibration, the body perceives audible sound via vibration of the inner ear, while non-audible sounds are perceived as vibrations. Particularly sub-sonic (low) frequencies have been known to cause whole-body vibrations that cause nausea and feelings of discomfort and depression. Also, it is important to remember that hearing abilities change with age – notably, there are high-pitched frequencies that can be heard primarily by young people, but this ability diminishes already in early adulthood. However, hearing loss can also occur as a result of exposure to noisy environments, but this is injury-driven hearing loss rather than age-related.

Table 5.3: Parameters that influence sound and hearing (adapted from Bohgard, 2009 p.p. 351–352).

LOUDNESS (AMPLITUDE)	Sound travels in waves, which have different amplitudes corresponding to loudness. The ear has limits for how much loudness it can tolerate before permanent hearing injuries occur.
PITCH (FREQUENCY)	Pitch or frequency (the wavelength of the sound) defines the "tone" of the sound, and differences in pitch delivered in a sequence can be distinguished by the human ear as melody or signals that can be associated with meaning. The human ear (and body) has sensitivity to a wide range of frequencies, but is unable to hear very high pitches well (such as dog-whistles).
LOCATION (DIRECTION)	Thanks to stereo hearing (involving both of our ears), humans can determine which direction a sound is coming from by interpreting the differences in loudness and pitch between the two ears. This ability is so exact that it is actually possible to create "sound illusions" that convince a listener that a sound source is moving in space. This is done by recording sound in a quiet room, using two separate microphones spaced apart by about the width of a human head.

Touch

The tactile sense, also known as *haptics*, is what allows us to perceive differences in pressure, temperature and frequency (as in vibrations) – most frequently through nerve receptors in our skin that are sensitive to stimulation from bending of hairs in the skin, and to pain. Particularly the hands are sensitive to very small sensations, but evolution has made most of our skin able to register slight touches (as light as that of a spider web).

5.4. Human cognitive processes

Cognition is the overall process of handling information. It is the combination of sensory stimulation, focus, perception, working memory, long-term memory and interpretation, leading to decision making and response.

There are two categories of mental processing of information; either the process is in response to sensory stimuli and is unconscious/automated (bottom-up), or it is a conscious chain based on desires, previous experience or knowledge, expectations and generalizations (top-down).

Attention

Attention means devoting a human's mental resources to a task or event at hand. Undivided attention focuses all our cognitive processing capability to one stimulus. When our attention is divided between two or more information sources, our ability to correctly process stimuli and interpret information is decreased.

Human attention functions best when events come at regular, relatively frequent intervals, but once activity frequency is too low, our attention levels fall, and there is a risk that small status changes or subtle signals will be missed (Bohgard, 2009). The ability to keep focus on a process for duration of time is called *alertness* or *vigilance*. Since humans are not naturally good at remaining vigilant for a long time, it is important to support attention using enough sensory stimulation, the right amount of pressure and the right frequency of activity. A lack of this support is called a *monotonous* task or environment and leads to boredom and decreased motivation. Boredom is a mental state where our brain deactivates certain nervous centres and the human experiences weariness, lethargy and decreased alertness (Kroemer and Grandjean, 1997 p. 219). In this state, humans are less ready to perform tasks well or respond to sudden stimuli. Lapses in attention can lead to quality losses, accidents and inferior performance.

Memory

Memory is the process that allows learning through storage of information, experiences and rules in the brain. It is divided into long-term memory and short-term/working memory (STM). Working memory allows us to store new information temporarily in order to make sense of patterns and relationships between data points and mentally process the information into coherent chunks that can be stored in the long-term memory. The short-term memory also allows us to recall recent events, up to a couple of hours ago. However, our short-term memory capacity is limited in how many new information points it can take in at once. An established rule of thumb is "The rule of 7", which states that 7 ± 2 is the maximum number of unrelated items the STM can store at the same time. It is possible to train the short-term memory performance to increase capacity, mainly by using a technique called "framing" which means actively identifying a pattern, category or sequence that groups or contextualizes the items into coherent chunks. Examples include associating items with a story, an experience or a theme.

One way to decrease the load on working STM (thereby) is to practice tasks and movements until they are stored in the long-term memory. This training decreases a human's sensitivity to stress by liberating working memory so that its limited capacity is no longer occupied by routine actions.

After information has been processed, the human brain has enormous storage capacities in its long-term memory. Recalling information from there can be either easy for strong memories or frequently practiced behaviours, but may sometimes be dependent on appropriate cues that stimulate recall of events and experiences months or years ago (Kroemer and Granjean, 1997 p. 180; Bohgard, 2009). When we perceive something, this often allows association to items in our long-term memory.

Memory can be categorized as in Table 5.4.

The ability to recall and store information both from short-term and long-term memory is deteriorated by stress, fatigue, hunger, disturbing sounds, etc. Particularly stress can affect the capacity of our STM to the point where tunnel vision occurs, leaving the human fixated on handling only one infor-

Table 5.4: Categorization of memory.

Declarative memory: requires active recall	**Non-declarative memory: does not require active recall**
• *Semantic memory* – meanings, concepts, understandings. *Examples:* language, abstract knowledge about the world • *Episodic memory* – past personal experiences and events, known as *autobiographical* memory. *Examples:* places, dates, times, associated emotions	• *Procedural memory* – also known as *implicit* memory. This type of memory is associated with motor learning and is not consciously recalled, but translates automatically to actions or movements. *Examples:* riding a bike or tying shoelaces. • *Perceptual memory* – Allows recognition of sensory stimuli as meaningful. *Examples:* recognizing faces, voices, smells.

mation source and unable to take in additional sensory stimuli, a situation which could prove to be dangerous. Some memory recall deterioration may also result from age, but this is highly individual – keeping the mind active and stimulated can lessen such effects.

Perception

Our capacity to take in information from the environment, associate it with meaning and mentally organize it is called perception. This capacity is based on previous recognition, knowledge and experiences, which gives us a basis for selecting, interpreting and categorizing information. This basis for making meaning is what creates our mental models, or expectations of how things appear. These preconceptions speed up our mental processing capacity, but also make us susceptible to illusions. Illusions are when our interpretation of sensory signals are mismatched with reality. Examples include optical illusions (Figure 5.2) and when the brain automatically filters out information that it has learned to sort as meaningless (Figure 5.3). It is important to note that our expectations and the context that information appears in greatly influence what the brain filters as meaningful information or categorizes as having a certain meaning.

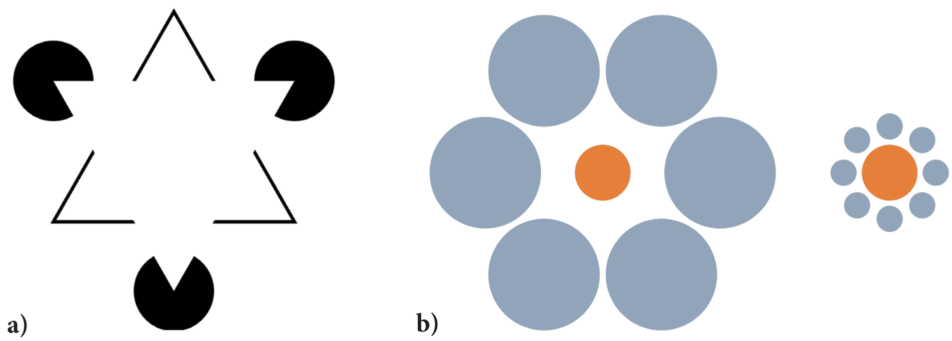


Figure 5.2: Examples of optical illusions: in some cases we a) see things that aren't necessarily there, as in the Kanisza triangle, or b) interpret the size of identical shapes (the orange dots are the same size) incorrectly due to confusing "clues" from surrounding information, as in the Ebbinghaus illusion.

Images sourced from Wikimedia Commons (both credited to Fibonacci/Wikimedia Commons, 2014a and 2014b).

Figure 5.3: Many people cannot see anything wrong with this book title. Can you?

Image by C. Berlin.

Mental models

The idea of "mental models" provides a language for speaking about expectations that people have. What is important is that these expectations sometimes lead a worker or user to look for specific cues in order to interpret their surroundings or a machine interface, and will then interpret them according to previous knowledge and experiences. There may sometimes be a mismatch of the mental model with the actual reality, which can result in errors or mistakes. Therefore it is very important to clearly convey the correct mental model of a tool, product or system. This is especially true for instructions and in education or training.

For example, the word "tree" is a visual or auditory signal that carries a symbolic meaning, but that symbol does not actually tell us what the tree looks like, how tall it is, how wide, how leafy, etc. Most human adults have learned that a tree can appear in many different ways and still be classified as a tree; this means that the mental model of a tree has some degree of uncertainty, but can generally be expected to have a trunk, branches, and leaves.

However, "Palm tree" may set different expectations on what that tree looks like, and depending on what kind of palm tree a human has encountered before, they may expect anything from a very long, smooth trunk with long leaves and coconuts at the top, to a short, wide mess of rough, fibrous trunk exploding into an array of fan-shaped pleated leaves. These are examples of two different mental models of a palm tree, and they are based on knowledge, experience and cultural background.

The same can be said of mental models of a "factory": in different minds, the expectations of what a factory looks like may be very different, depending on familiarity with different sectors, exposure to historical or cultural representations, childhood encounters, etc.

5.5. The role of expertise: The SRK model and types of mistakes

As we practice anything, be it physical or cognitive, we gradually develop skills. We progress from being a novice (a beginner) who is dependent on instruction, via an intermediate state where become less dependent on confirmation that we are doing things right, to a highly skilled state of being an expert, where actions, rules of thumb and cause-effect relationships have been internalized and stored in our long-term memory (or as some say figuratively, in our bones).

This progression from novice to expert has been described by a classic theory known as Rasmussen's SRK model, short for Skills-Rules-Knowledge (Rasmussen, 1983). This theory states that humans make decisions and solve problems in three different modes:

- **S** – Skill-based: actions performed without consciousness and routine actions; sensory- motoric responses
- **R** – Rule-based: actions governed by rules, procedures and old knowledge; involves recognizing signs and associating to related process status, which is then associated with stored rules.
- **K** – Knowledge-based: actions which require explicit thinking and problem solving; based on identifying the meaning of symbols and making a plan. Includes trial and error.

(Adapted from Rasmussen, 1983)

A novice frequently operates in the knowledge-based mode, dominated by cognitive processes that are highly dependent on short-term working memory, which is limited in how much new information it can store. Novices can therefore need more time to interpret and perform tasks, be more easily overwhelmed or mentally overloaded by their work environment and tempo, and make more mistakes based on forgetting or misinterpreting rules. As they learn, intermediate novices gradually adopt more rule-based action, which is based on accumulated, stored knowledge. An expert, on the other hand, acts and reacts almost instinctively in the skill-based mode, with greater task speed and fewer mistakes. When errors do occur, they are more like slips or lapses of concentration – simply put, "sloppiness".

A related theory by Reason (1990), characterizes different types of errors that relate to different levels of cognitive processing:

- **Slip**: correct plan but incorrect action; easily observable.
- **Lapse**: correct plan but incorrect action; more unnoticed causes (such as forgetting).
- **Mistake**: incorrect plan; caused by incomplete or incorrect knowledge.

(Adapted from Reason, 1990)

5.6. Mental workload

Measuring mental workload is complex because an assessment of total workload should, to be fair, take consideration of all the different components of cognition and of surrounding factors that are known to influence mental performance. Also, many of these factors are hard to measure objectively, which leads to the conclusion that measuring mental workload is often a measurement of the individual's perception of it. However, this information is still useful, as it can be used as a before-and-after type baseline for evaluating cognitive ergonomics improvements. If a measurement is made before a change and the individuals asked perceive an improvement after it, the mental workload can be interpreted as lessened for that workforce.

NASA (NASA, n.d. and Hart and Staveland, 1988) has developed a rough questionnaire method for measuring total mental and physical workload, called NASA-TLX (Figure 5.4). This lets individuals rate their workplace or task with regards to six different components of physical and cognitive loading and support.

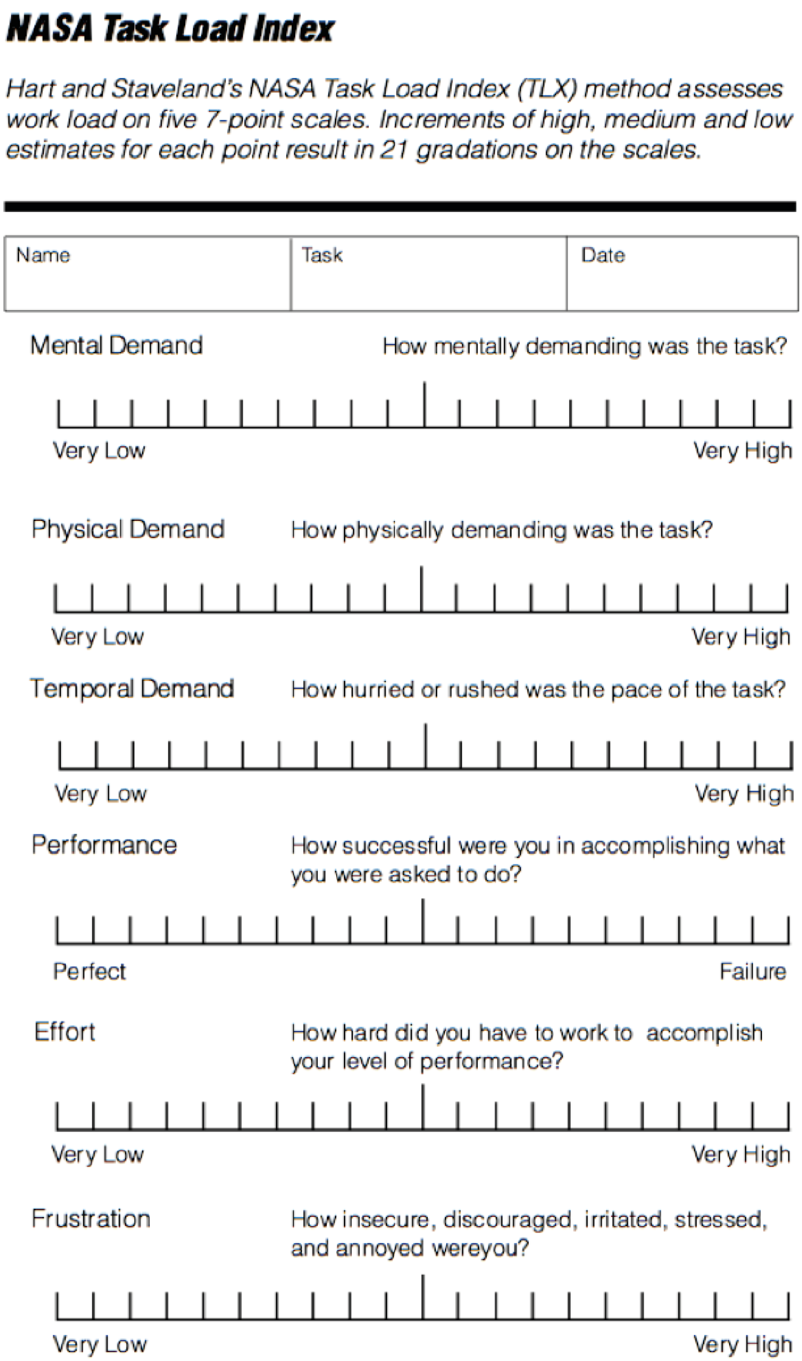
5.7. Designing to support human mental capabilities

Design principles

The following sections offer specific design principles geared at supporting the human cognitive capabilities of attention, perception, memory and mental models. This list is adapted from a more extensive one by Bohgard (2009 pp. 394–399).

The thirteen design principles are:

1. Minimize time and effort for finding information
2. Proximity/closeness
3. Engage multiple senses
4. Legible displays
5. Appropriate number of information levels
6. Avoid only knowledge-based data
7. Redundancy
8. Avoid similar objects



NASA Task Load Index

Hart and Staveland's NASA Task Load Index (TLX) method assesses work load on five 7-point scales. Increments of high, medium and low estimates for each point result in 21 gradations on the scales.

Name	Task	Date

Mental Demand — How mentally demanding was the task?

Very Low — Very High

Physical Demand — How physically demanding was the task?

Very Low — Very High

Temporal Demand — How hurried or rushed was the pace of the task?

Very Low — Very High

Performance — How successful were you in accomplishing what you were asked to do?

Perfect — Failure

Effort — How hard did you have to work to accomplish your level of performance?

Very Low — Very High

Frustration — How insecure, discouraged, irritated, stressed, and annoyed wereyou?

Very Low — Very High

Figure 5.4: The NASA-TLX form with its six sub-scales (NASA, 2014).

Source: NASA Ames Research Center; Used with permission.

9. Minimize the amount of short-term memory data
10. Show anticipated system status
11. Consistent/natural representation
12. Illustrated realism
13. Show movable objects for dynamic information

Table 5.5: Key design principles for supporting attention (adapted from Bohgard, 2009).

1. Minimize time and effort for finding information	Efficiency and motivation of work decreases when too much time and effort is spent searching for relevant information. This includes having to look for information in different places, in different menus, displays, etc. Frequently used information should be easily accessible and emphasized, and thematically related information should be grouped together.
2. Proximity/closeness	Similar or related information sources should be visually linked. Use physical nearness; indicators such as lines, arrows or boxes; or a uniform format of colour, pattern, shape, typeface or the like. In the case of auditory signals, use easily recognizable differences in pitch, loudness, repetition rate, rhythm and melody to distinguish similar and non-similar information.
3. Engage multiple senses	When needing to pay attention to large amounts of simultaneous information, it helps to engage multiple senses. Alternate between vision, sound and touch to deliver different types of signals.

Supporting perception

Table 5.6: Key design principles for supporting perception (adapted from Bohgard, 2009).

4. Legible displays	Legibility means "possibility to read". Support perception of text using high contrast, appropriate illumination, sufficiently large text, a clear font and the correct viewing angle.
	From an auditory perspective, use clearly distinguishable sounds (for example use a clearly different pitch to the surrounding ambient sounds that normally occur in the environment) – as for loudness, remember that the purpose is to convey information, not to jolt, scare or distract the listener. For both of these aspects, be careful to design so that legibility is possible for elderly workers with decreasing vision and hearing.
5. Appropriate number of information levels	It is advisable to limit levels of information to three, since increasingly nested structures challenge expectations of where to look for information and take a long time to search through. To ensure that colour-vision impaired can distinguish between colours in an interface, it is advisable to limit colour codes to two. It is also hard to distinguish more than five levels of line thickness, shape differences or fonts. (Sounds cannot, as a rule, be presented hierarchically, since they are transient in time.)

6. Avoid only knowledge-based data	Quite frequently, the preconceptions and expectations of a human will override purely responsive reactions to stimuli; therefore, to ensure that unexpected signals are correctly interpreted, such messages must be reinforced and emphasized, for example with more central placement on a display, flashing, size increase or colour change.
7. Redundancy	It is possible to reinforce accurate interpretation of a message if it is presented in more than one way, using several modalities or senses (for example, both visual and auditory cues can be used for alarms) or more than one sensory representation in the same sensory domain (e.g. image + text, shape + colour or sound signal + voice).
8. Avoid similar objects	When stimuli (such as objects, symbols or sounds) appear to be similar, the brain associates the same meaning to them, which may lead to confusion or misinterpretation if they have different functions or meanings. Therefore, it is important to signal differences in function with clear differences in appearance, size, duration, placement, structure, etc.

Supporting memory

Table 5.7: Key design principles for supporting memory (adapted from Bohgard, 2009).

9. Minimize the amount of short-term memory data	As far as possible, free the short-term memory from loading. Use the operators' "real-world knowledge" and learned behaviours to lessen dependency on working memory resources. Use the idea of the "magical number" 7 ± 2 as a maximum for simultaneous sensory stimuli.
10. Show anticipated system status	Design the system or interface to signal future states (for example showing a progress bar in software). This removes the mental load from the operator of calculating or guessing what will happen next based on available data, and makes the task into a simpler perceptive one. Letting the system do the forecasting frees the operator's mental capacity and supports *proactive* action; in the opposite case, a mentally overloaded operator can only respond *reactively*. For sounds, designed transitions in loudness or pitch can indicate changes in state over time (for example the decreasing pitch of a running-down motor).
11. Consistent/natural representation	If operators (usually experienced ones with many learned routine behaviours) are used to a particular configuration or interface design, changing the design too drastically from the familiar layout (such as changing colour coding) may be a source of mistakes and slips. New designs should correspond to learned rules and interpretations among the operators.

Supporting mental models

Table 5.8: Key design principles for supporting mental models (adapted from Bohgard, 2009).

12. Illustrated realism	Use visual cues that correspond to reality when designing information – the aim is to correspond to the operator's mental model of a measurement (such as showing temperature on a vertical scale) or a place (such as on a process status display, where machine statuses should be arranged the same way as the machines in reality).
13. Show movable objects for dynamic information	Use animation, sound modulation and other dynamic representations, making sure that movement indicating status changes over time match the operator's mental model of the process change. For example, a sound that decreases in pitch might correspond to a sinking or lowering movement.

5.8. Cognitive ergonomics supports used in industrial production

Having introduced the concept of cognitive ergonomics and the capabilities of the human mind, we will now bring it closer to home and look at how this topic affects the operator in production industry. Many different tools and methods that aid the operator from a cognitive perspective exist in the assembly environment, limiting the mental capacity required. Interestingly, a number of these methods came about purely from the desire to optimize the performance of systems, rather than to specifically provide operators with cognitive support; the added cognitive benefits sort of came about as an added bonus almost unintentionally. This section will introduce various different ways in which cognitive ergonomic considerations are effectively being used in the production environment. The key aspects we will discuss are:

- Design for assembly
- The use of fixtures
- Kitting
- Standardized work
- Work instructions
- Poka yoke
- Pick by barcodes
- Pick by light
- Pick by voice
- Andon systems

It is important to note that no single solution is accepted as the go-to standard approach; rather, the solution is dependent on the nature of each individual business at that time, given their unique requirements, size, strengths and weaknesses. In some cases, businesses choose to adopt one approach at one time and then switch to another or multiple approaches as new issues arise within their business activities. Typically, this decision depends on characteristics such as cost, quality, delivery time and delivery time reliability, production system flexibility, and product flexibility. Certain concerns are generally considered to have a higher priority than others at different times. All of these support systems are based on the idea that it should be hard to do things wrong.

5.9. Design for Assembly

A recurring problem in industry is that all too often the product is designed without consideration of the fact that the product has to be put together by an assembler in a production facility. Design for assembly (DFA) is a method which aims to encourage designers to think about the assembly implications of their design, for instance by minimizing the number of required components and enabling as simple an assembly method as possible (Boothroyd, 2002). This should in turn lead to reduced times and cost during the manufacturing stage, while maintaining quality.

DFA aims to enhance the level of communication between the manufacturing and design teams, to ensure an optimized solution meeting the requirements of both parties is achieved. Taking DFA into consideration during all stages of the product's design and development right from its conception reduces the need to make design changes late in the process. The DFA procedures and design rules that should be followed differ depending on whether the product is manually or automatically assembled. The general DFA guidelines try to address two key areas, the handling of parts and the way in which parts are connected or fastened.

The basic concepts of the DFA methodology will be briefly introduced below; however, to gain a full understanding of this method, the exact details on how to carry it out on a real product and the quantitative tools that exist can be found in Boothroyd's *Product Design for Manufacture and Assembly* (2002).

The following are general guidelines that should be considered during the design of products, as they will have a positive impact on the assembly stage of the product, aiding the operator with their work tasks from both a physical and cognitive perspective.

Where possible, parts should:

- Use geometrical features: symmetrical, or obviously asymmetric for instances where symmetry can't be achieved.
- Design parts that cannot be attached incorrectly.
- Use shapes or features that ensure parts won't stick together when in mass storage containers.
- Avoid shapes or features that will cause parts to tangle when in mass storage containers.
- Easy to handle, avoid very small or excessively large, slippery or sharp parts that could be difficult or hazardous to handle.
- Reduce the count and part types.
- Ensure sufficient access and visibility is provided

Having symmetrical or obviously asymmetrical shaped parts will ease the task of the assembler and reduce mental load as the way in which the product should be assembled is much more obvious, so to some extent the shape of the part acts as an unspoken intuitive work instruction to the assembler. It also contributes to time saving in assembly as it reduces or eliminates the need for the operator to reorient parts during assembly. The other guidelines are more related to physical ergonomics considerations and the reduction of poor postures and potential frustration areas for the operator, such as constantly having to spend time untangling small springs from each other or straining their neck to ensure parts are aligned and attached correctly.

5.10. The use of fixtures

Providing assemblers with nothing but a table and a few tools would likely result in high levels of frustration, dissatisfaction, disorder, confusion, poor posture, MSDs and eventually absenteeism. To remedy these problems, carefully designed fixtures are installed at workstations to ease the mental workload on operators and improve performance and efficiency. A fixture is a device that holds or supports the work piece during manufacturing operations. It enables the part to be held securely in a specific orientation, freeing the users' hands so other parts can be attached to it and necessary processes such as tightening carried out. Fixtures can also be used to hold tools supporting their weight so the operator only needs to ensure their position relative to the product and not take the weight.

A jig is a device that is pretty similar to a fixture, but also provides support in the processing operations by guiding cutting tools. The complexity and usefulness of fixtures varies, in some cases a simple device locking the part to the table top is sufficient; however, for more complex heavier products a much more sophisticated fixture is necessary, with additional capabilities, such as the ability to rotate, etc.

A number of considerations should be taken when designing fixtures to ensure they are optimizing the operator's capabilities both physically and cognitively, as they can play a significant role in providing the operator with cues and clues. The alignment of fixtures on the workstation should correspond to the order the assembly tasks should be carried out as well. The alignment of fixtures should also take into the consideration the way in which the material will be supplied to the workstation, so as to reduce the time spent orienting the material. By having a fixture that determines how the product should be orientated, the need to recall details from memory is reduced, which is particularly beneficial for operators who work on several product variants. The shape of fixtures is often a negative form of the part or component that needs to be assembled so also acts as a device to aid the assembler.

5.11. Kitting

Kitting is a method where all the required components necessary to make a product or subassembly are delivered to the operator's workstation inside a container called a kitting bin. The container often uses templates or is structured in such a way that the components can only be stored one way. Having a structured layout provides support for the assembler indicating in which order the parts should be removed and assembled, while supporting the kitter by visually showing what parts are required and in what quantity. The kit also acts as a memory trigger or early warning symbol because if the box is not empty when the worker has completed their task it is clear they have made an error somewhere during the assembly. While the value of this technique has been questioned from a materials handling viewpoint, as we will see in a later chapter, there is no doubt that from a cognitive perspective it benefits the operator.

5.12. Standardized work

Standardized work is a key part of lean manufacturing philosophy; it stops everyone from taking the "this is my way of doing things" approach and rather provides an optimized standard method that all workers should take (assemblers, machine maintenance, managers, etc.). This method means workers don't need to choose between numerous possible ways of completing the task, rather there is only one clearly defined way, the best way. By providing workers with a specific set method to carry out tasks, over time the process will become engrained in their memory, reducing the time and energy associated with memory recall. By combining all the different elements of the worker's task into a sequence, efficiency and productivity can be achieved as well as cognitive support for the worker. The use of other methods such as kitting contributes to standard work as the material is presented in a certain order, based on the standardized way the part should be assembled. Standardized work not only applies to the necessary sequence of tasks the assembler should conduct; it also applies to the state of the workstation. So pictures are often displayed showing what the normal condition of the workstation is and how it should be left and the end of a shift. In Toyota's Total Quality Management Philosophy, having standardized processes is key, as it provides the baseline needed to facilitate continuous improvement (kaizen-implementation of incremental change) (Womack, 1996). Workers are encouraged to identify potential areas of improvement that could become the new standardized procedure, which helps to create a satisfying and fulfilling work environment. Standardized work generally involves a high level of documentation. This can be particularly beneficial for training purposes, making it easier for new personnel to get to grips with quickly.

5.13. Work instructions

In its simplest form, a work instruction provides the operator with written guidelines or pictures of how the part should be assembled. Some work instructions can be quite open, only specifying the key distances or torque required with little guidance on the specific details of how the operator should actually perform the task. Other instructions utilize standardized work principles, ensuring operators are aware of the only correct way of implementing the necessary tasks. Instructions can be provided in paper form or through specialized training; however, the recent trend is for production facilities to have computers and screens located at the workstation. These provide operators with information and the necessary instructions (both text and pictures) as to how parts should be assembled. The operator has access to all the parts stored on the system and can obtain the necessary information by entering the part identification number. In some systems instead of manually typing in the part identification number to view the instructions, the operator simply scans an ID card and instructions for the part in question are provided; this method contributes to quality control as all defects can be traced.

More complex systems utilize picking by light. Initially the user is guided to the necessary material, then for assembly operations a light ball is situated where the production step is carried out and is illuminated when necessary. A sensor then picks up the assemblers presence and provides them with a current work instruction on the display screen. Only when the task has been correctly carried out can the assembler move onto the next step. For instance if only five screws have been mounted instead of the required six the system won't allow the operator to conduct the next step and an alarm will sound, alerting them of their error. This method also limits the need for operators to spend time and energy retrieving information from their memory or trying to correctly interpret a scenario. This is particularly valuable in environments where a high number of similar product variants exist, providing operators with the correct level of support. Such systems can be used anywhere and by operators of any nationality as the onscreen instructions can be in several languages. This ensures that a standardized way of work is followed throughout the whole company regardless of the geographic location of the different sites. Using a software based system also means that should any modifications to the assembly instructions need to be made; the system can be updated with no hassle with changes being made to all stations on the line simultaneously.

5.14. Poka yoke

A number of mistakes in production leading to defects and reduced quality are a result of assemblers simply forgetting to do something. Poka yoke was introduced as an attempt to combat this issue, eliminating defects by correcting or alerting humans of their errors as soon as they occur. *Poka yoke*, a term that originated in Japan, means "mistake proofing" and is concerned with preventing errors from becoming defects before the fact. Many production facilities purposely implement tools, equipment or procedures for error proofing, making it very difficult for mistakes to be made. By only providing one way of holding or storing the part, both kitting containers and fixtures at the workstation act as poka yokes.

Pick by barcodes

This method utilizes barcodes and an optical barcode scanner. A terminal provides the operator with real-time data collection information about where they need to go, what they need to pick and in what quantity, using either text or images. The operator uses the device to scan the barcode on the storage box and the terminal provides them with information regarding the desired quantity. The barcode scanner and terminal are either handheld, secured around the lower arm, or truck-mounted. This system tends to be more cost-effective than pick by light in lower volume environments. However, unlike other picking systems, the operator needs to look at the screen to retrieve the necessary information, which can be an inconvenience. This system is considered to be one step up from using a paper sheet to carry out picking tasks; however, it is not suitable for certain work environments when operators need to wear protective clothing such as gloves.

Pick by light

This method uses lights positioned on shelves, flow racks or work benches to direct and indicate to the operator what they should do next. At the right point in the sequence, the light will guide the operator to a certain location. Once they have completed the task the light will either go off automatically based on sensors or the operator will manually confirm the action by clicking the illuminated button, triggering the next light in the sequence to illuminate. In addition to a light, some systems are fitted with a display showing the necessary quantity or other information.

Despite being called pick by light, this method is not limited to picking. It can also be used to provide information about assembly tasks, for instance which tool should be used and what torque should be applied. The system can also indicate the correct storage container for items to be placed in after assembly ("put to light"). This system is considered more user-friendly than picking by barcode, as the operator's hands are kept free. Many argue that this system is the fastest picking method, as users don't need to refer to a screen or wait to hear instructions; rather, their attention is instinctively drawn towards the light. Should changes be made to the assembly line, the light modules can be easily moved and updates made to the software infrastructure.

Pick by voice

This system is similar to pick by light but uses the sense of hearing to gain the operators' attention, rather than lights. Each operator wears a headset and is provided with the necessary information to know what to pick, in what quantity and where it is located. In this method both the user's hands and eyes are free. To confirm the pick, the operator can use voice control where they will repeat some of the product information (e.g. the last four digits of the barcode), or a sensor positioned in the container will detect their selection. Unlike pick by light, this technique can be used even when multiple operators are working in the same area. The use of both pick by voice and pick by light make it relatively easy for new workers to learn their new work tasks quickly.

Andon

Andon systems provide a visual display that all workers can see to show the status of the plant floor. Enhanced visualisation is said to not only create a sense of belonging in teams, but also point out when problems in the process occur, alerting management, maintenance and other workers down the line who depend on the affected station. Empowering operators to stop the production processes encourages an immediate response, which in turn should enhance the overall quality and reduce waste (Alzatex, 2014). Generally the worker at the directly affected station pulls a cord triggering an alarm or flashing lights to alert the rest of the workforce that a problem has occurred; this can also be automated. Once the issue has been resolved, the andon is deactivated so that work can continue as normal. Many industry facilities have andon coaches whose role is to resolve any issues as soon as they arise.

Study questions

Warm-up:

Q5.1) Name the five senses.

Q5.2) Did you use your long-term or short-term memory to answer the question above? Explain why.

Q5.3) Name three key design factors for designing visual information.

Q5.4) What are the four main cognitive processes that a workplace design can support?

Q5.5) Using the SRK model by Rasmussen, explain the difference between how a novice and an expert process information when performing a task.

Q5.6) How do poka yokes help to support human cognitive abilities?

Look around you:

Q5.7) Imagine (or even better, visit) an airport, train station or bus terminal. What visual, sound and tactile cues are there to help people know where to go and what to do in order to start their journey?

Q5.8) Habits matter when it comes to sensory stimulation — some signals are so familiar that our brains may have learned a routine to not interpret them as new information. Reflect on which sounds you are able to ignore and which ones shift your attention while you are working — strangers talking around you in a café? Listening to music? Beeping noises? Someone calling your name? Birdsong? The clinking of glasses and plates? The sound of crashing glass?

Connect this knowledge to an improvement project

- List the main sensory information sources (vision, sound, touch, etc.) and consider whether the worker could use other senses to be alerted to the status of the system.
- Also consider whether any sensory inputs, or a combination of them, risk to overwhelm or confuse the worker.
- Identify the tasks that need to be performed to a certain quality level – what conditions would be optimal to reach this quality level?
- Use principles of cognitive abilities and limitations to design aids to the work, such as instructions, guides, signals and fixtures.

Connection to other topics in this book:

- Good cognitive ergonomic design of a workplace can help to improve the quality and efficiency of operations, usually by decreasing the occurrence of errors and waste of material and time – this leads to good economics (see Chapter 11). Therefore, it is a good idea to measure the status of these improvement potentials and losses before and after a cognitive ergonomics improvement, to gather evidence of how much improvements can make a difference from a cost perspective. This will also help the workplace improver to formulate a good business case.
- Environmental factors (Chapter 12) are in themselves stimuli of human senses that can confuse or overwhelm the human at work. Taking these factors into account should always be done alongside considerations of making cognitive ergonomics improvements, and care should be taken so that adaptations to the environment (e.g. using gloves, protective equipment, etc.) do not hinder the human's cognitive abilities.

Summary

- There is a need to design workplaces for workers' mental capacities, as well as their physical.
- Workplace designs that lessen the impact of fatigue can help to decrease unnecessary mental workload and avoid hazardous accidents.
- The brain, aided by the senses, processes and interprets information from the environment, enabling decisions to be made.
- Cognitive abilities are a combination of skills, experience, pattern recognition, attention, memory, ability to focus, expectations and associations.
- Vision is connected to perception, with the human mind always looking for patterns and structure that can be determined as meaningful.
- Contrast, colour intensity and strength of lighting all affect a human's ability to take in visual information.
- Sound complements vision – particularly in environments that can overload us with visual stimuli, sound can be used as a warning for workers.
- Cognition is a combination of sensory stimulation, focus, perception, working memory, long-term memory and interpretation.
- Memory enables information, experience and rules to be stored in the brain.
- Short-term memory allows us to recall recent events but is limited in how many information points it can store, typically 7 ± 2 chunks of information.
- After information has been processed, it can be stored in the brain's long-term memory, which has enormous capacity.
- Recalling information from the long-term memory is easy for frequently occurring events, but cues (significant signals) are often required to stimulate recall of events from long ago.
- The 13 design principles introduced should be considered when designing to support attention, perception, memory and mental models.
- Tools such as DFA, standardized work, fixtures, kitting, poka yoke, picking aids and andon should be used in industry to support workers.

Notes

1 Also known as the "reptile brain".

2 Knowing the position of parts of our body in space and what condition our muscles are in, i.e. whether they are contracted or not. This is also called *proprioception*.

5.15. References

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