DEVELOPMENT OF SIMPLE GUIDELINES TO IMPROVE ASSEMBLY INSTRUCTIONS AND OPERATOR PERFORMANCE

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Assembly instructions is an important means for supporting operator performance in final assembly. An operator at a production line, whether experienced or novice, will encounter situations that include the assembly of new products or new variants. Instructions that are developed without consideration of these processes can cause unnecessary cognitive load and lead to poor operator performance. This paper describes an experiment that shows that assembly instructions can increase operator performance and presents nine simple guidelines. The Importance of including the operator view is stressed and how the guidelines should be implemented in practice is discussed.

Keywords: Assembly instructions, operator performance, cognitive processes, final assembly, experiment study.

1. INTRODUCTION

An operator at a production line, whether experienced or novice, will encounter situations that include the assembly of new products or new variants. In these situations, the operator will have to rely on support from for example colleagues, experts or assembly instructions, and the performance will be affected by the quality of this support. In comparison with the first two, assembly instructions have the advantage that they can provide a standard working procedure. However, experience from industry tells that if they exists, they are rarely used; either because of poor quality or due to their extensive amount of information. Klein et al. (2004) suggested that problems seen in human- automation interaction arise because the support of interaction and coordination of human and machine has become secondary. Therefore, managing complexity is connected to improving the operator performance i.e. to decrease process errors, achieve high quality, achieve good working conditions, fast processes, quick change-overs and to decrease cost (Schleich et al., 2007; Papakostas et al., 2010; Heilala and Voho, 2001).

To be able to optimize human performance, information should be arranged so that it fits the operator's cognitive processes (Rasmussen, 1983). Cognitive processes are the mental processes in which humans become aware of and process information (Osvalder & Ulfvengren, 2009). They involve perception, through hearing and vision, but also the memory and attention (Osvalder & Ulfvengren, 2009). Instructions that are developed without consideration of these processes can cause unnecessary cognitive load and lead to poor operator performance (Clark et al., 2006). The lack of, or insufficiency of, assembly instructions can lead to deficiencies in working procedures that can lead to quality defects, which in turn can lead a great amount of direct and indirect costs, but also unnecessary stress and frustration among workers. How a person understands a situation drives his or her actions (Bäckstrand et al., 2010; Hollnagel, 1997). Therefore, how a person understands a task will have an impact on their performance.

This paper aims to show the impact of instructions in final assembly as well as providing simple design guidelines on how to improve them. In order to investigate the role of assembly instructions a study consisting of 41 experiments was carried out and lay ground for the formation of simple design guidelines that can be used to improve operator performance and productivity. This paper describes this study and gives to following contributions to the field:

- An experiment that shows that assembly instructions can increase operator performance
- Simple guidelines to improve assembly instructions

The guidelines are based on the notion by Agrawala et al. (2003) that both the structuring of the assembly procedure, planning, as well as design and structuring of the instructions, presentation, are important in order to support the cognitive processes. The study was based on experiments that also investigated the mood of the operators as well as the impact of the material facade on productivity and operator performance, however, these factors will not be described in this paper. Further, the paper is only regarding visual instructions.

2. RELATED WORK

This section describes previous work that provides information on how to design instructions. The section is divided into two parts, cognitive processes and design principles.

2.1. Cognitive processes

Cognitive processes are the mental processes in which we become aware of and process information. Cognition involves the human senses, such as vision and auditory perception, but also the memory and attention (Osvalder & Ulfvengren, 2009). Attention allocates the cognitive resources and helps to focus the the resources on relevant data in the instructional environment (Clark et al, 2006), while the memory helps to make sense of and store the information. The memory can be divided into long-term and short-term memory (Osvalder & Ulfvengren, 2009). In an assembly situation the short-term memory, also known as working memory, is active and process the information that is needed to perform the task (Ganier, 2004). The working memory, however, is a limited resource and can only keep 7±2 mental models active at a time (Miller, 1956). Mental models are reconstructions of external phenomena in our long-term memory that are used to interpret new information (Rook, 2013).

The employment of the cognitive resources that is needed for processing information is usually referred to as cognitive load. Clark et al. (2006) describes three types of cognitive load; *intrinsic*, *germane* and *extraneous load*. Intrinsic load is affected by the complexity of the task and germane load is the load that serves the learning in a positive way and is necessary for learning, whereas extraneous load does not add any value to the learning outcome. Since the cognitive resources are limited, they must be used efficiently by minimizing the extraneous load and increase germane load (Ibid). The intrinsic load can only be affected to some extent since it is determined by the complexity of the assembly task, but can be relieved by limiting the amount of information shown at one time (Clark et al., 2006).

2.2. Design principles

Agrawala et al. (2003) divide the design of information content for assembly instruction into two focus areas, planning and presentation, which are both of great importance. The planning includes establishing the most suitable assembly sequences that correspond to the human cognitive ability, while the presentation includes structuring the instructions as well as the visual design for the sequences (Ibid.). The presentation is dependent on the planning of the assembly.

Planning of instructions. Assembly instructions present tasks that include a certain sequence of operations. In order to make the tasks more intuitive and thereby make it easier to perform the assembly, the order in which the operations are to be performed should be planned. Two theories presented by Agrawala et al. (2003) are useful for understanding an assembly procedure can be planned. The first one is called hierarchy and grouping of parts. Parts have different degree of significance depending on their function and importance to the finished product. All parts can be hierarchically arranged and grouped by function or type of part and it is preferable to assemble all parts within a group in the same sequence. The second part is hierarchy of operations. Since parts are hierarchically grouped this will affect the perceived significance of the tasks involved in mounting them. In an assembly session, all actions can be divided on different hierarchy levels (Ibid.). A hierarchical task analysis (HTA) is a method that can be used to structure a sequence of tasks to describe in what order they should be performed to finish an assembly (Osvalder et al., 2009). In a planned assembly procedure, parts with high significance are often combined with lower significant parts in order to make the assembly task easier to understand (Agrawala et al, 2003).

Presentation of instructions. Information should be presented in a way that makes the assembly procedure clear and easy to follow (Agrawala et al, 2003) by showing a complete assembly cycle step-by-step, instead of presenting all operations at one time, the intrinsic cognitive load can be decreased (Clark et al., 2006). This work is based on the *planning* of the assembly procedure, including the HTA, described above. Information that the operator needs in the assembly situation should be easily accessible and easy to find, especially parts that are used often (Osvalder & Ulfvengren, 2009). The assembler should not have to waste time on searching for information, therefore associated information should be presented in physical closeness. Arrows, lines, equal colors and typeface can be used in order to strengthen the connection between information sources (Ibid.). Clark et al. (2006) also mention the importance of using arrows, lines and frames in order to link associated information.

It should be easy for the user to read text and find necessary details in instructions, for example by using high contrasts so that text and images become distinct (Osvalder & Ulfvengren, 2009). Clear and informative headings on each instruction step can be used to facilitate the location of informaton (Ganier, 2004). Information should be presented in different ways, for example by combining both text and pictures, in order to make the message easier to understand (Osvalder & Ulfvengren, 2009). It has been shown in several studies that mixed information formats increases performance (Ganier, 2004). Objects that look the same can easily be confused or cause confusion. Therefore it is important to highlight differences between objects that may be perceived similar, for example by using text (Osvalder & Ulfvengren, 2009).

Since the short-term memory is a limited resource, it should be relieved as far as possible. The number of stimuli presented at the same time should not exceed what a human can keep active in the working memory, information presented in each step of the instructions should therefore be kept to a maximum of 7±2 units (Osvalder & Ulfvengren, 2009; Inaba, et al., 2004). Consistent and uniform instruction design makes it easier for the user to comprehend the message and drastic changes, in for example layout, can lead to confusion (Osvalder & Ulfvengren, 2009). Inaba et al. (2004) also mention the value of being consistent in the presentation of information as it reduces the time it takes to understand the message. The presented information should be consistent with regards to reality. If information is realistic and possible to link to mental models it becomes easier to understand (Osvalder & Ulfvengren, 2009). According to Li et al. (2013), it is advantageous to use realistic illustrations or photographs to make not only the main object, but also the details visible, and thereby communicate the right information. Building mental models from information presented in pictures requires less cognitive resources than text does (Ganier, 2004). Instructions with pictures also have the advantage that they are suitable for people with reading difficulties (Ibid.).

3. THE EXPERIMENT

The developed guidelines for structure and design of assembly instructions are based on a simply assembly experiment performed by 41 participants. The results from the experiments, together with previously established knowledge in literature, laid ground for the proposed design guidelines. The experiments were carried out in two sessions, starting with 31 initial experiments that tested weaknesses and strengths of a set of instructions that was designed without consideration of cognitive processes. Based on the results from quality data, interview answers and related theory, the assembly instructions were re-designed whereafter a second experiment session with ten additional experiments was carried out in order to test the impact from the changes.

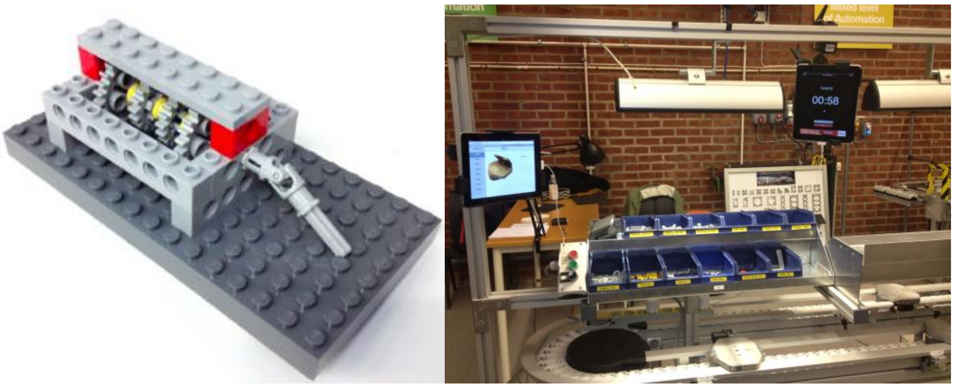

Fig. 1. Lego gearbox assembled in the experiment (left) and experiment set-up (right).

The experiment included multiple assemblies of a simple Lego gearbox, shown in Figure 1, that the participants got to build with a short tact time (50-70 seconds). Before the assembly started, the participants got the time that they needed in order to read through the assembly instructions, but they were not allowed to practice. The instructions were presented on a reading pad. The participants were allowed to use the instructions whenever they wanted during the assembly. The assembly instructions were presented on an iPad and placed as shown in the picture above. The assembly cycle was repeated five times, followed by a short interview, five additional assembly cycles and finally a more comprehensive interview. The achieved performance in each assembly cycle was measured by the number of parts assembled correctly. The interview answers were coded and quantified in order to serve as a reliable basis for analysis.

4. SIMPLE GUIDELINES TO IMPROVE ASSEMBLY INSTRUCTIONS

The interviews included questions about how the participant experienced the situation, if any work steps were more difficult than others and whether the instructions were sufficient and helpful or not. After transcription, the interview answers were categorized in order to quantify the answers. The quantification of the answers enabled an identification of the most frequently mentioned shortcomings, complex operations and the most crucial areas of improvement. To make it possible to measure an improvement in the perceived quality of the instructions, the answers were coded to find positive and negative answers. The results are listed in Table 1 where the words in parenthesis indicates what words that were used to determine positive versus negative answers. In the right hand column the percentage of participants whose answers fitted in to the category are listed.

Table 1. Interview results.

Comments regarding:	Category	Session 1	Session 2
Overall impression	Good (Clear, good, easy to understand, easy to follow)	56 %	100 %
	Not good (Not good at all, unclear, difficult to follow, no connection between text and pictures, ambiguous)	41 %	0 %
	Redundant (could have merged some steps, too many steps)	9 %	10 %
Pictures	Good (Helpful, clear, necessary)	16 %	40 %
	Not good (Too small, not connected to the text, insufficient, unclear)	28 %	0 %

Another important thing found during the interviews after session 1, was that 16 of the participants mentioned that they only used the instructions in the beginning and that they had learned the assembly procedure by heart after a while. Some of them mentioned that they, after a while, only used the last picture showing the finished product.

The operator performance were measured by calculating the number of correct assembled parts. The experiment showed an increase in operator performance of 10% from session 1 to session 2 (for more details, Li et al., 2014). In session 1, the most common errors were:

- Non-assembled axis (67% of the gearboxes): The assembly of the axis had been started but the axis was not attached to the gearbox.
- Wrong placement of gear box on ground plate (49% of the gearboxes): The gearbox was placed at a place not stated in the instructions.
- Plugs under the base plate (6% of the gearboxes): Two plugs instead of one were placed under the base plate.
- One or several pieces were missing on the axis (5% of the gearboxes): Pieces had been placed on the axis in a wrong way or some pieces were missing.

Two errors were identified as errors highly likely to occur: *Non-assembled axis* and *Wrong placement of gear box on base plate*. They had different characteristics:

- Assembly of the axis was the most complex activity (it included most parts and most assembly steps), hence often not fully assembled when the tact time was out.
- The placement of the gearbox on the base plate was not crucial for continuous assembly of the gearbox and might have been perceived as having low significance for the function of the product, hence the error was not necessarily detected by the operator.

The re-design of the instructions followed a structured procedure that consisted of a *planning* phase, including planning of the assembly procedure and planning of the instruction steps, and a *presentation* step, including a visualisation of the planned instruction steps. The re-design was based on related research and on the experiment results, including operator performance data and interview answers.

4.1. Planning of instructions

The changes made in the planning phase are named and described in Table 2. In the two right-hand columns the background from theory and experiments are described.

Table 2. Two steps for planning instructions, based on theory and empirical results.

Change	Description	Theoretical background	Results from experiments (performance measures and interview answers)
1. Division of the instruction steps according to the assembly procedure	Presented each assembly operation as one instruction step	Decrease intrinsic cognitive load	The structure was mentioned in several interviews, for example: “It was almost too many steps” and “It was tough to scroll between the pictures (...) and at the same time remember all the small details”
2. Separate presentation of the finished product and complex steps	Displayed pictures above the workstation as a complement to the assembly instructions	Make crucial information easily accessible	Many interviewees mentioned that they mainly used the instruction step that showed the finished gearbox after having assembled a while, for example “In the end I only used the last picture [showing the gearbox]”. The separate presentation eliminated the need for wasting time on having to scroll between information steps. Two of the most common errors regarded the axis, which was a complex part with many components, also mentioned in interviews.

By following the results from steps 1 and 2 a hierarchical task analysis (HTA), was performed in order to map the process and to get an overview of the necessary steps and in what sequence they should be performed, shown in Figure 2.

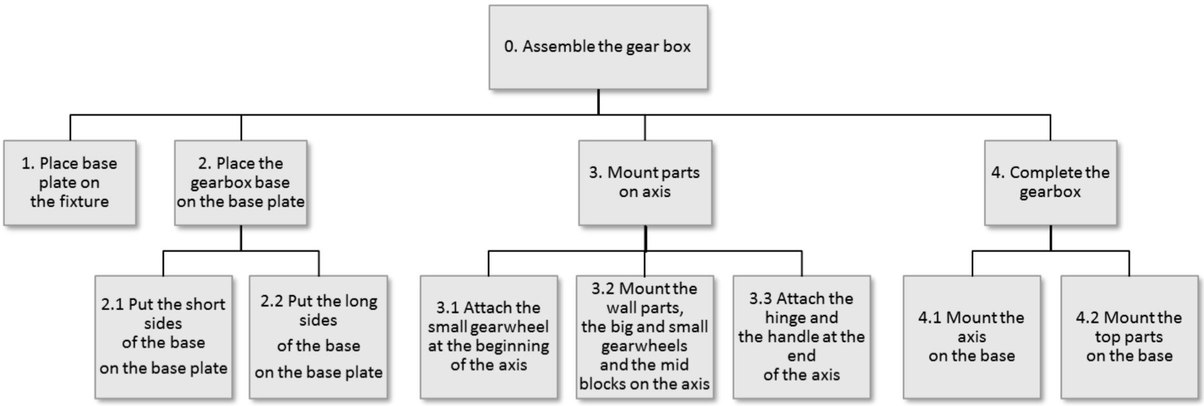

Fig. 2. HTA of instruction steps in the new instructions.

Figure 2 describes the division of the instruction steps according to the assembly procedure. In the previous assembly instructions, the instructions on how to assemble the axis were presented in three steps. In the re-design the same information were reduced to include only one step.

Many participants mentioned that they only used the last picture in the end, therefore a separate presentation of the finished gearbow was added, easily accessible for the operator and placed above the assembly station. The same thing was done with the picture of the finished axis, which was a complex part that many participants struggled with.

4.2 Presentation of instructions

The changes made in the presentation phase are described in Table 3.

Table 3 Five steps for presenting instructions, based on theory and empirical results.

Change	Description	Theoretical background	Results from experiments (quality measures and interview answers)
1. Consistent layout	Design of a layout that were used in all instruction steps.	Minimize the extraneous cognitive load.	40 % of the participants said that the instructions were not good, which could partly have been to the layout. One interviewee said: “The structure of the instructions was not good at all”
2. Clear and realistic pictures	Changed from computer-made illustrations to photographs when possible	Minimize the extraneous cognitive load. Support mental models	28 % of the participants stressed that they were not pleased with the pictures and they were described as unclear and small, for example: “You saw the pictures, but it was hard to see which parts were which” and ”If there is one big picture (…) I want that picture to be really clear”
3. Highlighted differences between similar objects	The difference between similar parts were marked with text, numbers and	Minimize the extraneous cognitive load.	That one or several pieces were missing on the axis was one of the most common errors. It was also mentioned in interviews: “Those round ones [the gearwheels] were a bit

	dimension indications.		tricky, when you are stressed you can not tell which one is which”
4. Enhancement of the complex and low significant steps	Highlighted significance by adding arrows and marks. Added clear pictures on complex parts.	Make crucial information easily accessible Enhance significant details	The most common error was non-assembled axis. It was noticed during interviews that this instructions step was unclear: ”[Regarding whether it was something that was unclear] Yes, the order in which the gearwheels were to be placed” The second most common error was the placement of the gearbox on the baseplate, which was also mentioned in the interviews: ”Some pictures were too small, for example the placement on the base, so you had to look carefully”
5. Elimination of unnecessary information	Removed information that did not add any value to the task	Minimize the extraneous cognitive load.	Some interviewees mentioned that the information was redundant, for example: “It was almost too many steps” and “I would prefer to have to read as little as possible”

4.3. Development of simple instructions

By combining the steps from the *planning* and the *presentation phase* a design of simple instructions is suggested, see Table 4. The simple guidelines are structured according to instructional components: *structure*, *layout* and *pictures and text* of finished product. The guidelines regarding structure are to be used during the *planning phase*. The guidelines regarding layout and pictures and text are to be used in the *presentation phase*. The guidelines are based on the re-design of instructions tested in experiment session 2. They are formulated to give specific improvement suggestions that can be applied in many settings. The simple guidelines to improve assembly instructions are summarized in Table 4.

Table 4. Design of simple instructions.

Guideline	Connected to phase	Description
Structure	Planning	- The structure should be based on a planned procedure of assembly, for examble by the use of HTA (Osvalder et al. 2009, empirical studies). - Support the instructions by adding separate presentations with pictures of the finished product (empirical studies). Depending on the space available in the instruction layout, the separate presentation can be placed either in the same information presenter or on a separate presenter. A separate presentation can also be added with pictures of high complex parts.
Layout	Presentation	- The layout should make it easy to find information and be consistent throughout the instructions (Osvalder & Ulfvengren, 2009; Inaba et al, 2004). - The instructions steps should include headings that are clear and consice, intuitive and informative (support the understanding of the task) (Ganier, 2004).
Pictures and text	Presentation	- The instructions should have a high focus on pictures, and text should only be used when pictures are not sufficient (Ganier, 2004). - All pictures should be realistic (Osvalder & Ulfvengren, 2009; Li et al., 2013), photographs are to prefer when possible. - In order to be clear the pictures should be big, have high contrast and reduced shadows (Li et al. (2013), . - Text and pictures should only include relevant information (Osvalder & Ulfvengren, 2009). Eliminate unnecessary details in pictures.

		- Differences between similar objects should be highlighted (Clark et al., 2006; Osvalder & Ulfvengren, 2009). This could be done by the use of information enhancers like arrows, numbers, measure indicatiors, marking, enlargements etc.

5. DISCUSSION

The importance of instructions in assembly is often underestimated even though they can have a great impact on operator performance (Clark et al., 2006). The guidelines presented in this paper are important since they will help to develop instructions that can support the operator's cognitive ability and, as shown in empirical studies, increase the operator's performance. The cognitive processes can be captured by the activities of *planning* and *presentation* that are presented by Agrawala et al. (2003). If assembly instructions are not designed from an operator's perspective, information can be superfluous or insufficient and result in poor operator performance (Clark et al., 2006). In this study the cognitive processes were captured with help from recognised design principles, but there were shortcomings that could be improved further.

In this paper, interviews with operators not only had a great impact on the design guidelines, but also on details in the re-design of the instructions. With this background it is recommended to always interview the operators that are going to use the assembly instructions.

The guidelines presented in Table 4 are supported by theory and empirical studies, presented in Table 2 and Table 3. The support from theory gives them credibility, which is reinforced by results from testing in assembly experiments. The guidelines were tested in an assembly experiment with successful results, but further research is needed in order to find if these are optimised and if there are further improvements that can be made. One important factor that needs to be investigated is that after the original assembly setup had been tested, not only the assembly instructions but also the material placement was changed according to Li et al. (2014). Therefore parts of the result could be due to these changes and it is hard to separate the causes.
The working procedure described below is an example of how the guidelines can be used in practice. The working procedure is based on theory and empirical studies. The planning phase includes steps 1-2 and presentation phase steps 3-5. Step number 6 is recommended in order to make sure that the operator perspective is captured.

1. Mapping of the assembly procedure (Agrawala et al, 2003)
2. Planning of instruction *structure* (Agrawala et al., 2003; empirical results)
3. Creation of instruction *layout* (Osvalder & Ulfvengren, 2009; Inaba et al, 2004; empirical results)
4. Creation of instruction *pictures and text* (Ganier, (2004); empirical results)
5. Enhancement of *pictures and text* (Clark et al., 2006; Osvalder & Ulfvengren, 2009; empirical results)
6. Test the instructions and interview users (empirical results)

The experiments were performed in a controlled environment and the guidelines have not been tested in a real industry setting, which could be a subject for future studies. Even though there are areas that could be improved, the experiments form empirical support that shows that these guidelines actually work. Further research is needed to ensure industrial applicability.

6. CONCLUSION

This paper shows that operator performance in manual assembly can be improved by the support of well-designed assembly instructions. The experiment showed that the operator's view is important and served as a basis for the suggested simple guidelines. Simple guidelines were proposed that could serve as a checklist for people designing assembly instructions. It is recommended that the working procedure described in this paper is followed in order to capture the operator's perspective. Further studies are needed to strengthen the suggested guidelines and to support industrial application.

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