Initial Development of a Cognitive Load Assessment Tool

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ABSTRACT

Interest in cognitive or mental workload has over the last couple of years increased drastically from a manufacturing application perspective. More and more, people are becoming aware of the cognitive limitations that may have great impact on production outcome. The more easily observable area of physical ergonomics has been successfully investigated for a long time and it would seem as though focus has broadened to also include cognitive ergonomics. Considering the effects that a large cognitive load has on human performance, knowledge regarding the role of the cognizing human in a manufacturing environment could potentially have significant effect on production outcome (i.e. quality and productivity). With this in mind, developing and using methods and tools for assessment of the cognitive burden associated with particular tasks or workstations should be and is of substantial interest to the manufacturing industry. Whatever assessment methods exist in the scientific literature today are almost exclusively expert tools where significant expertise in the area of cognitive ergonomics/psychology/science is required. This paper reports parts of the development process and initial version of a non-expert tool for assessment of cognitive load in manual production environments, primarily manual assembly.

Keywords: Cognitive load, assembly, manufacturing, assessment

INTRODUCTION

This paper presents initial development of and assessment tool for cognitive load. Development of the tool has included identification of other cognitive load assessment tools (NASA-TLX, CLIMATE, SWAT etc.), physiological measurement technologies that indicate cognitive load levels (heart rate variability, eye tracking, skin conductance etc.), as well as connections between these tools and technologies with available, assessable factors in manufacturing. This has resulted in identification and classification of factors suitable for assessment of cognitive load, organised into a framework consisting of two separate factor components; *environmental factors* (shift, production rate etc.) *sensor data* (heart rate, skin conductance etc.) *task factors* (variant flora, batch sizes, tool use etc.), and *work station factors* (instruction quality, workstation design etc.). The developed tool in its initial version, which is reported here, handles primarily the task and workstation factors. It is designed for easy use by production personnel, technicians and team leaders and is aimed at, pro-actively, identifying risks in task and workstation design where a high cognitive load might lead to errors or difficulty of work. Thus negatively affecting production outcome. The current tool consists of an evaluation form for 12 separate factors that are weighted together to form an assessment of a task performed at a workstation. Future development of the tool will include validation and further weighting of the factors as well as development of a reactive module incorporating sensor and environmental data such as physiological measurements and contextual input into the tool. Since the tool is to be used by non-experts, it will not require a researcher or anyone with any major knowledge of cognitive psychology or human factors. For the tool to be usable by these user roles, most likely production leaders and technicians, a handbook that

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will cover a brief introduction and guidelines on how to assess each factor identified in the tool will accompany the tool.

Two modes of cognition

Perception, decision-making, problem solving, memory processes et cetera are examples of cognitive activities that enable the human being to experience and act in the world. These cognitive processes are constantly processing information that indicates that human beings always experience some level of cognitive load. Cognitive load (or mental workload) refers to the mental/cognitive demand that performing a specific task imposes on the human's cognitive system. The level of cognitive load is constantly fluctuating as a response to the stimuli that the situation, the task, and demands are imposing on the human. This is naturally individual and depends on the individual's experience and previous knowledge. While some situations make it possible for the individual to perceive and interpret the stimuli and the pattern of information and without an apparent effort generate an appropriate response, some other situations demand conscious awareness and reflection. This implies that some cognitive processes of an individual are more demanding than others.

In order to develop our tool properly, there is a need to better describe the ways in which technology interacts with people and with human cognition. There are many modes of cognition, in which different kinds of thinking can take place. Norman (1993), for example, describes two different types of cognition that are particularly relevant for accomplishing the task of developing this tool. He denotes them as *experiential* and *reflective* cognition. Roughly speaking, experiential cognition is characterized by an automatic nature and the reactions to the situations appear to flow naturally. This is likely to be due to experience and, depending on the task, sometimes years of training are required in order to achieve this. Norman (1993, p. 23) explains this with the words: *"Experiential thought is reactive, automatic thought, driven by the patterns of information arriving at our senses, but dependent upon a large reservoir of experience"*.

The reflective mode, on the other hand, is about concepts, planning and reconsideration. Reflective cognition does often require external support (computational tools, writing et cetera) and also the aid of other people. Norman (1993, p. 25) expresses: *"Reflective thought requires the ability to store temporary results, to make inferences from stored knowledge, and to follow chains of reasoning backward and forward, sometimes backtracking when a promising line of thought proves to be unfruitful. This process takes time."*

Similarly, Kahneman (2011) differentiates between the automatic operations of *System 1* (which he generally refers to as 'fast thinking', which is similar to experiential cognition) and the controlled operations of *System 2* (which he generally refers to as 'slow thinking', which is similar to reflective cognition). The process of demanding and effortful mental work is related to system 2 in which the demands of memory and other aspects of performing non-automatic cognitive tasks actually put some constraints on the cognitive processes, resulting in a slower thinking process because of the limited available cognitive capacity, resulting in increased mental load. Broadly stated, Kahneman (2011, pp. 20-21) describes the two systems as follows:

- *System 1* operates automatically and quickly, with little or no effort and no sense of voluntary control.
- *System 2* allocates attention to the effortful mental activities that demand it, including complex computations. The operations of System 2 are often associated with the subjective experience of agency, choice and concentration".

Kahneman (2011) points out that some of our mental activities become fast and automatic because of prolonged practice, although they from the very beginning needed conscious attention, e.g., reading skills which normally runs on our automatic pilot in the skilled reader. The limited capacity for attention is the central pinnacle for mental load, and when acting beyond that limit, failure appears. The division of labour between the two systems is very efficient, it minimises effort and optimises performance, in most of the time. However, System 1 has some biases, and sometimes provides the wrong reaction and this cannot be turned off. This becomes obvious when there is a conflict between the two systems. One major task of System 2 is to overrule or provide a reflective and conscious "second opinion" of the automatic reactions of System 1. This is for instance common when perceiving so called optical illusions, like the Müller-Lyer illusion (see Figure 1), or when perceptual information is conflicting, as is the case in the Stroop test where subjects are asked to report the name of a colour (e.g., "blue," "green," or "red"), denoting another colour (e.g., the word "red" printed in blue ink instead of red ink) (Stroop, 1935).

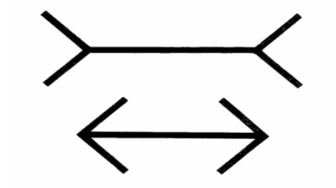

Figure 1. The Müller-Lyer illusion

Looking at figure 1, although consciously knowing via System 2 that the two horizontal lines have the same length, the automatic reaction when visually perceiving the two lines via System 1, offers another answer that is hard to deny, namely that the lines seem to be of different length. Following this line of argument, humans sometimes suffer from *cognitive illusions*, i.e., illusions of thought, which are quite hard to detect and overcome. The reason is that System 1 operates automatically and cannot be switched off by choice, and biases cannot be avoided since System 2 has not received any hint that there might be an error. A promising way to overcome this bias is learning to recognise particular situations in which mistakes are likely to appear. Continuously questioning our thought processes via System 2 is not a viable approach, however, since it is impractical, too slow and has a limited capacity (Kahneman, 2011). These failures in translating our environment are by no means limited to perception but are present in all cognition in the form of cognitive biases.

To sum up, the both modes of cognition; (1) *System 1/Experiential cognition* and (2) *System 2/Reflective cognition* are needed and neither is superior to the other, but they differ in requirements and function, as described earlier. It should be pointed out that they are essential for human cognition, although each mode requires different kinds of technical support to function properly. Figure 2 below displays the two modes of cognition in the so called "cognitive iceberg" model and visualises that Experiential cognition/ System 1 are the mode that is less demanding, and has the largest capacity, while the Reflective mode/ System 2 requires a higher degree of awareness, has a limited capacity, and is the mode we usually assume is the place in which "thinking" actually occurs. However, these two modes of cognition do not cover the whole cognitive spectrum, but it make it possible to highlight and compare certain characteristics of human cognition. In everyday life, we use a mix of these modes simultaneously, and the challenge when designing technology is to avoid forcing the use of technology towards one extreme or the other. That is, there is a need to have a proper balance between reflection and experiencing, so the human cognizer is not forced to use her/his limited conscious capacity to interpret the user interface as such, instead the human cognizer should use the cognitive capacity to solve the problem at hand or make an appropriate decision.

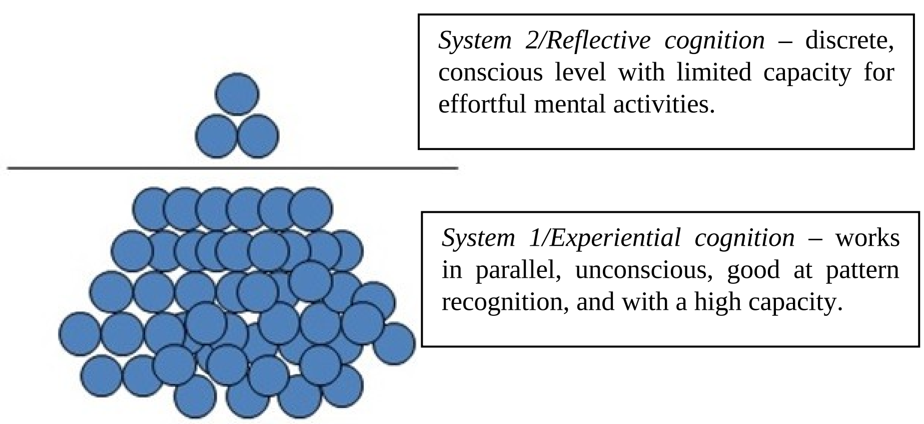

Figure 2. The cognitive iceberg model, depicting the two different types of cognition – System Cognitive Engineering and Neuroergonomics (2019)

1/Experiential and System 2/Reflective cognition.

Cognitive load

The most central form of psychological demands, according to Karasek and Theorell (1990), is mental workload. Mental workload refers to the amount of mental effort required to perform a task, and is increasing at such time pressure. It is also possible to describe these psychological demands in information processing terms, as the amount of disorder or disorganization in a task that the employee is forced to arrange an organized state. As an example, Karasek and Theorell mention the tasks a chaotic office supervisor must manage and track order in. To create this system causes stress on the employee's cognition and require intense concentration without distracting thoughts (Karasek & Theorell, 1990). This example can serve as a metaphor for a messy computer-based interface; whether the information in the interface is not arranged in a logical way that supports the user's cognitive abilities (e.g., pattern recognition, which is an automatic process belonging to System 1), he/she must make the mental effort to find out how information is organized (belonging to System 2), which also takes power from the actual task.

What Karasek and Theorell (1990) describe as *mental workload* can also be referred to as *cognitive demands*. Eisele (2007) describes how the cognitive requirements of different types of stimuli in the psychosocial work environment in varying amounts stimulates mental activity. Hultberg, Dellve, and Ahlborg (2006) adopts a more restrictive attitude when they equate cognitive demands of problem solving. Such a limited view of the cognitive demands is likely to overlook other important loads that may be imposed on human cognition, such as decision-making, joint attention, or information in an interface with poor usability. It is also important to distinguish between the requirement in itself - the external requirement of problem solving - and the response to this requirement - the practice of problem solving as a cognitive process. This view of cognitive demands are seemingly stronger, as it has a broader scope that includes several different causal factors, not just problem solving. Eisele’s (2007) description also has a clearer focus on external demands - stimuli in the psychosocial work environment - which is closer to Karasek and Theorell’s (1990) original argument that the demand-control model based on the requirements that come from the individual. Another advantage of Eisele’s perspective is the clarification of the cognitive demands as part of the psychosocial work environment. Cognitive demands are thus, in short, factors in the psychosocial work environment that requires an individual's cognitive abilities. The higher cognitive demands, the higher the cognitive load that the individual is forced to work under. Karasek and Theorell (1990) distinguish initially between high and low demands. Hultberg et al. (2006) argue that it is now getting jobs that have low requirements, and therefore choose instead to distinguish between reasonable and unreasonable demands. Unreasonable requirement then is a factor that can lead to stress in the individual. Whether this occurs depends on the degree of control and social support that the individual has to take to deal with these demands (Hultberg et al., 2006; Karasek & Theorell, 1990). Such an abundance of information that the user is difficult to absorb is also known as "information overload" (Case, 2012).

Attention

When it comes to trying to define the capacity limitations of human cognition, attention and memory are the most central cognitive processes to analyze. Attention is a psychological concept that traditionally has been quite hard to define, even though most people believe they know what it is. Despite this, or perhaps because of it, many attempts to understand it have been made. One of the more popular descriptions of attention, and also one that satisfies this paper’s aim very well, dates back to the late 19th century and was formulated by the founder of American psychology, William James (1890/1950, p. 402) who said:

> “Everyone knows what attention is. It is the taking possession by the mind, in clear and vivid form, of one out of what seem several simultaneously possible objects or trains of thought. Focalization, concentration, of consciousness are of its essence. It implies withdrawal from some things in order to deal effectively with others, and is a condition which has a real opposite in the

confused, dazed, scatterbrained state which… is called distraction"

According to Wickens and McCarley (2008) the importance of attention in cognition can be seen at two different levels.

1. One of the three limitations on human information processing

Along with memory and response time, attention is one of the main limiters of human cognition. The study of attention capacity has always been of great interest to psychologists ever since the days of William James. In applied attention psychology this becomes even more relevant as researchers continuously study for instance; how many tasks that can be done at once?, how fast humans can switch from one task to another?, etc (Wickens & McCarley, 2008).

2. Attention is a prerequisite to many other cognitive abilities

Kahneman (2011) acknowledges the role of attention in cognitive limitations and argues that the limited capacity for *attention* is the central pinnacle for cognitive load. Without attention, it would be impossible to keep items in short term memory or to relocate them to long term memory. It is essential in decision making and, according to current perceptual theories, it is vital in perceptual processing (Gibson, 1986; Rookes & Willson, 2000; Wickens & McCarley, 2008).

Attention is not only of great academic interest, but it has also major applied importance in society. The areas where the deployment of attention or an increased understanding of attention is of importance can vary widely from distracted drivers to the reliability of eyewitness testimony to advertising. There are also other applied domains to which attention is closely related. In the study of human error, attention is given much room, particularly when it comes to attention lapses and slips (Norman, 2002; Reason, 1990). This is also closely related to the study of situation awareness (Endsley, 1995), a field of study focused on a user's internal model of current and future states in a dynamic environment. Also, designing systems that comply with the nature of human attention is of great interest in human-computer interaction, human-machine interaction etc. (A. Dix, Finlay, & Abowd, 2004; Jennifer Preece, Rogers, & Sharp, 2002; J. Preece et al., 1994).

Memory

Aside from attention, memory, specifically short term memory, is one of the major limitations of human cognition. Already in 1956, George Miller showed how human short term memory is limited to handling 7±2 chunks at a time, a chunk being anything that carries meaning, a word, a digit, a person, a symbol etc. (Miller, 1956). This is of course highly relevant to assessing cognitive load as the failure of workstation design can easily lead to unnecessary strain on short term memory, which we know is one of the most limited parts of human cognition.

FACTORS OF ASSESSMENT

The rough characteristics of human cognitive processing/load have been the basis for the development of the cognitive load assessment tool, presented in this paper. Identifying what situations lead to a heavy cognitive load has been essential and together with previous knowledge as well as valuable input from colleagues and industry partners, regarding manufacturing, has led to the identification of 12 relevant and observable factors for assessment of cognitive load.

A brief description of the suggested factors can be found below. Note that the unit of analysis is on the workstation level (including both the human and his/her working environment in the unit of analysis), including the tasks and the workstation design/layout. Each factor should thus be considered by their impact on each workstation, not individual tasks. In a later version of the assessment tool, these factors should be accompanied by examples and motivations of good and poor design according to the cognitive and design literature. The factors identified in the current version of the tool include both task- and workstation-related factors. Also, a more detailed theoretical background to the development of the tool and the assessment factors can be found in Lindblom and Thorvald (2014).

Task-based factors

Saturation

The saturation of a task or a workstation can and should be measured through time studies. Most industry have normative descriptions of how much time should be spent on each task and the comparison of this value to the balance of the workstation (the time set aside for the whole workstation), reveals a value for the saturation of each workstation. Naturally, the saturation of a workstation affects stress in the workers as well as their ability to recover between assemblies.

Variant flora (batch sizes)

It is a well-documented fact that the variant flora does have significant effect on production efficiency and it can easily be argued that this effect relates to the mental workload of the worker (Thorvald, 2011). However, the concept of variant is only relevant in, more or less, one-piece production where there can also be said to be a volume product. In many manufacturing companies, one does not consider variant and volume products but different types of products are instead batched together. This greatly benefits ramp up times and allows for routine work by the worker, but does not perhaps comply with lean production, low fill rate through MTO (Make To Order) and other current manufacturing paradigms. However, considering only the mental workload of the worker, batching can become a quality risk when batches are small and workers are expected to adjust to new batches relatively often. What would be considered a high variant flora or a small batch size is very dependent on the product and differences between variants or batches and thus this factor would have to be calibrated internally.

Batching of variants

A common strategy in mixed mode assembly is to batch variants in sets of two or more variant products to reduce ramp up time between product types. The reduction in ramp up time is not exclusively relevant to engineering and production aspects but is also present in assessing the cognitive efforts of the worker. This factor is Boolean.

Level of difficulty

The level of difficulty should be assessed on the entire station and is an estimation of the required physical and mental effort to perform a task. In our experience, in many manufacturing plants there is already an assessment made prior to a task/workstation being introduced to the production line. However, this assessment is often focused on physical ergonomics such as heavy lifting or walking distance and rarely handles cognitive aspects of workplace design.

Difficulty of tool use

The difficulty of tool use should be assessed station wide based on accessibility and operation of a tool. If several tools are used, the assessment should be a mean of these. Similarly to assessing level of difficulty, this is an assessment not rarely done in manufacturing today but focus on cognitive aspects is scarce.

Level of attention required

An assessment on how much focused attention must be applied to the task. This is largely dependent on the presence of product variants and variations in information presentation.

The workstation factors

Number of tools used

A simple metric describing the number of tools used during normal work at a workstation.

Mapping of assembly sequence to workstation design

An assessment of how well the workstation design complies with the assembly sequence. For instance, tools and parts that are used together should be placed together and in the correct order. See Dix et al's (A. Dix, 2002; A. Dix et al., 2003; A Dix, Ramduny, & Wilkinson, 1998), Norman's (1993, 2002), and Kirsh's (1995, 1996, 1999, 2001) work on triggers, place-holders, the intelligent use of space and other important concepts relevant for task analyses to capture the rich ecology of work environments in assembly lines from a interactivity perspective.

Parts identification

Parts identification can be done in several different ways. The traditional way is through article numbers and material racks but other approaches can include kitting and alternate parts identification syntaxes.

Quality of instruction

An assessment of the general quality of the instructions used to gather information about the work. There exist a lot of guidelines within the Human-Computer Interaction (HCI) area for instructions, see, e.g., Clark et al.'s (2006) evidence-based guidelines to manage cognitive load, Black et al.'s (1987) work on minimal instruction manuals, Carroll et al.'s (1988) minimal manuals, and Eiriksdottir and Catrambone's (2011) procedural instructions, principles, and examples, to mention a few.

Information cost

The cost of information can be described as an assessment of how much physical or cognitive effort that is required to utilize the information (Thorvald, 2011).

Poke-a-yoke and constraints

Poke-a-yoke is a Japanese term that means "mistake-proofing". A poke-a-yoke is any mechanism in a lean manufacturing process that helps an equipment operator avoid (*yokeru*) mistakes (*poka*) (Shingo, 1989). Its purpose is to eliminate product defects by preventing, correcting, or drawing attention to human errors as they occur. *Forcing functions* - A forcing function is an aspect of a design that prevents the user from taking an action without *consciously* considering information relevant to that action. It *forces* conscious attention upon something ("bringing to consciousness") and thus deliberately disrupts the efficient or automatized performance of a task. Using a forcing function is self-evidently useful in safety-critical work processes. It is however also useful in situations where the behaviour of the user is *skilled*, as in performing routine or well-known tasks. Execution of this type of tasks is often partly or wholly automatized, requiring few or no attention resources (controlled processes), and it can thus be necessary to "wake the user up" by deliberately disrupting the performance of the task (interactiondesign.org).

A COGNITIVE LOAD ASSESSMENT TOOL

The cognitive workload assessment tool has primarily been developed as a proactive tool for workstation design and evaluation. The purpose of the tool is to guide workstation designers in designing for reduced cognitive load and to educate them on factors that are argued to have affect on the cognitive load of the user. It is a tool designed for quick assessment of cognitive load connected to a workstation and a task.

An engineer, working with design of new workstations and evaluation of current ones, uses the method as a guide for reducing the cognitive efforts required by the worker to perform a task efficiently. The engineer goes through the factors of the assessment tools (see examples of scores in figure 3), guided by the accompanying handbook, helping him/her to make an accurate assessment. The result of the assessment will imply how much cognitive effort the worker, according to the current setup, will be expected to employ. The tool will also, with upcoming development, advise the engineer/evaluator where to make changes in the workstation to reduce the workers' cognitive load.

Variant flora

Description The variant flora is relevant to manufacturing organizations running a mixed mode assembly flow. A flow where volume and variant products are assembled intermixed and not according to a batching strategy.

Measurement: Percentage

How to evaluate (method) Assessment of what percentage of daily output is made up of volume products

Estimated current level 4

Level	Description
L4	65% or fewer volume products
L3	65-75% volume products
L2	75-90% volume products
L1	90% or more volume products

Figure 3. One of the factor pages used for evaluation.

When all factors have been analysed and a level has been picked for each of them, the user navigates to the results page and is shown the collected data and a consolidation of the factors according to the weights discussed earlier (Figure 4).

	Factor	Est	Weights	Results
Task	Saturation	4	0,02	0,083333333
	Variant flora	4	0,10	0,416666667
	Batching of variants	1	0,06	0,0625
	Level of difficulty	2	0,10	0,208333333
	Difficulty of tool use	3	0,06	0,166666667
	Level of attention required	1	0,11	0,111111111
Workstation	Number of tools available	4	0,01	0,027777778
	Mapping	4	0,13	0,527777778
	Parts identification	4	0,12	0,472222222
	Quality of instruction	1	0,12	0,118055556
	Information cost	1	0,08	0,083333333
	Poke-a-yoke and constraints	1	0,08	0,083333333

Interval	
> 3.2	High cognitive load
2.5 - 3.2	Moderate cognitive load
1.7 - 2.5	Low cognitive load
1 - 1.7	Very low cognitive load

Sum: 2,361

Figure 4. The results page of the Cognitive Load Assessment Tool.

In the current version of the tool, the results page shows the consolidated and weighted scores and calculates and colour codes the overall score. In coming versions of the tool, recommendations will also be made here based on what factors are assessed at a high level and the weights associated with them.

The Handbook

The tool developed here is intended to be used by non-experts. I.e. it will not require a researcher or anyone with any major knowledge of cognitive psychology or human factors. For the tool to be usable by these user roles, most usually production leaders and technicians, the tool will have to be accompanied by a handbook of some sort. This handbook will be developed further in coming work and is regarded a crucial part of the tool implementation. The handbook will cover a brief introduction and guidelines on how to assess each factor identified in the tool.

Introduction to cognitive load

For the user to be able to make accurate assessment on what cognitive load is and why it is important, an introduction on the subject is required. This introduction will describe and discuss common cognitive limitations and give examples of how this can occur in a manufacturing environment.

Assessment of factors

A brief introduction to the respective factors and how to assess each factor individually. The handbook will also provide examples of each level of assessment in both text and picture form.

Assessment of results

A quantified summary of the results will be provided in the tool and the handbook will to a larger extent help the user understand what a particular result means. It will give explanations on why a particular score has been achieved and what it may mean to production output.

Recommendations

Perhaps one of the most important parts of the handbook is not only to assess the cognitive workload connected to a particular task, but also give recommendations on actions if this workload is deemed too high. These recommendations will be largely intertwined with the individual factors and they will also discuss actions to take when a reduction of the cognitive workload cannot be made. An example of this might be to advise the user on where to allocate extra resources on quality control.

FUTURE WORK

In this paper, we have investigated the area of cognitive load and its pertinent factors with the purpose of developing a tool for assessing cognitive load, a work that has been started although much work is still to do. The tool is at the moment created as a standalone, proactive tool, designed to prevent situations where a worker is exposed to higher levels of cognitive load.

Upcoming work on the cognitive load assessment tool will include three main parts; validation of weights and factors, development of the handbook and defining the intervals for high, moderate, low and very low cognitive load. Regarding the former, the tool NASA-TLX has been discussed extensively as a tool for evaluation and validation of our method. It is still our aim to use NASA-TLX for this and plans for validation of our factors are taking form with the intent of carrying this out during the upcoming year. The handbook will naturally be developed further; in fact, this work is already under way, and work on defining the intervals for different levels of cognitive load will take place as soon as the tool is ready for testing.

The general approach, while still being developed, is to use the tool to assess several workstations and to use the NASA-TLX method to get the workers assessment on the mental demands associated with the particular task and workstation. This should give enough foundation to evaluate and adjust the appointed weights to the factors.

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