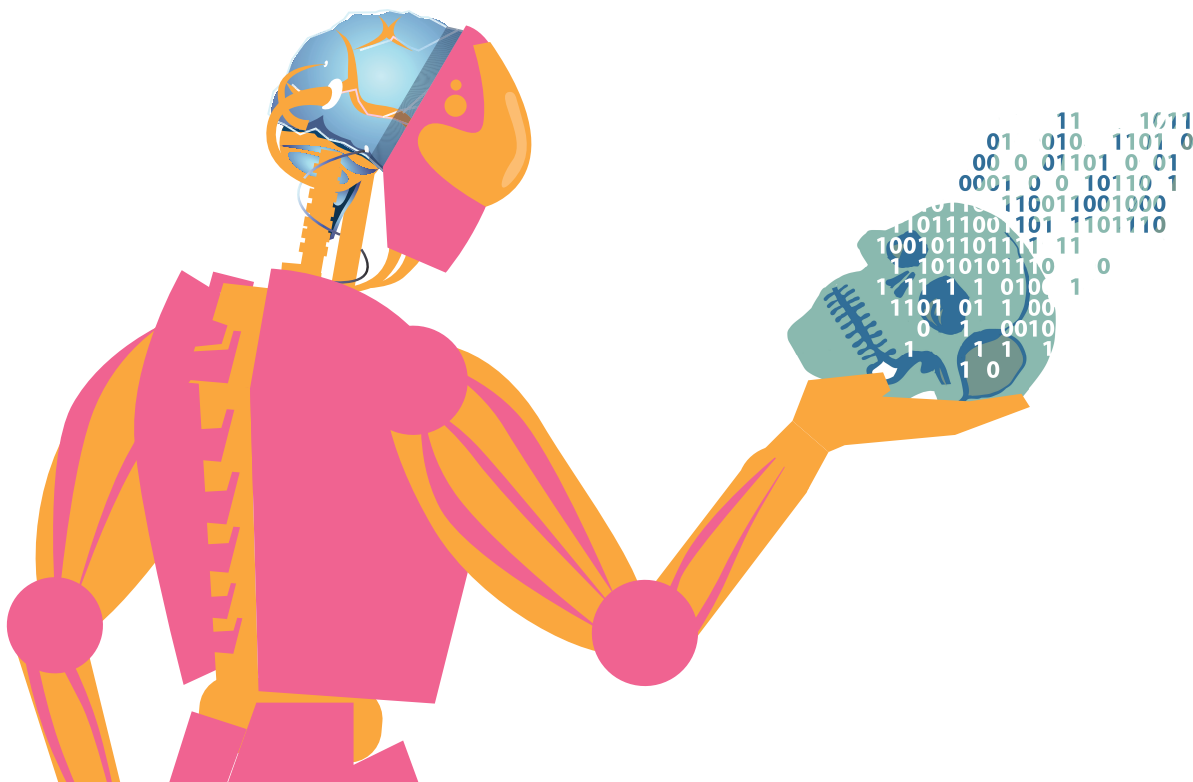


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Factors contributing to high cognitive workload in “expert operators”: a case in automotive manual assembly

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Abstract: Assembly work in manufacturing companies is frequently associated with monotonous, repetitive tasks and heavy physical loading. Vehicle manufacturers have during the last 20 years increased their share of product variants, placing high demands on the operators' abilities to make the right decision at the right time, using their cognitive skills. Operators must be able to memorise, improvise and perform assemblies with high quality and under time pressure. This case study aims to examine cognitive workload factors in manufacturing from the perspective of skilled operators with multifaceted work tasks, involving high levels of complexity and performance demands. Multiple cognitive workload analysis methods were utilised on a team of expert operators performing the assembly of customised equipment, mainly at the stages of final assembly when the product is almost complete. The study also reflects on what resources the operators use as a team to solve cognitively demanding tasks.

Keywords: Cognitive workload, Expert operators, Manual assembly.

1. Introduction

Manual assembly work in manufacturing companies is an area that is frequently associated with monotonous, repetitive and heavy physical loading. In Sweden, most manufacturing companies assess and map the physical workload according to the national systematic work environment legislation (Swedish Work Environment Authority, 2001). One area that is currently under-investigated within manufacturing and manual assembly is the cognitive workload affecting the operator. Work-related psychosocial conditions are often mapped at the case company by yearly employee surveys. While these give more of an overall view of the conditions, they rarely point out which factors in the environment cause the cognitive workload.

Vehicle manufacturing companies, along with other industries, have during the last 20 years increased their share of product variants. This is a result of increased competition between companies and increased demand for individually customised products. When the number of variants increase, so does the demand on the operator's ability to make the right decision at the right time, using their cognitive skills. The operator needs to be able to memorise, improvise and perform assemblies with high quality, and most likely under time pressure.

Different models of a vehicle might demand different assembly solutions for the same assembly and adding or replacing special features or devices can create even more complex and diverse work tasks. The interest for individually equipped vehicles has increased and the number of possible customisation choices is enormous. These individual customisations can include both interior and exterior equipment.

An operator's cognitive abilities both limit and benefit the assembly. To be able to decrease or optimise the mental or cognitive workload for the operators, it is important to have knowledge

about what factors are affecting the operator's cognitive abilities in their work environment. How do they cope with demands and are there solutions (technical, organisational or personnel-related) that could contribute to easing the mental workload?

The aim of this case study is to identify present cognitive workload factors within manufacturing from the perspective of operators with multifaceted work tasks, often with high levels of complexity and high demands on performance (as this affects product quality). The study will also reflect on what strategies the operators use as a team to solve cognitively demanding tasks. The outcome can be used as a first indicator of which cognitive functions are affected by the assembly work, and what individual, environmental or organisational factors contribute the most towards perceived high cognitive workload.

2. Methodology

The research question for this study was: *What factors (originating from the Human-machine system) affect the perceived cognitive workload for an expert operator within manual assembly?* This was investigated using multiple cognitive ergonomics assessments from established literature to explore how the team works together, how decisions and judgements are made, what mental models the team uses to solve tasks and problems, and how the mental workload stemming from the work tasks is perceived by the operators. The methodology for data collection and analysis included on-site observations, interviews, HTA (*Hierarchical Task analysis*; Annett, 2003), NASA-TLX (*Task Load Index*; Hart & Staveland, 1988), ACTA (*Applied Cognitive Task Analysis*; Militello et al., 1997) and SAM (*Self-Assessment Manikin*; Bradley & Lang, 1994). NASA-TLX was selected because of its extensive track record of use in production industry, and for covering both the demands of the work and the human's resources. To complement the NASA-TLX with a method that covers the *causes* of high cognitive workload, ACTA was used as a probing interview guide. In order to also include aspects of work satisfaction, opportunities for control and levels of "arousal", the SAM was used. All materials for the assessments were translated to Swedish, to ensure the participants' comprehension of the questions.

The study and necessary translations were carried out by a main investigating researcher (IR) who visited the assembly site several times. The IR acquired permission from plant production management (PM) to observe and interview a selected team of expert operators.

2.2 Sample

Table 1: Overview of the three expert SE operators.

	Operator 1	Operator 2	Operator 3
Gender	Female	Male	Male
Body size, constitution	Short, petite	Tall, large build	Tall and slim
Years of experience at the case company in automotive assembly	12	17	12
Previous assembly experience	Engine assembly	Chassis, special assemblies and cab trim	Final assembly

Years working at the Special equipment (SE) unit	3	1	2
Language preconditions	Native Swedish speaker	Non-native Swedish speaker	Native Swedish speaker

The subjects in this case study were selected by the IR and plant management as a *purposive sample* (Maxwell, 2005), selected on the basis of being a team of highly-skilled collaborating colleagues, working at a special equipment (SE) installment unit within the automotive company. All were expert special assembly operators tasked with performing the assembly of customised equipment, mainly at the stages of final assembly when the vehicle is almost complete. Table 1 summarises some basic information about each SE operator (SE-Op).

2.2 Procedure

The SE-Ops in the selected team were informed about the study by the PM and were asked for their consent to participate. The IR then explained the purpose of the study to the participants and which instruments would be used, as well as provided a working definition for cognitive workload (using the NASA-TLX scope as a starting point) and confirmed that the SE-Ops understood. After an initial group interview about their work scope, the IR observed the SE-Ops performing some work tasks on-site, and using a think-out-loud protocol, the SE-Ops described their tasks and thinking to the observing IR as they worked. They also described how they planned their day and the rest of the work week. The IR interviewed each SE-Op individually in the on-site office space about work time, spare time activities, how they worked, collaboration with other factory workers and with evening shift personnel, how they felt about their workplace, and personality traits.

At a second visit, the IR showed the SE-Ops a first draft of the HTA and sociotechnical system map, which the SE-Ops commented and suggested amendments to. Following this, the IR carried out a NASA-TLX assessment, an ACTA interview and a SAM assessment together with each of the SE-Ops (Operators 2 and 3) in their office, spending about 30 undisturbed minutes with each person. Operator 1 was not available at this time and carried out the assessments with the IR one week later.

At the third visit, the IR carried out the three assessments with the remaining SE-Op.

Finally, the IR compiled a total description of the cognitive workload for the three SE-Ops and presented it to them for member checking and verification. They confirmed that the result was coherent with their own perception of the workplace, work tasks and workload. This confirmed result is reported in the next section.

3. Results

The SE operators described their work to the IR to establish a sociotechnical map of the work system (Figure 1), and a HTA over the work tasks (Figure 2).

The Special Equipment customisation ordered by a customer triggers a so-called “S-job”, where a customised solution is first constructed by an SE designer, and a list of S-jobs is constructed by an SE Assembly planner who creates a Bill of Materials (BOM) and an assembly task list (Figure 1). When a new solution is constructed, the SE Assembly planner is informed, then the SE-Ops. The SE Assembly planner must ensure that the Special Equipment is possible to assemble at the production line, or that the task is taken to the SE unit and that the SE-Ops are informed about what to do. If the SE-Ops discover incorrect information in the assembly task list, they alert the SE designer and SE Assembly planner of the mismatch. They also inform the Internal Materials

Centre (IMC) if materials are wrong (leading to the IMC operator changing the material) or missing.

The team shares a goal of manufacturing customised high-quality trucks. They act as a problem-solving team, their communication is decentralised and they interact autonomously and intensely. Their manager is regarded as an external coach rather than a work leader; all assembly is guided by human decisions and actions, so the level of automation is low.

At the SE unit, all of the SE operators performed all occurring tasks, unless someone's body size (too short, too wide etc.) or any pain or ailment hindered them from performing the task. The team members were also aware of each other's strengths and physical limitations, so they made sure to help each other. The SE team didn't perceive their workload as unevenly distributed, i.e. no single person performs more or heavier lifts than the others, and nobody has a more repetitive task load.

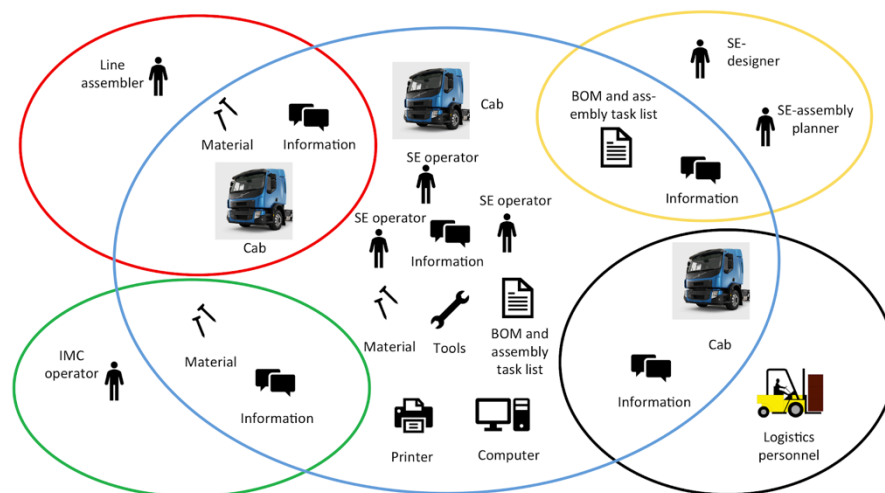


Figure 1: Sociotechnical map of the work system, based on interviews with (and member-checked by) the SE operators.

The HTA resulted in a structured decomposition of the work tasks (including the execution plan), which was member-checked by the SE-Ops. The main steps of the overall work of “SE Assembly” were identified as: 1) *Print the BOM and assembly task list.* 2) *Compare if lists match.* 3) *Check material.* 4) *Define assembly order.* 5) *Define workstation for each cab.* 6) *Inform forklift driver about cab destination.* 7) *Pre-assembly.* 8) *Assemble according to BOM and assembly task list.* These steps constitute the top level of the HTA shown in Figure 2.

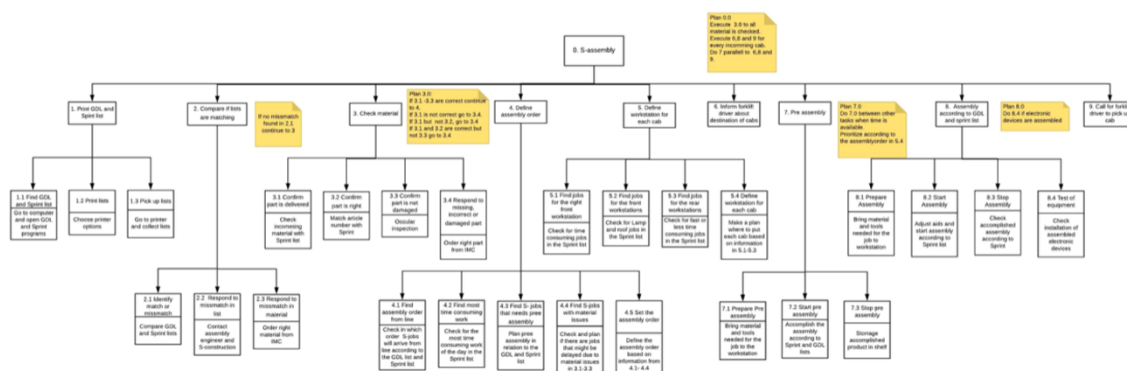


Figure 2: HTA of the work performed at the SE unit, based on interviews with (and member-checked by) the SE operators.

Although the HTA provided clarity regarding sequential work order, it was decided that for further probing with ACTA, the IR chose to concentrate the rest of the analysis to the steps 3) *Check material* (referred to here as “Material handling”) and 7) *Pre-assembly* (“Assembly”), as the operators expressed that these two aspects of the job brought about very different cognitive challenges. Much of the Material handling work involved contacting and relying on actions from colleagues outside of the SE assembly area.

The SAM assessment (Figure 3), which has participants select their “position” on a visual analogue scale using stylized human figures as representations for three affective states (*Pleasure*, *Arousal* and *Dominance*) showed that the operators’ affective state of mind regarding the job was fairly similar regarding *Pleasure* (described to the SE-Ops as “well-being”) and *Arousal* aspects, indicating a positive attitude towards their work, but a difference was found between Operator 2 and the others in the *Dominance* aspect. The interviews revealed that this was attributable to being “the new guy” who felt slightly less experienced compared to his colleagues.

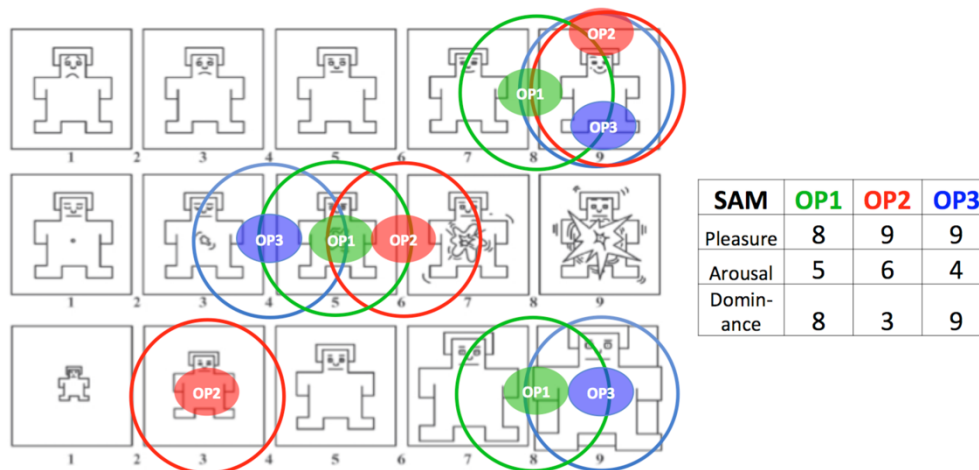


Figure 3: Self-Assessment Manikin (SAM; Bradley & Lang, 1994), used to determine the affective state of the operators

The NASA-TLX assessment (Figures 4 and 5) involves the participants rating the task demands based on six workload factors (*Performance*, *Temporal demand*, *Effort*, *Physical demand*, *Mental demand*, *Frustration*), marking their rating (on paper) on a visual analogue scale. The scales have 20 increments but are not explicitly numbered; instead, each end of the scale has a guide word to orient the participant’s choice. However, for scoring purposes, the placement of the participant’s mark is translated into a value between 0 and 100. It is very important to note that for all NASA-TLX scales except one (the *Performance* factor, whose lower end of the scale indicates a “Perfect” execution), a high score tends to indicate high workload, implying an undesirable state. Therefore a “low” score on Performance should be interpreted with care, potentially as a high demand.



Figure 4: NASA-TLX weighting of workload factors for the two tasks Assembly and Material handling, resulting from pairwise prioritization of each factor.

The assessment was performed both with and without *weighting*, a process where all six factors are systematically shown in pairs to the participant who prioritizes each factor over the other 15 times, leading to a relative prioritization “weight” of each factor. Figure 4 shows how each SE-Op weighted the different factors for the two selected tasks using this pairwise prioritization process, leading to the conclusion that in Assembly, in spite of high *Performance* demands, the SE-Ops did not feel that *Frustration* was more important than any other factor (weight =0). However, in the Materials handling work, considerable discrepancies between the SE-Ops’ weighting regarding *Temporal demand* and *Frustration* were identified.

The left side of Figure 5 shows the average assessment scores the three SE-Ops gave for each workload factor, while the right side shows the weighted result, i.e. the scores multiplied by an average of the three SE-Ops’ weightings of each factor.

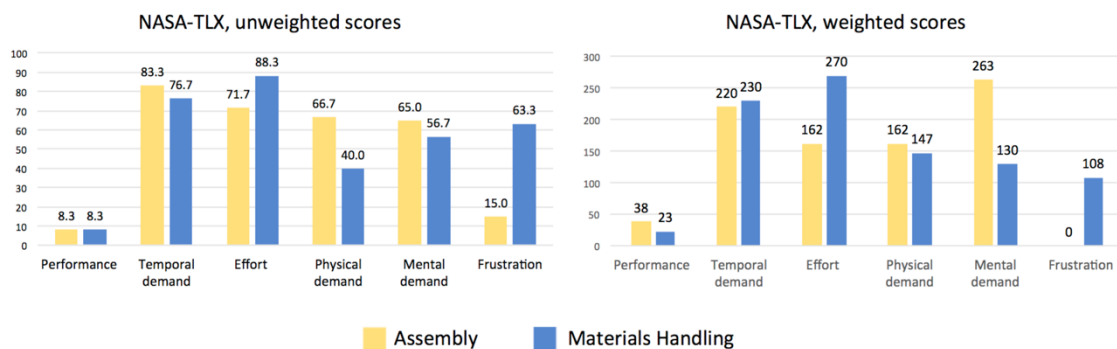


Figure 5: NASA-TLX results for Assembly vs. Materials handling; unweighted and weighted scores (note the difference in scale)

Although this “averaging” approach has a tendency to slightly misrepresent the factors for which differences are large (especially in such a small group of operators), the results give a contrasting view of the relative importance of each factor for the overall loading. The weighted vs. the unweighted NASA-TLX results also reveal differences in workload factor importance between different SE-Ops. The weighted version shows that the factor “Performance” is overall the most important (Although it should be noted for clarity’s sake that in NASA-TLX, the ideal Performance assessment score is a low one).

The ACTA assessment (combined with the interviews) probed the findings of the NASA-TLX assessment using the six probing themes *Past and future*, *Big picture*, *Noticing*, *Job Smarts*, *Opportunities*, *Self-Monitoring*, *Anomalies* and *Equipment difficulties*. The result of the probing interviews was extensive and rich and many examples were given by the SE-Ops that explained the previous assessment findings. Table 2 summarises the most important ACTA findings.

Table 2: Summary of ACTA result: Assembly and Materials handling

Difficult cognitive element	Why is the task difficult?	Common errors	Cues and strategies used
<i>Assembly</i>	<ul style="list-style-type: none"> • Need to keep all instructions in one's memory 	<ul style="list-style-type: none"> • Unable to assemble product due to errors/ mistakes made on the regular line • Wrong information in the assembly task list 	<ul style="list-style-type: none"> • Keeping high performance due to high product and part knowledge. • Open-minded colleagues that can be asked and help out. • Plan ahead and check at line assembly for mistakes • Sharing the same mental models
<i>Material</i>	<ul style="list-style-type: none"> • Mixed incoming materials • Need to order material if missing, wrong or damaged • Not able to rely on incoming material 	<ul style="list-style-type: none"> • Wrong part in right package. • Parts missing • Damaged 	<ul style="list-style-type: none"> • Double check article number of part. • Keep several steps ahead • Order material in advance

4. Discussion

Few empirical studies exist in the literature of how skilled manual assembly operators deal with cognitive workload. This study has therefore contributed to knowledge with an empirical examination of a high-skill assembly scenario.

The interpretation of the exercise with the sociotechnical systems map and the HTA indicated that the three SE-Ops had a shared mental model that they drew much support from in their work. The SAM analysis partially showed a shared affective state in relation to the job demands, but the observed discrepancies (that were complemented by interview findings) seemed to be explained by relative differences in SE assembly experience as well as personality traits (Operator 3 had a very calm disposition). The NASA-TLX results from the weighting exercise, as well as the separate scoring of the Assembly and Material handling tasks, indicate that while individual differences in cognitive resources exist, the areas where the SE-Ops gave similar assessments of the workload exist can give a fairly good assessment of the harmfulness of the situation. It should be noted, however, that the NASA-TLX does not take teamwork into account, and that the average scoring should be handled with caution.

During the ACTA analysis, one of the SE-Ops found it difficult to answer some of the questions in the office setting (possibly because of language difficulties), but was later able to complement some missing or misunderstood answers to ACTA questions after returning to the assembly site again. When performing the work physically, he was more readily able to connect some of the ACTA probe questions to his work situation and managed to gradually describe his insights to

the IR as he worked. This points to a potential difficulty with the ACTA instrument as a stand-alone method; some insights may be difficult to describe if the worker has not previously verbalised their thoughts and actions in words. Some tacit knowledge about cognitive activity is perhaps only possible to elicit in-situ while work is on-going.

5. Conclusions

The cognitive workload in the presented automotive industry case was examined and elaborated using multiple cognitive ergonomics assessments from literature. The results from the multiple analysis methods successfully complemented each other in giving insights to the Special Equipment team's cognitive loading and resources. It was found that two dominant task types, Assembly and Materials handling, exposed the team to rather different levels of cognitive workload. Overall the NASA-TLX indicated that a high mental workload was present, but the interview and ACTA results clarify that this is not seen as a problem since the mental challenge enriches the work with more content, requiring the SE-Ops to make decisions and come up with solutions, thus distinguishing the job as being more stimulating compared to regular on-line assembly work. On the other hand, the Materials handling task involved both high mental workload and frustration, due to the time aspect and the fact that the SE-Ops themselves cannot affect the conditions and feel in control. The Weighted vs. the Unweighted NASA-TLX results also provide different insights by highlighting differences in workload factor importance between different SE-Ops, as well as between the different tasks. The weighted version showed that the factor "Performance" is overall the most important – perhaps not surprisingly, as the most important value delivery for this workplace is Product quality.

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