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UTILIZATION OF MOBILE EYE TRACKING DATA TO IMPROVE ENGINEERING DESIGN EDUCATION

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ABSTRACT
A central part of basic engineering design education aims for imparting profound knowledge of how commonly used machine systems are designed and how they work in detail within a technical product. In this context, a basic challenge lies in teaching to analyse complex systems that are usually characterized by a high number of interacting parts and interfering movements. In our basic engineering design education at ETH Zurich, we recognized that high-performing students in functional analysis are able to gain more insights from analysing machine systems than low-performing students. Indeed, high-performers are not only effectively using previous knowledge, they are also more successful in identifying relevant parts. This observation raises two questions. (Q1) Which previous knowledge is required to single-handedly be able to fully understand how a specific system works? and (Q2) How can we support students in drawing special attention to the relevant parts and the areas revealing their role within the system? In order to answer these questions, we conduct a mobile eye tracking study, including concurrent reporting. Students are asked to analyse a small, but complex machine system and to explain how it works. This paper highlights the differences between successful und and non-successful functional analysis and discusses them in the context of the two questions presented above. The two main results of this paper are that successful students had a wider knowledge-base of mechanical systems and that analysis strategies like "following the flow line of force" gives a guide rail. Both helped them to identify single subfunctions and to evaluate their importance.

Keywords: mobile eye tracking, functional analysis, comprehension process, engineering design

1 INTRODUCTION

One of the main challenges in basic engineering design education is to impart the ability to functionally analyse technical systems. The most promising approach in our lecture courses is not only to present simple standard components taken out of context. We show and analyse in detail realisations in more complex everyday products with combinations and modifications of standard components. The intention is to enlarge the students' knowledge base and to motivate them to construct new technical systems by combining and creatively using standard components.

In order to survey and improve our educational approach in functional analysis we are interested in how students gain insights while analysing technical systems. This raises two questions. (Q1) Which previous knowledge is required to single-handedly be able to fully understand how a specific system works? and (Q2) How can we support students in drawing special attention to the relevant components and the areas revealing their role within the system? For the purpose of answering these questions, we conducted a mobile eye tracking study, comparing high- and low-performing students.

Using a glasses-integrated mobile eye tracker allowed the participants to move freely while operating with the examined object, the so-called stimulus. The used stimulus was a small, manually operatable, but complex technical system. It could be disassembled in order to investigate all system components and it could be manipulated to observe how they interact. The subsequent data analysis focused on the similarities and differences of the high-performing students in comparison to the low-performing students. Based on the conclusions, recommendations for the basic engineering design education are presented by answering both research questions.

2 BACKGROUND INFORMATION

This chapter presents background information to facilitate the access to the subsequent chapters. It is divided in two sub-chapters: the functional analysis as theoretical background and eye tracking as the primary used tool for data acquisition in the presented study.

2.1 Functional analysis

Functional analysis. This method aims to break down a system into its basic functions and to map them to potential physical components for realisation. The results of the functional analysis are presented as a top-down functional tree and a bottom-up product tree [1]. This promises to help developing new product-concepts with a "thorough analysis of the requirements [and to] foster the search of alternative solutions" [1].

Alternative analysing methods. The functional analysis provides a framework to analyse both, an existing and a novel product. The challenge is to find the basic functions of the examined product. In literature, there are several methods to gain this necessary information. This section focuses on two widespread analysing-methods. Pahl and Beitz suggest to analyse forces and motion in mechanical systems along the flow line of force analogue to flow lines in fluid mechanics [2]. Albers and Wintergerst picked this approach up and exceeded it. The C&C^2 approach adds connections to the environments and to other structures to consider their influences and interactions [3]. Both methods abstract the function structure while a reference to the embodied design remains. This "match[es] a designer's intuitive thinking and expectations for efficient work support" [3].

Function-behaviour-structure framework. Gero and Kannengiesser present a framework of the fundamental processes in designing – the function-behaviour-structure framework [4]. Especially the analysis and the evaluation processes are directly connected to the functional analysis and provide a cognitive model. They describe how information from the external world are interpreted and compared to the expected information in the designer's inner world.

Comparison expert & novice. Jarodzka et al. examined how an expert's analysis process differs from a novice's in perceiving and interpreting information of complex, dynamic visual stimuli in the field of biology. They found that experts use knowledge-based shortcuts by connecting observations with related information of their own knowledge. Further, experts focus more on relevant information than novices, which leads to faster performances [5].

2.2 Eye tracking

Why & How to use eye tracking. Eye tracking is able to obtain qualitative and quantitative insights into user's cognitive processes. Further, it helps to "reveal often-not-fully-conscious processes that led to [the user's behaviour]" [6]**.** Raw-data is captured by video cameras detecting reflexions of infrared light shone on the eyes. This raw-data is calculated to a gaze point by an algorithm to the gaze-data. The algorithm divides additionally the gaze-data in events of fixation (eye relatively motionless) and saccades (eye moves to next fixation). This gaze-data can be analysed subsequently with a method called area of interest (AOI) analysis. An AOI represents the participant's focus in the respective field of vision. AOI specific values show the perceived importance of single AOIs [6].

*Eye tracking in education***.** In literature, there are several examples of how eye tracking is utilized in education. It is employed in high schools [7] as well as in universities [5][8] and in different fields (e.g. biology [5] or engineering [8]). Eye tracking aims at improving the education design by examining how experienced students or experts perform in field-specific challenges [5][7]. Mussgnug et al. discuss how eye tracking can be used with different group sizes (>20p, 3-20p, 1-2p) and what kind of knowledge can be imparted to students, when using eye tracking as an educational tool [8].

Additional verbal protocol. Gaze data alone is not sufficient to conclude to a person's train of thought. Using additional, gaze-independent source of data helps to close this gap. One suitable tool for eye tracking is a verbal protocol [6]. If it is aimed to receive information in the functional context, Ruckpaul et al. recommend to use the concurrent reporting (during performance). If metacognitive information is sought, they recommend cued retrospective reporting (after performance). In cued retrospective reporting participants use their own gaze video to report their train of thought. Further, they show that concurrent reporting has no influence on the participant's gaze [9].

3 METHOD

In the following, the study's implementation, data acquisition and data analysis are presented. The mobile eye tracking study was conducted with 12 mechanical engineering students to examine the functional analysis behaviour of mechanical engineers. Further, it was aimed at searching for differences based on gaze data between successful and non-successful students.
The stimulus of this study was an original turning unit of a sun-blind. This unit adjusts the blade angle in three positions (opened, semi-closed, closed). All unit components are presented in Figure 1.

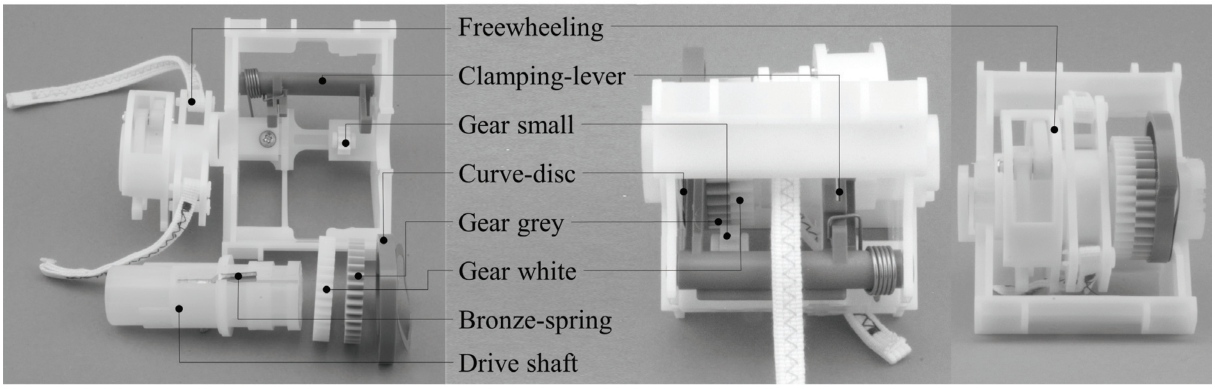


Figure 1. Components of the sun-blind turning unit

Constant start conditions. A video presented the task and additional information for constant start conditions to all participants before starting in the functional analysis. The participants' task was to understand the delayed tilting mechanism of the presented stimulus. The additional information ought to facilitate the start in the functional analysis of the stimulus. It contained its turning function as described above, the attribute of lowering with the blinds turned in semi-closed position and that the unit tilts the blinds to the full-closed position with the 34th turn of the drive shaft.
Study implementation. The participants could use two units of the stimulus for the functional analysis and a pen to mark components. One unit was assembled and could be used to examine how all components move together. The other unit was demountable as it is presented in Figure 1 on the left-hand side and could be used to find hidden components (e.g. bronze spring) or to examine components' characteristics. To decrease the participants' stress level, they were informed that there was no time limit. It was their decision when they finished the functional analysis. However, to not temporally exceed any reasonable analysable datasets, the experiment was stopped by the moderator if the participant did not manage to fully find and understand the searched mechanism within 20 minutes from start-time.
Data acquisition. The participants' system-analysis process was tracked in first person perspective including the calculation of the gaze point via the SMI Eye Tracking Glasses 2 Wireless with a sampling rate of 60 Hz and a tracking accuracy of 0.5° over all distances. In addition, all participants were asked to think aloud to get an access to the participants' inner train of thought.
Qualitative data analysis. In the subsequent data analysis, the study data was at first analysed qualitatively. Based primary on gaze-data and supplemented by think aloud audio-data a participant-analysis-protocol was generated. The protocol contained a description of the participant's functional analysis in 30-seconds-steps. It marked the participants' moment-specific analysis focus, their actions and if certain functions were understood or not. This information enabled to find the participant's main moments of insight and gives an overall impression of how the particular participant went through the understanding process of the presented stimulus.
Quantitative data analysis. The quantitative data-analysis focused on the characteristic of the AOI specific dwell time. AOIs of this study were the main-components of the stimulus (see Figure 1, left-hand side). The connection of the gaze point to the related AOI and thus the information what a participant gazed at a specific point in time is achieved manually with a method of SensoMotoric Instruments (SMI) called Semantic Gaze Mapping. After this intermediate step, the AOI-time-relation is made and can be illustrated as an AOI-Sequence Chart (see Figure 2). The start-point (t=0) is connected to the participant's analysis start. This illustration was used to find links among single AOIs defined by the participant's gaze and hence to deduce on the participant's analysis focus.

Combined data analysis. The combination of the qualitative and the quantitative data analysis results was performed to depict the participants' main moments of insight in the quantified gaze data. The necessary highlighting step was performed combining the AOI-gaze-data from the quantitative data analysis with the moments of insight from the qualitative data-analysis. The AOI-gaze-data were selectively blanked off so only the moments of insight remained (see Figure 2). The combined data analysis focused, based on this intermediate step, on the sequence, the concentration, the complexity and the number of insights and compared the results of the two participant groups.

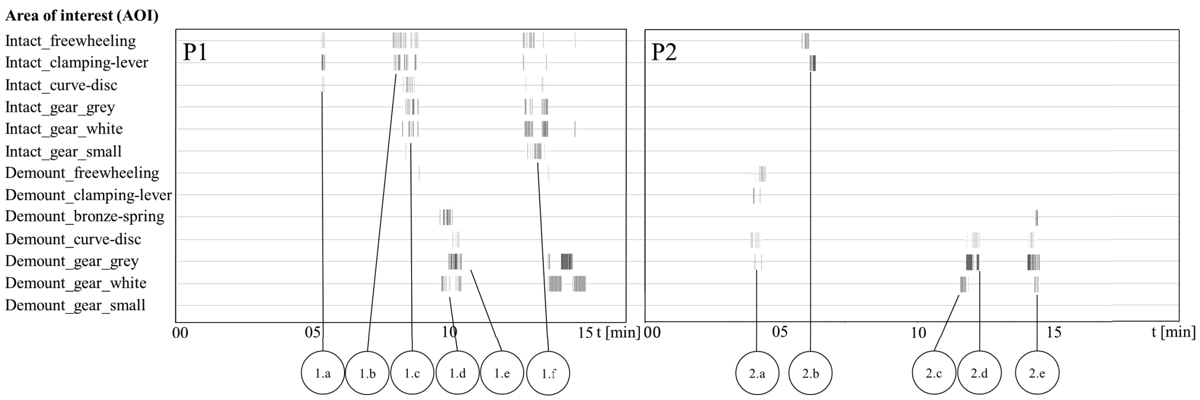
4 RESULTS

In the functional analysis, 6 out of 12 participants succeeded and fully understood the presented stimulus. They are following called high-performers. The other 6 participants non-succeeded to do so and are following called low-performers. In each group, one participant's gaze data set was qualitatively not sufficient to be analysed. For this reason, the data sets of 5 high-performers and 5 low-performers were analysed.

Figure 2 shows respectively the moment of insight (MoI) AOI Sequence Chart of one representative successful participant P1 (left) and one representative non-successful participant P2 (right) over their complete analysis process. Participant P1 completely understood the function of the turning unit in approx. 16 minutes. The moderator stopped the analysis process of participant P2 after 20 minutes.

Success criteria. Five subfunctions have to be recognised and understood to fully understand the function of the sun-blind turning unit. In the following, these five subfunctions are listed according to the flow line of force. The subfunctions 1-4 together effect the mechanism of the full-tilt delay and had to be understood to be counted as successful.

1. relative displacement of gear-wheels (gearing mechanism causes unequal revolution speed)
2. freeing of bronze-spring (combination of hollow in grey gear-wheel and relative displacement)
3. triggering of curve-disc (bronze spring gearing into recess of curve-disc)
4. triggering of freewheel (curve-disc removes disabling-lever)
5. activation of freewheel (disabling-lever invalidates freewheeling & attached cords turn blinds)



1.a	Approach, curve-disc is trigger		2.a	Approach, curve-disc is trigger
1.b	Insight, activation of freewheel		2.b	Insight, activation of freewheel
1.c	Insight, triggering of freewheel		2.c	Part-insight, relative displacement of gear-wheels is possible
1.d	Insight, freeing of bronze-spring		2.d	Insight, triggering of curve-disc
1.e	Insight, triggering of curve-disc		2.e	Part-insight, freeing of bronze-spring (completing part-insight 2.c)
1.f	Insight, relative displacement of gear-wheels			

Figure 2. MoI AOI Sequence Chart of a successful (left) & a non-successful participant (right)

Group independencies. No group-specific pattern was found respective the sequence of insights. Participants started at different subfunctions, no matter if high-performers or low-performers. This led to different sequences of insights regardless if the analysis was successful or not.

Analysis similarities. Concerning the moments of insight in general, both high- and low-performers showed similarities. In these short time spans (approx. 10-50s), the related AOIs were gazed at predominantly and formed an insight-pattern (e.g. Figure 2, 1.a).

Analysis differences. Differences in the insights between high- and low-performers were the frequency, the complexity and the number of insights. Respective the insight frequency, Figure 2 shows a characteristic difference between a high-performer (P1) and a low-performer (P2). Although participant P2 had his first insight earlier than participant P1, he stumbled and had a long period with no insight (2.b to 2.c). In contrast, participant P1 has a higher insight frequency, starting with insight 1.b. The insights 1.b to 1.e appeared within approx. 2:30 minutes. This is characteristic for high-performers. In the start-up phase, they collect information and slowly create an image of the system. In the end phase, one insight triggers the next and all relevant subfunctions are connected to each other. Relating to the insight-complexity high- and low-performers also showed differences. High-performers often correctly combined the information of one observation with another one received before. For example, participant P1 understood that the movable grey gear frees the bronze-spring when it is turned to the key-position (gear-wheel-hollow over bronze-spring, insight 1.d), remembering the discovery of the bronze-spring minutes ago. In contrast, participant P2 needed two attempts to fully understand this subfunction (insight 2.c & 2.e). The main and crucial differences between high- and low-performers were the number of insights. All low-performers missed the insight how the relative gear wheels displacement works. The gaze data of the low-performers showed no insight-pattern with the small gear included (representatively see Figure 2, right-hand side). This component is essential for the resulting relative movement in the gearing mechanism. Some low-performers observed the relative movement of the grey and white gears and took it as given. Other low-performers broke the analysis off because they could not find its origin.

5 DISCUSSION

As introduced, the two research questions of this paper were (Q1) Which previous knowledge is required to single-handedly be able to fully understand how a specific system works? and (Q2) How can we support students in drawing special attention to the relevant components and the areas revealing their role within the system? Based on the results of this study we would like to answer both.

Answering Q1. Generally speaking, a wide knowledge base helps to perform two important steps in the functional analysis. Firstly, it enables to connect an observation with a related fact in the owner's memory, a so-called knowledge-based shortcut [5]. Many high-performers combined the observation of the gear wheels' relative movement or the unequal number of gear wheel teeth and the engagement in the small gear wheel with their knowledge of a strain wave gearing. This knowledge enabled them to understand the function of the relative displacement without having examined it in detail. Oftentimes, it triggered the action of counting the gear wheel teeth to verify this assumption (see Figure 2, insight 1.f). In contrast, the results of the data analysis show that no low-performer could estimate the function and the importance of the small gear wheel. Many assumed that its function is to underpin the two other gear wheels. This result indicates that they were unaware of a possible relative displacement realisation by a different number of gear wheel teeth combined with an equal gear wheel diameter (white and grey gear wheel, see Figure 1). Secondly, a wide knowledge base helped to identify and to evaluate the importance of a system's subfunction. In the study, the understanding process of the freewheel was a time-consuming analysis part. Although almost all participants managed to understand its function, some needed nearly half of their analysis time to comprehend this aspect. In some cases, this led to an abortion due timeout. Hence, the ability to recognise this function and to assume that it is not related to the searched mechanism helped to prioritise the analysis focus on the gear mechanism and to save time. Consequently, presenting in the basic engineering design education many examples of realisations of standard and of complex functions helps to develop a required knowledge base; especially examples of unorthodox usage of standard components in everyday-products (e.g. toys, tools, etc.), shows the variety of mechanical mechanisms. This enables to connect the knowledge of an abstract function like a freewheel with its possible realisations and to know different functionalities of standard components (e.g. gear mechanism or springs).

Answering Q2. Aside the recognition of subfunctions and subsystems based on the comparison to the own knowledge it needs an overlaid analysis strategy to gain a structure and thus reliability. It is important that basic engineering design education imparts this mindset to the students to improve their ability in functional analysis. The data analysis showed that low-performers did not follow consequently the flow line of force in and out of the system but rather trusted in their own assumptions without checking them. This partially led to irritations when they found facts which did not go well with their assumptions and thus sometimes led to an own defined abortion of the functional analysis. High-performers on the contrary checked their analysis-status by following the flow line of force from their own entrance to their current end. With that, they found gaps in their own defined flow line of force and they searched for the following subfunction to be understood. Guided by this trail, they connected functions of subsystems or components to adjoining subsystems or components. According to the data-analysis results, it has no influence on the understanding success with which insight the participants started. Thus, it is not necessary by force to start with the entering of the flow line of force in the system as long as the functional analysis follows it in both directions and is able to capture it completely, including its entry and leaving. Consequently, using analysis-strategies like the discussed one helps to identify relevant components and to understand their role within the system. For this reason, it is important to convince students in basic engineering design education of the meaningfulness of such analysis strategies.

Limitations. The dominating limitation of this study is that only the analysis-processes of one stimulus could be compared. Further limitations are the number of participants and the mobile eye tracking technology. Although the data-analysis rises comprehensible results, comparing two groups with five members each allows no definition of a general rule. Considering the highly individual analysis process further investigation is advised to strengthen this study's results. The mobile eye tracking technology rises the limitation of the so-called parallax error. This error occurs when the gazed object is not in the calibrated distance from the participant. If the analyst is not aware of its occurrence, the wrong AOI is related to the current gaze point. As well, the AOIs of this study themselves reveal as a limitation due to the small diameter, especially when the size of the AOI is smaller than the precision of the eye tracking system (0.5°). To compensate this issue, argumentation is not connected to single AOI-hits but to AOI-cluster and combined with think-aloud data.

6 OUTLOOK

We conducted this study to survey and to improve our educational approach in functional analysis. As discussed before, presenting a wide range of mechanical mechanisms in everyday products helps to develop a knowledge base, which can be referred to in a functional analysis. Further, imparting the mindset of using strategies in functional analysis is important so students gain structure in analysing technical systems. This motivates us to follow this track presenting many examples and exercising the application of analysing strategies in lecture. In the discussion, only the functional analysis method of "following the flow line of force" was evaluated because all students were educated in this method. It would be interesting if different methods lead to different functional analysis behaviours. Regarding the results of this study, it is recommended to reconduct this study with more participants, different stimuli and at different universities. This will show if the results are group-, stimulus- or site-specific.

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