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DIFFERENCES IN ANALYSIS AND INTERPRETATION OF TECHNICAL SYSTEMS BY EXPERT AND NOVICE ENGINEERING DESIGNERS

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Abstract

A major part of daily work for engineering designers is the analysis of existing products for finding malfunctions and possibilities to improve them. The visual perception and cognition are very important. The paper focuses on differences in the perception and cognition during analysis and interpretation of technical drawing between expert and novice engineering designers. An experiment with 34 subjects, 11 novices and 23 experts, investigates those differences. For observing the input and output parameter of the perception and cognition processes, eye trackers record the point of gaze during the experiment and the subjects verbalise their thoughts.

The experiment shows, the interpretation of the system differs significantly. Expert engineers analyse technical systems more in depth, interpreting the embodiment design in the context of the overall system. Novices describe systems on a surface structure of components and its functions and hardly connect the embodiment to the systems context. The findings support the development of methods for guiding novice engineering designers to interpret the embodiment design on the level of the overall system and not only on a surface level.

Keywords: Eye Tracking, Human behaviour in design, Design cognition, Design perception

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1 INTRODUCTION

For most engineering designers, enhancing existing products is the major part of their daily work. Thereby, the engineer has to analyse the existing system, which means gaining a full comprehension, in order to find malfunctions and to find possibilities to improve them. These improvements are evolved in a process of synthesis, which alternates with the analysis (Matthiesen, 2011). These two proceedings are the main operations during the development of the embodiment design. Focus of this research is the activity of analysing a technical system with the help of technical drawings. During the analysis, the engineer has to find and receive the required information and interpret the information in the given context. Perception and cognition are the keys to understand the given system (Stachowiak, 1973). The embodiment design of a system is documented in drawings, CAD models and physical models. Thus, the visual perception is very important for analysis processes in engineering.

An experiment was developed to investigate on differences on the perception and cognition of engineers with varying expertise during the analysis of technical drawings. The subjects were grouped into novice engineering designers, in our case students, and a group of experts with several years of work experience. All subjects were shown a technical drawing and they should describe what they perceived until they understood the presented technical system. The research question is, if there are differences in the analysis and interpretation of technical drawings by expert or novice engineering designers, in order to assess if it is necessary to develop individual methods for supporting each group of expertise during their analysis processes. The paper investigates the mental activities of perception and cognition from two sides, the captured information through eye tracking and the processed information with the think-aloud method. The presented research is a first step towards guidelines and methods for engineers during analysis of technical systems.

After giving an overview of the perception and cognition of technical drawings and introducing eye tracking and the think-aloud as observation methods, the experiment is described in detail. Chapter 4 presents the analysis and the results of the experiments before the paper closes with a discussion and conclusion on the findings.

2 PERCEPTION AND COGNITION OF TECHNICAL DRAWINGS

Stachowiak (1973) describes the process of internalisation, processing and externalisation of data in the human mind. This process also takes place while analysing technical systems. Stachowiak (1973) defined the theory of several semantic stages for modelling and conversation. The zeroth stage is the actual material information, e.g. a technical drawing. The first stage represents the perception model, which is build by capturing of information of the zeroth stage, and the cogitative model, which is formed by interpreting the perceived information. The externalisation of the interpreted information builds the second stage, e.g. the description of components or functions of the technical system by the engineer.

As data collecting methods, this paper introduces eye tracking and the think-aloud method. These methods help to record which information of the zeroth stage could be perceived (via eye tracking) and to generate externalisations of the interpretation (via think-aloud). Further, two process models for the first sematic stage, the perception and cognition, in the field of engineering design (Hahne, 2012) and physics (Chi et al. 1981) are presented.

2.1 Previous examinations on the interpretation of technical drawings

For interpretation of technical drawings, Hahne (2012) proposed a process model, which describes different phases of interpretation. He defines the analysis of technical drawings as an interpretation problem and divides the process into three main phases - the preparation phase, the interpretation phase and the reflection phase. The preparation phase takes place before the actual analysis of the drawing starts when the interpreter reads the task and prepares himself for the upcoming analysis. The interpretation phase is divided into three parts: the incubation, the conception and the argumentation. During incubation, the observer gets an overview of the drawing and draws first associations to known problems. During the conception phase, the interpreter analyses the system and develops problem-solving concepts, which he adapts according to his experiences. During the argumentation phase, the interpreter puts the concepts into a broader context and analysis the drawing in detail. He searches for arguments for the correctness of the problem solving concepts. The reflection is the post-processing

phase during which the interpreter compares the results of interpretation with the motivation and analysis task.
For verifying the proposed model, Hahne (2012) used the observation of eye movements in order to detect the different processes of interpretation. He expected increasing or decreasing effort of mental processing which he equates with the durations of gaze fixations (see Figure 1).

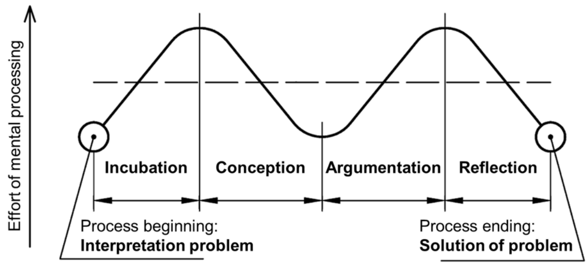

Figure 1. Mental processing during the interpretation phases (according to Hahne, 2012)

Hahne (2012) could not verify the exact sequence of incubation, conception, argumentation and reflection, but he concluded the existence of different phases of interpretations by observing the expected increase and decrease of the fixation duration.

2.2 Surface structure and deep structure

Experts and novices differ in separate ways while problem solving tasks. As researches in physics by Chi et al. (1981) show, novices tend to engage problems on a simpler level than experts do. In an experiment, both groups were asked to categorize physics problems. After that, they should explain the reasoning for their groupings. Through a cluster analysis, similarities were found in the categorization of each group:
According to Chi et al. (1981), the novices paired problems based on "surface" structures, like objects, physical terms or the physical configuration described in the problem. The verbal descriptions of the novices support the suggestion that they categorized by the surface structure. Experts did not categorize the problems by similarity of keywords or diagrams in the task description. Instead, they used the major physical principle for assigning the problems to categories. Mainly the two groups differ in the schemata they are using; where experts have procedural knowledge, novices only have sufficiently declarative knowledge, lacking abstracted solution methods. This paper examines the transfer of these findings to engineering design and the analysis and interpretation of technical systems.

2.3 Eye Tracking and Think-Aloud

Understanding the perception process is a very challenging task. The major processes capturing, interpretation and construction take place in the human mind as well as the inner models. They are not visible to the observer. However, with eye tracking and the think-aloud method the possible in- and output of this process could be observed.
Eye tracking allows the observer to retrace the subjects approach through his/her own point of view. The most common eye trackers in use are video-based trackers. They operate with an infrared illumination and an eye video camera. All video-based systems calculate the viewpoint by means of the location of the pupil centre and the corneal reflection of the infrared light (Holmqvist et al., 2011). There are static and mobile eye tracking systems. For static stimuli, which are shown on a monitor, static eye trackers are preferable. This is the case for the analysis and interpretation of technical drawings. Remote systems work without physical contact and allow few head movements of the subjects. Illumination and eye video camera are mounted on a table in front of the participant. Matthiesen et al. (2013) show the applicability of eye tracking for research on the human behaviour in design.
Think-aloud methods are well established in empirical research and help to get an idea of cognitive processes of humans. (Ruckpaul et al., 2014) investigate the influence of combining think-aloud and eye tracking in research on analysing technical systems. Concurrent think-aloud is recommendable for studies on the functional context as much information is elicited about shape and function. During the retrospective think-aloud, more information about the participant's procedure is elicited.

2.4 Research question

The goal of the presented research is to observe the approaches of expert and novice engineering designer during the analysis and the interpretation of technical systems in order to assess if it is necessary to develop individual methods for supporting novices or experts during their analysis processes. The research presented in this paper focuses on technical drawings as representations of technical systems. Respectively, the main research questions of this paper are: Are there differences in the analysis and interpretation of technical drawings by expert or novice engineering designers? How can we detect these differences and do we need individual methods for each group of expertise in order to support the analysis processes?

The perception and cognition are the main mental activities for the analysis and interpretation. Thus, an experiment is conduced, which is presented in the following chapters. The independent variable is the rank of expertise. The dependent variables are the gaze data and the verbalised thoughts, which represent the input and output of the perception and cognition process. The two above-mentioned models, the interpretation process model by Hahne (2012) and the model of surface structure and deep structure by Chi et al. (1981), are applied to a new experimental design in order to compare and add results to their findings.

3 EXPERIMENT

In the experiment, two technical drawings of gearboxes were presented to each participant. The task for the participants was to understand the technical system. The assignment was consciously chosen to be wide, to analyse differences in the level of understanding and the duration of the examination, later referred to as the depth and width of the analysis. When the subject stated that he/she understood the technical system, the experimenter faded out the drawing. The duration of presentation was limited to 180 seconds. As shown by (Gero and Tang, 2001) and (Ruckpaul et al., 2014) concurrent think-aloud is recommended for studies on the functional context. Because one research question of this paper is to investigate on differences in perception and interpretation of technical drawings, concurrent think-aloud was used. Due to the wide assignment, it had to be verified if the participants understood the presented technical system. Therefore, the experimenter asked questions about functions and technical details of the systems after the presentation. The subjects were neither informed about the limitation of presentation time, nor that questions were asked after the analysis.

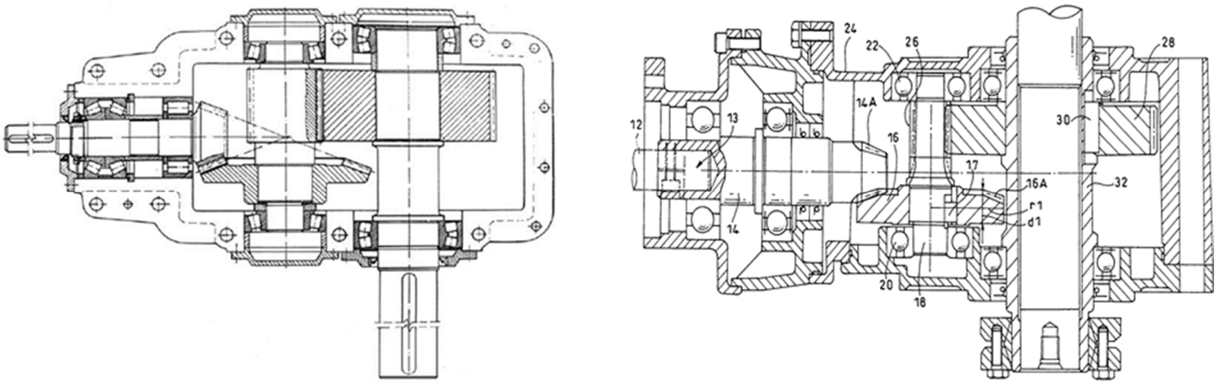

Figure 2. Presented drawings, first gearbox on the left (Steinhilper and Sauer, 2012) and second gearbox on the right (Yamamoto, 2008)

Followed by the presentation of the first drawing, shown in Figure 2, the participants were asked questions about the types of the bearings and sealings. The last question on the first drawing was about the assembly of the gearbox. The second drawing is part of a patent specification and shows a more complex gearbox. The experimenter asked questions about the fixation of the shafts, the fabrication of the housing, the transmission and the function of a particular shaft-hub connection.

At the end of the examination, the participants were asked about their approach during the analysis of the drawing. Thereby the observed approach could be compared to the personal opinion.

3.1 Hardware Setup

The stimuli were presented on a 22" monitor with a resolution of 1680 x 1050 pixels. To record the eye movement a binocular remote eye tracker SMI RED 250 was used. A webcam, mounted on the top of the monitor, recorded a video of the subjects. The audio of this video was used to record the outcome of the think-aloud. The experimenter executed and controlled the experiment.

3.2 Test persons

To investigate the differences of expertise, following groups of subjects participated in the experiment.

- 7 mechanical engineer students who finished their second academic year
- 4 mechanical engineer students who finished their third academic year
- 14 research assistants with up to 5 years of work experience in product development
- 2 mechanical engineer lecturers with 14 and 38 years of work experience
- 7 mechanical engineers with 5 to 35 years of work experience

In order to analyse differences in the perception based on the experience, two groups were defined. The first group persists of 11 students and the second group of 23 engineers.

3.3 Coding scheme

To quantify the results of the think-aloud a coding scheme was developed. The coding scheme classifies between surface and deep structure as mentioned in chapter 2.2. The deep structure is sub-divided into two categories, comments on functions and on further interpretation. In addition, the amount of mistakes should be quantified, as well as statements referring to elements, which are not shown. Therefore, following categories are defined:

- Components (surface structure)
  - Components without referring to a connection to another component ("gear-wheel", "shaft", "radial shaft seal")
  - Details of the presented system ("cast housing", "cylindrical roller bearing with flanges")
  - Descriptions of the location ("the shaft on the top right corner")
- Functions (deep structure)
  - Functions ("this cover seals the housing")
  - Flow of power, force or momentum ("the shaft transfers the momentum to the gear-wheel"
  - Interactions ("this part is not fixed on the shaft, so it can move")
- Further interpretation of the embodiment to the context of the overall system (deep structure)
  - Abstraction ("separation of functions", "wedge effect")
  - Evaluation and integration of knowledge, which is connected to the embodiment design ("massive bearing", "high load rating")
  - Assembly ("to assemble the housing…")
- Not shown elements
  - Not shown components ("there should be a sealing")
  - Not shown functions ("it is not possible to shift gears")
- Mistakes
  - Wrong titling of a component or misunderstanding of a function

The transcripts are divided into units of meaning, which can be single words if the subject mentioned components without a context, parts of a sentence if more than one entity is referred to or whole sentences. Quotes, which do not match any category, like requests to the experimenter, are not coded.

4 ANALYSIS AND RESULTS

4.1 The four stages of visual examination

The statements to the approach during the drawing analysis were compared to the recorded gaze path video. The generally applied approach was similar by nearly all participants. Four stages of visual examination can be distinguished.

1. Identifying

   During the first 1-6 seconds the subjects distinguished what kind of system they look at, often commented with statements like: "Ah a gearbox". The gaze-path covers a relative small area, which indicates the relevance of the peripheral vision during this stage. The durations of the fixations are shorter than the average.

2. Overviewing

   After identifying the system, the subjects get a general idea of the presented drawing. In this stage, they find out how many shafts are installed and how many transmission ratios are presented.

3. Analysing

   In this section the participants analyse the components, which are fulfilling the main function, as converting the torque and pivoting the shafts. Most participants said they were following the flow of power and force. However, not all of them did follow the flow of power strictly. This stage is marked by long fixations during the analysis, sometimes disrupted by phases at which the participant searches components or has to re-orientate.

4. Reviewing

   During the last section some participants searched for distinctive features and auxiliary functions in the drawing. If an interesting housing, a special concept for assembling or sealing was pictured this is what the subjects identified during the last section. Stage 4 was not observed on all participants.

The stages identification and overview match the incubation phase of Hahne (2012). The stage analysing and reviewing include Hahne's phase of conception and argumentation. Due to think-aloud the two phases alternated often. Thus, the division in analysing the main function and reviewing the drawing for auxiliary functions is more reasonable.

To analyse the subjects' course of fixation durations during the examination of the drawings, an exemplary diagram is used, presenting the smoothed fixation duration over time by one research assistant and one student (see Figure 3). To smooth the raw data, a polynomial of the sixth degree was used.

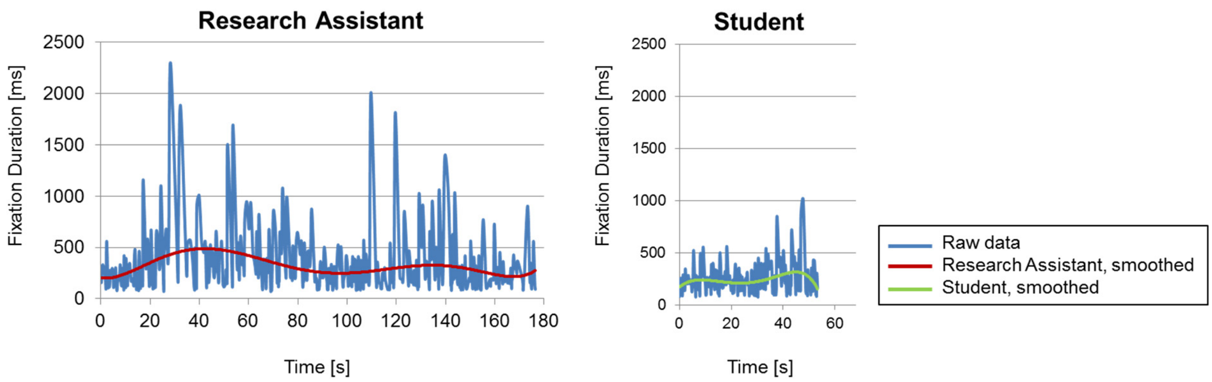

Figure 3. Course of fixation duration for expert and novice observers

As shown in chapter 4.5, the mean fixation duration is lower for the students than for the engineers. In addition, subjects with small deviation from their average fixation duration (±75 ms, student in Figure 3) could not answer as much questions as subjects with higher deviations (+165 ms and -120 ms, research assistant in Figure 3). Not all subjects have the same characteristics during their analysis, as (Hahne, 2012) proposed. However, with every transfer to another stage of examination, the course of the fixation duration shows a change. This indicator could be a maximum, minimum or a turning point depending on the subject. Combined with the concurrent think-aloud method, this type of diagram can support the analysis of the subjects approach. The smoothed data allows the researcher to easily identify phases of intense analysis, which are implied by long fixation durations. Furthermore the four stages of visual examination can be identified. Following studies should examine how far this research-tool is suitable for other representation forms of technical systems and eye tracking glasses.

4.2 Exemplary analysis of the drawing examination

To show the differences in the drawing examinations two approaches on the first drawing will be given. The examples are from a student and a research assistant.

A student, who finished his second academic year, only looked 55 s on the drawing until he said that he understood the system. He follows exactly the four stages and was aware of his approach. He starts with low fixation durations during the first stage (0-3 s). However, in his second stage (3-7 s) his fixation duration is above the average value. As Lohmeyer et al. (2013) proposed this seems to be a typical behaviour of the unexperienced subjects. They start with a more direct search, without understanding the overall function. Then he spends 22 s on differing the "standing and moving parts" as referred to in stage 3. In his third stage, analysing (7-32 s), the fixation duration is below his average value. This could be the reason why he fails answering most of the questions. Instead of scrutinizing the drawing, he skims over it and does not perceive enough information. The remaining time, he analyses the bearings and the housing. At the end of his last stage the fixation duration drops, which is typical for all subjects, who terminate their analysis by themselves. Although, he said that he paid attention to the housing, as the eye tracking also proofs, he could not answer the question where the level of the housing parting is. In spite of his structured approach, he was not able to answer the questions about the sealing and could only name some types of the shown bearings. He also answered fewer questions to the second drawing than the average.

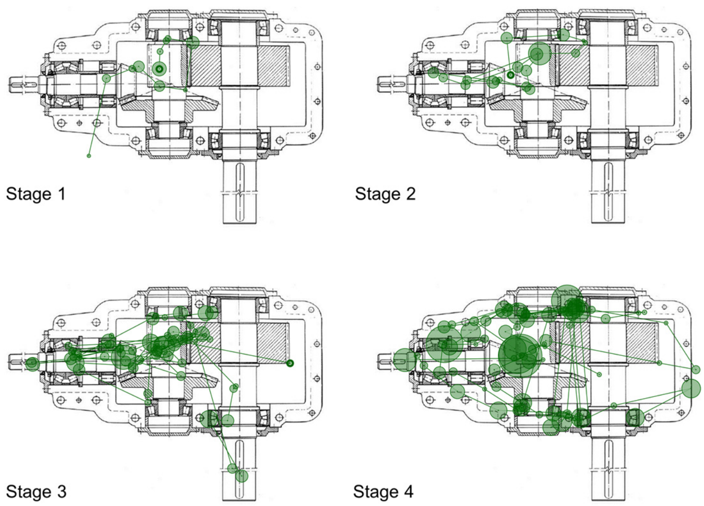

Figure 4. Scanpath of the student's analysis (the centre of the circles represent the location of the visual focus, the diameter represents the fixation duration)

Another subject, a research assistant, examined the drawing until the limit of 180 s was reached. He also followed exactly the four stages. After 6 s he said, "OK that is a gearbox", after another 12 s he finished the second stage when he had an overall impression of the shafts and transmission ratios. During the first two stages, his fixation durations are below his average. The main part of his analysis lies in stage 3; he spends 112 s on the flow of power and force. He follows the flow of power from the left and thereby examines the bearing of each shaft. While he analyses an untypical bearing, he reaches a maximum in fixation durations, followed by a minimum, when he examines the diameter of the shafts. The duration of his fixations correlates with the complexity of his present analysis. During his last stage (130-180 s) he reviews the housing covers and the missing sealing with long fixations. He easily identifies the transmission ratio at the end of his last stage, which also correlates with the low fixation duration. As the scanpath in Figure 5 shows, he examines every single component in the drawing. The subject concludes the function and often interprets further the actual situation. He was able to answer 90 % of the questions to the first drawing, where he could not mention two types of bearings. His approach to the second drawing was very similar. Through his accurate procedure, he was able to answer 3 out of 4 questions correct. The missing question was about the fabrication of the housing, which he did not look at during the given time limit.

As the scanpath of the two subjects show, they often look at the same components but receive different information. For example, both subjects look at the housing of the gearbox. While the experienced engineer recognizes the level of housing parting, the student did not perceive this information. This means that following the four stages of visual examination is helpful but is not the only key to successful analysis and interpretation of a technical system. Thus, the following chapters investigate further correlations.

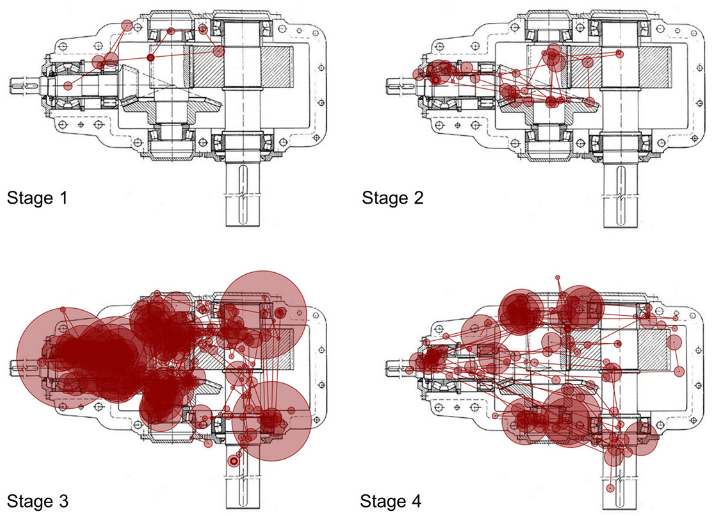

Figure 5. Scanpath of the research assistant's analysis

4.3 Width of the analysis

To analyse, how long the participants would spend on the examination of the drawing, they could determine the examination by themselves, up to the time limit of 180s. Between the students and the engineers, a significantdifference was found in the duration invested on the examination of the drawing. To consider a result statistical relevant in this paper the p-value has to be less than 0.05. While the mean value of the engineers is 90 s for the first drawing, the students mean value is only 57.7 s. The units of meaning per time were also calculated and differences between the two groups could not be found. This and the longer fixation duration of engineers lead to the significant difference that engineers talk more (mean value 10.9 units of meaning) than students (6.3 units of meaning) during their examination of the first gearbox.

4.4 Depth of the analysis

As shown in section 2.2 it seems that experts elicit "deeper" information from problems of their field (Chi et al., 1981). To analyse the differences between the students and the engineers, the results of the think-aloud were transcribed and categorized by the coding scheme presented in chapter 3.3. Because engineers articulated more units of meaning, Table 1 shows the relative distribution of articulated units.

Table 1. Relative distribution of the articulated units of meaning

		Mean value of the ratio	Standard deviation of the ratio	p-Value Levene test	p-Value t-test
Components	Students	0.428	0.175	0.687	0.339
	Engineers	0.356	0.213		
Functions	Students	0.484	0.141	0.488	0.727
	Engineers	0.463	0.166		
Further interpretation	Students	0.046	0.050	0.072	0.006
	Engineers	0.133	0.090		
Not shown elements	Students	0.022	0.031	0.226	0.247
	Engineers	0.043	0.052		
Mistakes	Students	0.020	0.035	0.000	0.219 (Welch test)
	Engineers	0.006	0.015		

Table 1 shows the distribution of categories mentioned during both drawing examinations. Students stated more components than engineers did. However, with a p-Value of 0.339 the difference is not significant. It was also presumed that engineers pay more attention to functions. In addition, the mean value is higher; the p-value shows no significance. The clearest difference can be seen in the code of further interpretation. Engineers integrated in average almost 3 times more often further knowledge, which they connected to the embodiment design, than students. This difference is significant and matches to the findings of Chi et al. (1981). This raises the research questions: Is the further interpretation only based on experiential knowledge? How can students be enabled to this kind of understanding?

Engineers mentioned more elements, which are not shown, like adjustment disks or paper seals. Also, they made fewer mistakes in specifying components and functions. However, both characteristics are not significant.

4.5 Duration of fixations

To get the subjects used to the think-aloud method and to receive gaze data of the subjects on a non-technical image, a reference image was presented. The reference image shows a cartoon of a harbour scene.

Experienced engineers are supposed to act more structured than inexperienced engineers. By the unstructured approach, novices often have to re-orientate (Lohmeyer et al. 2013). The reorientation is associated with short fixation durations, while the accurate analysis is associated with longer fixations. According to (Duchowski, 2007) longer fixations also indicate increased cognitive activities.

Table 2. Average fixation durations [ms] of examination

		Mean value [ms] Fixation duration	Standard deviation [ms] Fixation duration	p-Value Levene test	p-Value t-test
Reference Image	Students	224.88	43.94	0.039	0.855
	Engineers	222.17	27.93		
Gearbox 1	Students	214.84	57.64	0.707	0.092
	Engineers	250.66	54.83		
Gearbox 2	Students	241.22	61.22	0.664	0.19
	Engineers	277.30	77.30		

As shown in Table 2, the mean fixation durations of both groups are very similar during the examination of this reference image. A difference appears on the examination of the technical drawings. In agreeing to the suggestion, engineers have longer fixations on the technical drawings than students do.

Although the reference image only shows a cartoon image of a harbour scene, the mean fixation duration of the students nearly stays unchanged, even decreases, during the examination of the first drawing. This implies an almost unchanged cognitive function of the students, while the engineers increase their fixation duration by 12.8 %. For both groups gearbox 2, which shows a complex patent figure, is linked with an increase of the fixation duration.

The results imply that the cognitive function of the engineers is higher than the cognitive function of the students. These findings can be supported by the results in section 4.4. The analysis of surface structures requires less cognitive function and therefore shorter fixation durations as the analysis of deep structures, such as the function and further interpretation. This would explain the almost equal fixation duration during the examination of the reference image, where both groups mainly described the shown elements. The identification of function and the further interpretation of characteristics increase the mental activity during interpretation and thus, the fixation duration of the engineers. The question that therefore arises is as follows: Is there a causal association between the longer fixation durations and the analysis of the deep structures?

5 DISCUSSION AND CONCLUSION

In order to support the engineers while analysing technical drawings, it is important to understand their behaviour and needs during this process. During the analysis, perception and cognition are the key elements to build up an understanding of the problem. The research question of this paper is if there are differences in the analysis and interpretation of technical drawings by expert or novice engineering designers, in order to assess if it is necessary to develop individual methods for supporting each group of expertise during their analysis processes. This paper investigates on the mental activities of perception and cognition from both sides, the captured information through eye tracking and the processed information with the think-aloud method. An experiment with 34 subjects was conducted to detect differences.

The main findings can be summarized. The interpretation of perceived information differs significantly. Whereas the students were more likely to describe the system with surface properties like components and its functions, the engineers interpreted the perceived information of the embodiment design in the context of the overall system. Novice engineering designers hardly connected the embodiment design to the systems context and thus, did not analyse the system in depth. Expert engineers significantly more often interpreted the system in depth. These findings support the results of Chi et al. (1981), which can be verified for this field of research. Further, the capturing of information differs; experienced engineers analyse technical systems more closely in width and depth. They give themselves more time for the examination and even have higher fixation durations.

Hahne's phases of interpretation (Hahne, 2012) were not directly applicable but the process of fixation duration during the interpretation of technical drawings showed the same gradients. The observation also showed that a change in the fixation duration is a sign for a change of to the next stage of interpretation. By observing the process of fixation duration, a further difference between expert and novice engineering designer are visible. The deviation of fixation durations from their average value is higher for experts, however, there is no significance in the results.

The analysis processes of novice and expert engineers in principal are similar but differ in their width and depth. Thus, methods need to be adapted to the rank of expertise. Further observations on the analysis processes need to be conducted before the development of suitable methods is reasonable. Additional analysis of the presented experiment on the gaze path correlating the level of system understanding is in process. The existence of a correlation between a longer analysis of the technical drawing and a deeper understanding of the system needs to be approved. Concluding the presented research, it can already be stated that the interpretation of the embodiment design on the level of the overall system and not only on the surface level of components should be taught to novice engineering designers.

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