Design and Technology Education: An International Journal

23.2

Mobile Eye Tracking in Engineering Design Education

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Abstract

A central part of basic engineering design education aims for imparting profound knowledge of how machine elements are designed and building an understanding about 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 difficult to understand 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 sub-functions and to evaluate their importance.

Key words

mobile eye tracking, basic engineering design education, functional analysis, comprehension process, foreknowledge, high- & low-performers

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 design 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.

The glasses-integrated mobile eye tracker rises no restrictions in the body position. This allowed the participants to move freely while operating with the examined object. In the experimental science, an examined object is also called stimulus. The used stimulus was a small, manually operable, but difficult to understand 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 eye tracking data analysis, both qualitative and quantitative, focused on the similarities and differences of high- and low-performing students. Based on the findings, 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. Viola, Corpino, Fioriti & Stesina (2012) describe that 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 which represent complementary views. Both views are fundamental approaches to analyse systems that are difficult to understand by subdividing them into parts. This promises to help developing new product concepts with a deep analysis of the requirements and to motivate the search of alternative solutions. This method cannot only be used for developing new technical solutions but also to analyse systems starting with the product to find the realized functions.

The functional analysis is not uncontroversial as a method to design new systems. Kroll (2013) states that the functional analysis needs a development of a solution independent function structure in the designing process which is difficult to apply. Furthermore, he criticises that the method may lead in a designing task to illogical combinations of sub-concepts.

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 & Beitz (2003) suggest analysing forces and motion in mechanical systems along the flow line of force analogue to flow lines in fluid mechanics. Matthiesen & Ruckpaul (2012) 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. Both methods abstract the function structure while a reference to the embodied design remains.

Function-behaviour-structure framework. Gero & Kannengiesser (2002) present a framework of the fundamental processes in designing – the function-behaviour-structure framework. Here, a function is at first translated to an expected behaviour in the synthesis process. This expected behaviour is subsequently transformed to a structure in the so-called synthesis process. In the analysis process, the actual behaviour is reasoned from this structure. The actual behaviour is then compared to the expected behaviour in the evaluation process. 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. Expert and novices are compared in different fields like engineering, architecture, medicine and natural science. Jarodzka, Scheiter, Gerjets & van Gog (2010) examine 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 can show 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. Harrison, Kim, Kou, Shum, Mariano & Howard (2016) compare the performance of an expert and a novice in an ultrasound-guided regional anaesthesia using mobile eye tracking. Like Jarodzka et al., they observe that experts solve tasks faster than novices and that the expert focus more on the relevant objects while the novice differ between relevant and non-relevant areas. Demian & Fruchter (2006) and Deken, Kleinsmann, Aurisicchio, Lauche & Bracewell (2012) observe the interaction between experts and novices in the field of architecture/engineering/construction industry and in the field of aerospace. They find that experts connect presented design tasks with past solved ones including the context to understand the design as a whole to apply this to the current situation including the assessment of the solution space.

2.2 Eye tracking

Why & How to use eye tracking. Bojko (2013) states that eye tracking is able to obtain qualitative and quantitative insights into user's cognitive processes. Further, it helps to unveil often-not-fully-conscious processes that led to the user's behaviour**.** Raw data is captured by video cameras detecting reflexions of infrared light emitted on the eyes and the eyes' pupils. The reflexions stay approximately in the same position, but the pupils move with the eye movement, both seen from the perspective of the video cameras. From the relative position of the reflexions and the pupil of an eye, an algorithm is able to calculate the view angle for a specific point in time, the so-called gaze point. The algorithm additionally divides 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 an 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 (Bojko, 2013).

Eye tracking in education. In literature, there are several examples of how eye tracking is utilized in education. It is employed in high schools (Gomes, Yassine, Worsley & Blikstein, 2013) as well as in universities (Jarodzka et al., 2010), (Mussgnug, Lohmeyer & Meboldt, 2014) and across disciplines (e.g. biology (Jarodzka et al., 2010) or engineering (Mussgnug et al., 2014)). Eye tracking aims at improving the design of education by examining how experienced students or experts perform in field-specific challenges (Jarodzka et al., 2010), (Gomes et al., 2013). Gomes et al. (2013) analyse high school students with an eye tracking system while they play engineering competence specific computer games with different difficulty levels. Here, the students have to change the initial, non-functional state of a mechanical system into a functional state. The goal is to find different eye tracking patterns of high and low performing students. Mussgnug et al. (2014) 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.

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 (Bojko, 2013). If it is aimed to receive information in the functional context, Ruckpaul, Fürstenhöfer and Matthiesen (2014) recommend using 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.

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 (six Bachelor of Science students, six Master of Science students) to examine the functional analysis behaviour of mechanical engineers. 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, and closed). All unit components are presented in Figure 1.

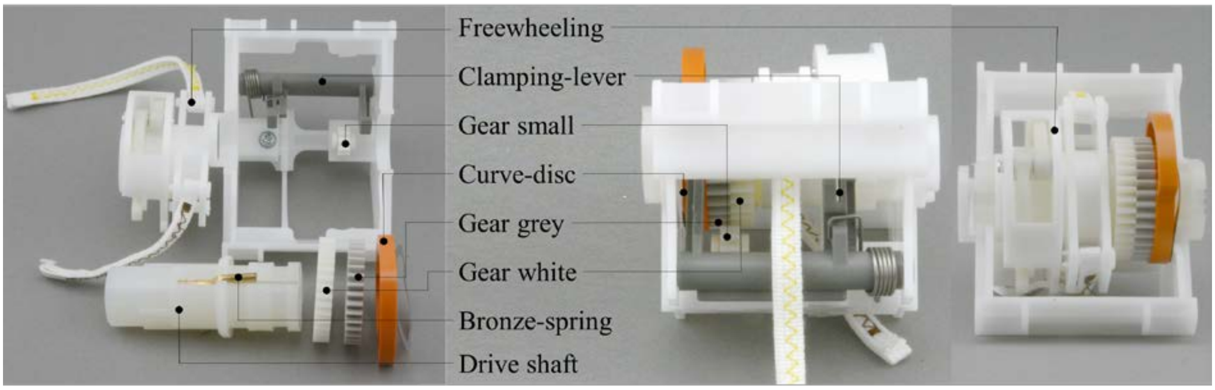

Figure 1. Components of the sun-blind turning unit with one disassembled unit (left) and one assembled unit (right)

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. The searched mechanism for the sun blinds includes a relative movement of two gear wheels, initiated by a different number of gear wheel teeth. This relative movement finally triggers a curve-disc that activates a free-wheeling mechanism, which turns the blinds (see Figure 1).

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. The participants stood in front of a table during the analysis process. One challenge with mobile eye tracking occurs when participants lead the stimulus near to their body. This entails that they look underneath the eye tracking glasses. The result is a tracking error because the needed eye characteristics (pupil and reflexions from the infrared light) cannot be detected any longer from the eye tracking cameras. Pilot studies, conducted in advance, showed a lower tracking error rate when participants stood and did not sit in front of a table due to a subconscious slightly higher gaze point referring to the scene view. The standing procedure also seemed to lead to a higher level of concentration. Additionally, the two units were placed on a pad. The pad was placed in the middle of the table and served as an orientation for the participants' handling space. This also led to a lower tracking error rate.

Data acquisition. The participants' system analysis process was tracked in first person perspective 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. The eye tracking glasses have three frame-integrated cameras. Two cameras are directed at the user's eyes. Combining the information of the pupil's position with the relative position of the reflexions from the infrared light emitting sources, an internal computer chip in the eye tracking glasses is able to calculate the user's raw gaze point data (see Figure 2). This gaze data is subsequently processed by the integrated algorithm of the BeGaze software into the three events saccade, fixation and blink. This categorized data is combined with images of the scene view from the third video camera on the front side of the eye tracking glasses. This can directly be used to show the participant's gaze path for a qualitative analysis or for a deeper quantitative analysis of underlying correlations. As an additional source of information beside the eye tracking data, the participants were asked to think aloud to get an access to the participants' inner train of thought during the functional analysis process. To encourage the participants to do so, the moderator served as a passive contact they could speak to. In cases when participants forgot to think aloud, the moderator remembered them to do so with a short hint.

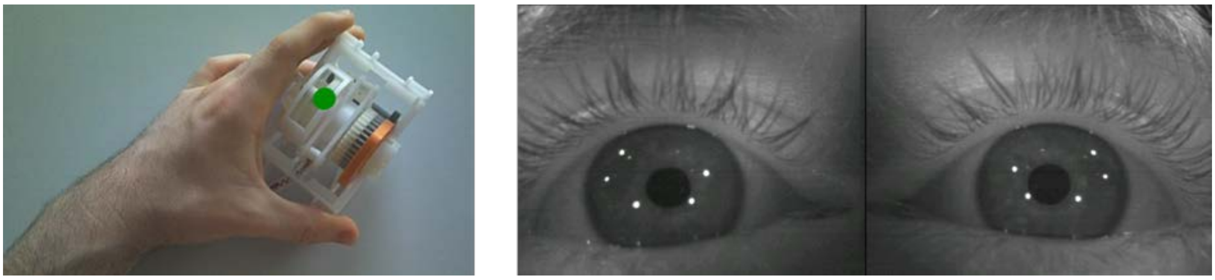

Figure 2. View from the scene view (left) and view from the eye cameras with reflexions (right); the dot in the scene view (on the freewheeling) represents the current gaze point, calculated with the information of the position of pupil and reflexions in the right image.

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. The layout of the protocol was icon based with a specific icon for every subfunction. This helped to compare the analysis focus path of different participants in parallel. Further, the protocol differentiated between analysing phases with incomplete comprehension of subfunction and phases of insights. This differentiation allowed to follow the insight path of all analyses and to find gaps but also jumps in it. 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). To start with the quantitative data analysis, one intermediate step is needed since there initially is no direct link between the gaze point and the AOIs looked at. To connect the gaze point to the related AOI and thus the information what a participant gazed at at a specific point in time, a method called Semantic Gaze Mapping was conducted. With this method, the dynamic stimulus of the mobile eye tracking video is manually transferred into a static stimulus of a picture (see Figure 3) by linking one specific fixation to its related AOI. Using the SGM method, two difficulties may occur. First, when AOIs are small or allocated near to each other, sometimes it is hard to decide which AOI is related to the specific gaze point. In those cases, one has to define rules describing the right approach. Second, the gaze point is calibrated to a specific distance. If objects are looked at in a different distance than the calibrated one, the presented gaze point is not in the right positon. For closer objects, the gaze point is presented too far downright and for further away objects accordingly too far upper left. This is a mobile eye tracking specific issue and has to be considered and corrected in the data analysis. After this intermediate step, the AOI-time-relation is made and can be illustrated as an AOI-Sequence Chart (see Figure 3). The start-point (t=0) represents the participant's analysis start. This visualisation of ET data 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 identify the participants' main moments of insight in the quantified gaze data and highlight them. 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 3). The combined data analysis focused, based on this intermediate step, on characteristic values of the participants' insights. These values are the sequence, the concentration, the complexity and the number of the insights. To find similarities and differences in the analysis, the results of these characteristic values of the two participant groups are compared.

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 did not fully understand the presented stimulus and are following called low-performers. In each group, the gaze data set of one participant was qualitatively not sufficient enough to be analysed. Consequently, the data sets of 5 high-performers and 5 low-performers were analysed.

Figure 3 respectively shows the Moment of Insight 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. Subfunction 5 completed the functionality of the sun-blind turning unit and was the exit of the flow line of force from the analysed system. This subfunction was not necessary to be understood to be counted as successful (compare to Figure 1 for the specific parts).

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)

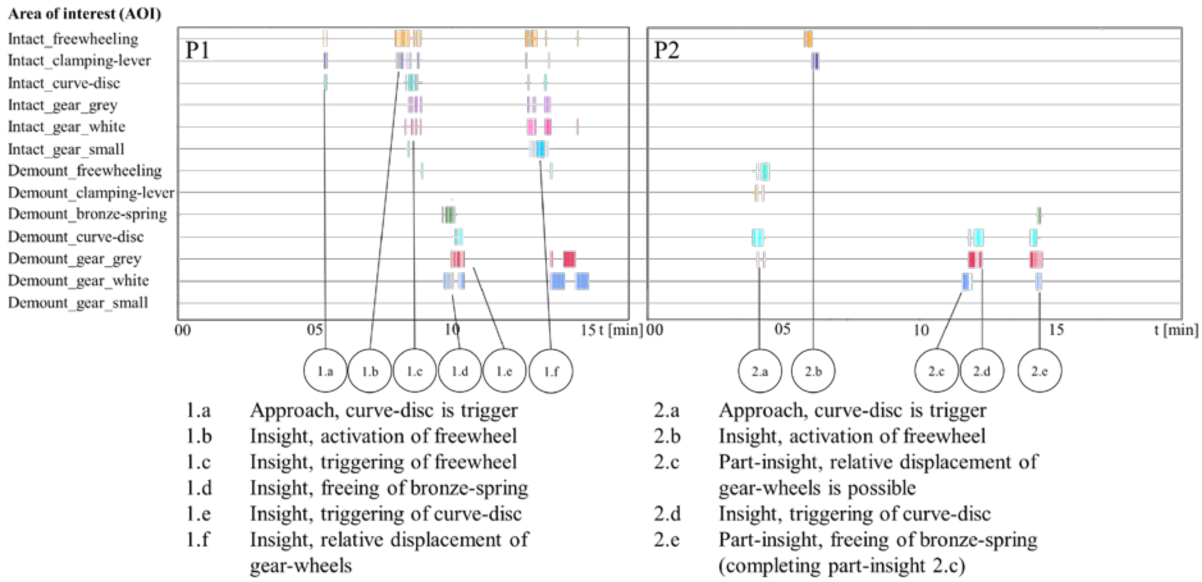

Figure 3. Moment of Insight AOI Sequence Chart of a successful (left) & a non-successful participant (right) with the specific insights of the respective participant

Group independencies. In the study, six students with a Bachelor's degree and six students with a Master's degree were analysed. No relation between the education level and success in the functional analysis of the presented system was found. The twelve students were equally distributed in both groups of high- and low-performers. All twelve students were taught in functional analysis in during their basic engineering education. No group-specific pattern was found as well 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 3, 1.a).

Analysis differences. Differences in the insights between high- and low-performers were the frequency, the complexity in terms of the combination of insights and the number of insights. Regarding the insight frequency, Figure 3 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. 150 seconds. 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 difference 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 3, 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 is required to single-handedly be able to understand how a system works. It 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 3, 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 relevance 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. It needs an overlaid analysis strategy to gain a structure and thus reliability in the functional analysis aside the recognition of subfunctions and subsystems based on the comparison to the own knowledge. 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 consequently follow 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 individual starting point 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. 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 train students in basic engineering design education in such analysis strategies and show the meaningfulness of such approaches. Further, it needs practice to learn such analysis-strategies. The results of this study show that time in education for itself guarantees no success in challenges like the presented one. Contra expectations, the Master's students were not more successful in this challenge than the Bachelor's students. The equally distribution of the students in both groups of high- and low-performers indicate that some Master's students focused in their education more on different fields than design and development where functional analysis is an important ability. This indication supports the approach to support and encourage students to practice functional analysis with technical systems by giving them the opportunity to do so in their basic engineering design education.

Limitations. The dominating limitation of this study is that the analysis-processes of only 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 analysist 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

The insights and learnings from this study lay in two fields. First, this study motivated us to develop new methods to analyse the eye tracking data. Second, it encouraged us to follow and to extend our approach in imparting the functional analysis.

The combination of qualitative and quantitative analysis of the eye tracking data led to a more intuitive visualisation than a standard heatmap or the gaze video which allowed to compare several participants at the same time in parallel. This approach shall be further developed in the future. In the preparation phase for the data analysis, the intermediate step of Sematic Gaze Mapping to connect the gaze point to the looked at objects needed a lot of time. The proportion of video time to analysis time laid in a range of four to ten. Currently, we develop methods to automate and semi-automate this intermediate step with approaches from the computer vision and artificial intelligence. The goal is being able to analyse the eye tracking data fully automated. This shall enable us to use mobile eye tracking in a 90 minutes lecture workshop from scratch, developing the test setup, conducting the test cycle and finally analysing the eye tracking data subsequently.

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. Currently, we extent this approach in our basic engineering design education lectures. Students analyse parallel to the lectures in an accompanying workshop predefined or self-chosen technical systems in small groups. Subsequent, they present their analysis results to their 500 fellow students and lead them systematically through the functional analysis. We expect a deepened knowledge and a higher motivation to go systematically though a system's functional analysis by the students. Further, we also expect a higher level of acceptance of this analysis method by the students when their fellow students show a successful result of this approach.

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