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Eye-Tracking supported design of digital assistance systems for smart factories

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Abstract

Cognitive assistance systems enable people to receive valuable support in their industrial work tasks and can offer the highest flexibility and individualization possibilities. The increasing need for knowledge and its growing importance lead to a great demand for user-centric cognitive assistance systems. In this sense, eye-tracking is a potential technology to provide better insights in Use behavior in the task fulfillment process. The analysis of the data contributes to understand where the person is directing their attention, how long they are looking at certain areas and whether potentially unnecessary distractions exist. In this way, data-based adjustments can be specifically identified to be able to increase reliability and efficiency in the process. EyeTracking is rarely used in the development of assistance systems for the manufacturing industry. The expected benefit and the effort remain unclear. We show what potential it can offer in the development of cognitive assistance systems and present recommendations for its integration in the design process. The results are based on the empirical findings of a manual industrial application of complex quality measurement of battery module housings for electric vehicles.

Keywords: Eye-Tacking; Human-centred design; Design methodology; Tools and technologies.

1. Introduction

Within the framework of Industry 4.0, smart factories are envisioned as highly complex, dynamic and flexible systems. This evolution requires the empowerment of employees, enabling them to act as proactive decision-makers and supervisors. Recognising the significant change in the role of workers in smart factories, the adoption of a socio-technical approach to work organisation is proposed. This approach not only gives workers more responsibility, but also promotes their personal development [1,2]. Recent systematic literature reviews on human-centred aspects of Industry 4.0, and the emerging concept of Industry 5.0, highlight the discussion around Human Cyber Physical Systems (HCPS). Such systems are central to merging artificial intelligence with human cognition, ensuring that humans remain integral to the decision-making process and enhancing the capabilities of the workforce [3]. In the following, we will therefore present a concept that uses eye-tracking to depict the user behavior of workers in the HCPS and show how cognitive assistance systems can support employees. Previous research has shown that skill levels can be classified by using AI to analyze device data that is generated in a manual measurement process [4]. However, the generation and interpretation of user-related contextual information remains a challenge. The specific research question on which this publication is grounded is how the interaction with a digital cognitive assistance system can be systematically explored based on a user needs evaluation with eye tracking technology. It is envisaged that in the next step the cognitive assistance system for the work tasks will integrate machine learning to

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perform more adaptive, user-oriented, context-sensitive, and higher quality assistance by capturing and processing data continuously from a quality inspection workstation.

2. State of the art

2.1. Design of cognitive assistance systems

Cognitive assistance systems are technical solutions designed to process information and support humans in executing their tasks [5,6], enhancing the capabilities of workers [7]. These systems facilitate the key phases of the human information processing: task perception (detect and recognize), task decision (assess and generate) and task execution (export) [8]. Composed of various components, cognitive assistance systems are able to collect, analyze, store and evaluate data and information. This integration promotes dynamic humancomputer interaction, providing feedback to users and allowing them to monitor and adjust their activities to meet specific task objectives. [9]. The development of cognitive assistance systems is a challenging task and research findings show dedicated innovative methods like design sprints [10] and CAS-QFD [11] that can support the development by meeting requirements in a manual assembly context. In general human-centered design is an approach to the development of interactive systems that aims to make systems fit for purpose by focusing on users, their needs, and requirements. The iterative approach as described in the standard documentation DIN EN ISO 9241-210:2019 and shown in Figure 1, increases effectiveness, efficiency, and user satisfaction [12]. In the evolution phase users are explicitly integrated in the design process.

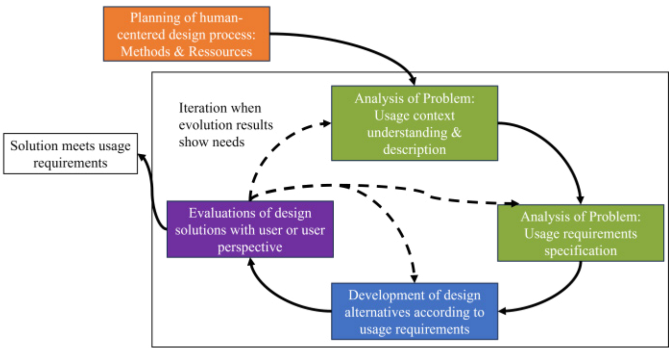

Figure 1: Human-centred design for interactive systems [12]

2.2. Eye-tracking

Eye-tracking is an experimental method for recording gaze positions and eye movements. It is a recognised method for investigating the distribution of a person's visual attention [18]. Based on Charles Bell's research findings, the movement of the eyes could be linked to neurological and cognitive processes [19]. This link to neurological and cognitive processes makes gaze analysis an interesting area of research for revealing attentional focus and emotional as well as cognitive arousal. The constantly improving quality of eyetracking devices and technologies now allows for in-depth analysis of cognitive processes, information acquisition strategies, and usability evaluations of human-technology systems. While eye tracking is still most used in psychology and neuroscience studies, there are now many applications in engineering and logistics and computer science [20]. Methods to track gaze include electrooculography, photo- or video oculography, scleral search coils and video-based methods [21]. Eye tracking studies can be performed by using stationary, screen-based systems or mobile, portable devices. Various filters and algorithms are used to categorise the recorded gaze into different types of eye movements [18].

2.3. The composition of eye movements

The different types of eye movements are presented: Fixations: Fixations are periods of time during which the eyes remain largely still and stable at a certain point [18]. As soon as the gaze is focused on a specific point, an image of the target object is generated on the fovea of the retina. Here, the received image is converted into electrical signals and transmitted to the brain [19]. For this reason, fixations play a key role in how people perceive and interact with the visual world. Saccades: Saccades are rapid eye movements that occur both before and after fixations [21]. These movements serve to direct the visual focus from a previously fixed point to a new object [22]. Saccades can be either voluntarily or in response to a visual stimulus [19]. During the duration of a saccade, visual perception is limited because no information is being transmitted to the brain. This phenomenon is known as saccadic suppression [23]. Smooth Pursuit: Another form of eye movement is the smooth pursuit movement. As the name suggests, they are used to track a moving object in the visual field with the eyes. In contrast to saccades, in which the eyes are moved abruptly, the target object is tracked as smoothly as possible. The purpose of following eye movements is to focus the image of the target object continuously on the fovea and thus enabling sharp vision. This makes it possible to visually capture information despite eyes movements [24].

2.4. Analysis methods for eye tracking data

The execution of targeted eye movements is the result of complex cognitive processes that include at least the selection of a target object, the planning of the associated eye movements and the final execution of the movement [18]. Eye tracking thus allows insights into the distribution of a person's visual attention, for example, by recording different eye movements and the associated measured values and then analysing them. In some studies, it may be useful to divide the visual stimuli or the recorded field of vision into smaller subareas for subsequent analysis. In eye tracking studies, such areas are called areas of interest, i.e. areas of particular importance, and are increasingly used in attention-based research areas such as marketing or usability studies [25]. The use of AOI allows a granular analysis of the recorded gaze data by considering only the relevant area-based metrics. The following paragraphs summarise quantitative and qualitative methods of analysing eye tracking data and their use in relevant literature.

Fixation Measures: Measured values based on fixations can be divided into two categories, namely the number of fixations and the duration of fixations. Both categories have been used to monitor cognitive strain and to analyse visual The number of fixations describes how many fixations of the eye can be identified in a specific, freely selectable period of time. The use of AOI can facilitate the interpretation of eye movements [25]. The fixation duration describes the period that the eyes remain almost still on a specific point in space. Chen et al., who investigated a visual search process paired with a memorisation task, were able to prove that the duration of fixation increases with increasing task difficulty [27].

Saccade Measures: Using visual search processes with varying levels of difficulty, Philips and Edelman [28] demonstrated that the difficulty of a search task has a direct influence on saccade amplitude as the more complex the search process, the smaller the saccade amplitudes became. Pupil Measures: Pupil measures include fluctuation in pupil diameter and orientation. These measures are often used to provide an insight into the internal state of a person. A detailed description of this and other procedures can be found in [18].

Qualitative analysis methods - heat maps and gaze plots: Heatmaps are used in eye tracking studies to visualise gaze data consisting of eye movements and their associated coordinates. They are suitable for visualising the spatial distribution of fixations over a defined time period [29]. A gaze sequence, often referred to in the literature as a scanpath, is a sequence of fixations and saccades that occur one after the other. These sequences of fixations and saccades are often visualised using a gaze plot [30]. Fixations are represented as nodal points and saccades as linear connections between successive fixations. Analysing the gaze sequence can be used to investigate the sequence of information processing or to examine the task mastery strategy of different test subjects in certain scenarios [31].

3. Approach and User Needs Analysis

3.1. Technical System

The technical system used consisted of the FARO Quantums Max and the FARO CAM2 v2023.0 measurement software, see Figure 2.

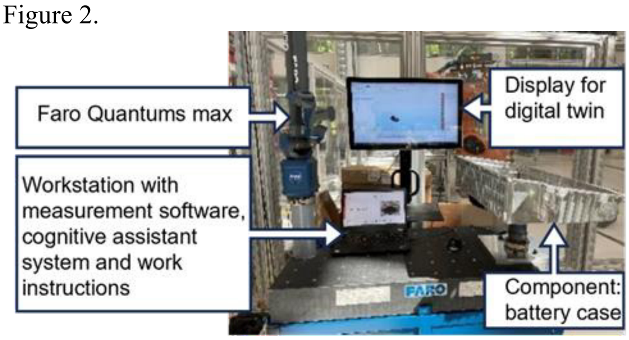

Figure 2: System for manual inspection

3.2. Measurement Setup

The measurement setup comprised the FARO Quantums Max, equipped with 7 axes and an additional 8th rotary axis. This apparatus was mounted on the measurement table, where the component was positioned. The measuring process employed the FARO CAM2 v2023.0 software, which was displayed on a screen positioned behind the measurement table. The precise steps could be observed on the workstation screen, situated on the side of the measurement table, as depicted in Figure 2.

3.3. Measurement Process

The measurement process included the initial tactile measurement of individual surfaces on the outside and holes on the inside for both surface quality and internal diameter and scans on the outside and inside of the component. In total, there were 33 tactile measurement sequences including 2 scans. The process times varied between 6 to 15 minutes. A schematic representation of the entire measurement process is shown in Figure 3. The sequence consists of the following tasks:

- Searching type 1: Starts with Measurement position is viewed until part is in correct position,
- Searching type 2: Starts with part is in correct position until measurement started by first measurement point,
- Measurement: Starts with first measurement point until last measurement point,
- Control: Starts with last measurement point until confirmation of measurement points and finalization of measurement sequence.

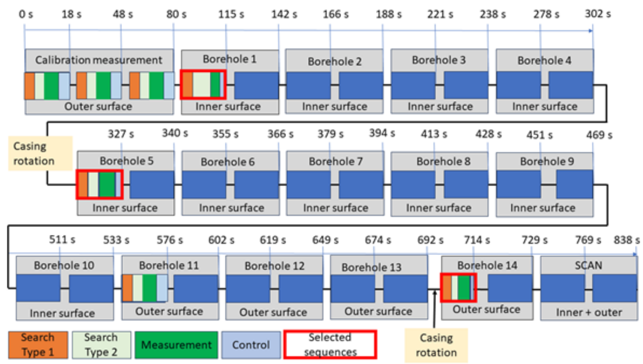

Figure 3: Sequences of measurement process

3.4. User Need Assessment Setup

The eye tracking glasses used in this work are the "Pro Glasses 3" model from Tobii AB. The device belongs to the group of wearable eye trackers and utilises video-based P-CR (Pupil-Corneal Reflection) technology. A detailed list of the installed sensors and the technical specifications can be found in the technical data sheet of the device, see [32]. In addition to the eye tracking recordings, the individual measurement processes of the test participants were also recorded using a video camera. The test setup, consisting of the measuring arm, the battery housing on the rotation platform, the digital assistance systems and the video camera used, can be seen in Figure 4.

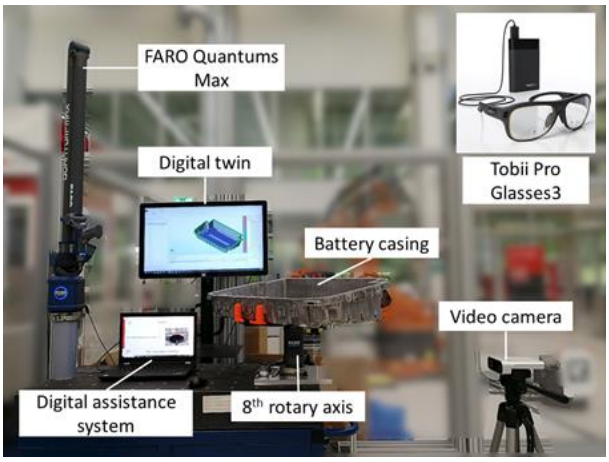

Figure 4: Test setup for the manual measurement process

3.5. User Need Assessment Analysis and results

In this experimental study the participants carried out a manual measurement process. The object to be inspected is a battery casing of an electric car. The test participants receive step-by-step instructions from a digital assistance system and further cognitive assistance from a digital twin visualization throughout the measurement process. The digital twin visualization shows a live view of the position of the tool center point and the position to measure on an interactive 3D CAD viewer.

3.5.1. Background of participants

To obtain eye tracking data that is as valid and reproducible as possible, the following exclusion criteria were defined for participation in the study. Subjects with certain eye diseases and/or wearers of certain visual aids were not included in the study. A total of thirteen test subjects took part in the empirical study for this research. All participants have a technical professional or academical background. The participants were selected so that they could be divided into three skill levels (beginner, advanced and expert).

3.5.2. Introduction and preparation

To guarantee that the requirements and framework conditions for carrying out the empirical study, the preparation for the experiment was always carried out in the same way. This includes aspects from the short introduction of the study, the introduction to the measuring device and the presentation of a questionnaire at the end of the study.

3.6. Recording of measurement process

After all preparatory steps were carried out and the eye tracking recording was started, the test subject could begin measuring the battery casing. If there were difficulties or problems during the measurement process, the test subjects were encouraged to ask for help at any time. The maximum duration of the recorded measurement process was set at 20 minutes.

3.6.1. Questionnaire

After the measurement was completed, the subjects participated in a survey with questions related to the perception of cognitive and physical demands during the measurement process as well as the usability of the digital assistance system and the digital twin.

3.6.2. Post Processing

Each eye tracking data set consists of a video from the scene camera, coordinates that show the spatial distribution of the detected eye positions, as well as pupil diameters and other metrics. To ensure valid and reproducible results, the following exclusion criteria were defined during post- processing of the data: Measurements with significant interruptions by hardware or software issues, or Gaze value below 70 %. Consequently, eight data sets remained.

3.6.3. Visualization and interpretation

Within the Tobii Pro Lab analysis software, AOI and Times-of-interest (TOI) can be defined, and data visualizations can be made via gaze plots or heatmaps. Both the monitor of the digital assistance system and that of the digital twin were defined as AOI. The third AOI was placed on the battery case. The Figure 5: Fixation assistance system, Figure 6: Fixation digital twin and Figure 7: Fixation battery casing show the average fixation durations per task of the different skill levels in two different measurement sequences (B4 and B9, as presented in Figure 3).

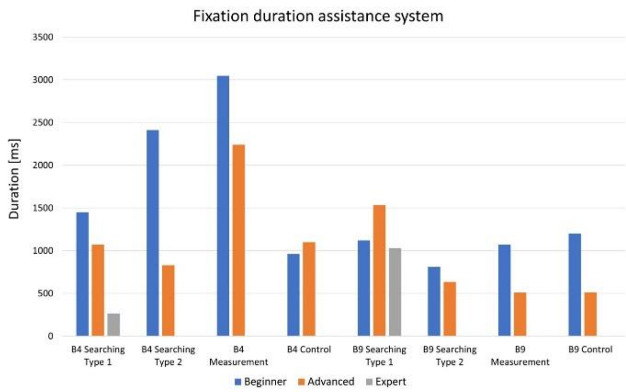

Figure 5: Fixation assistance system

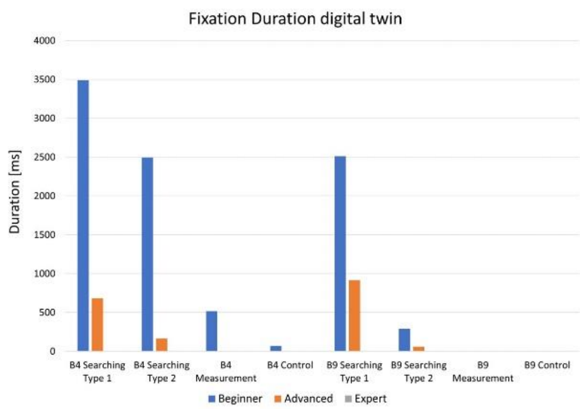

Figure 6: Fixation digital twin

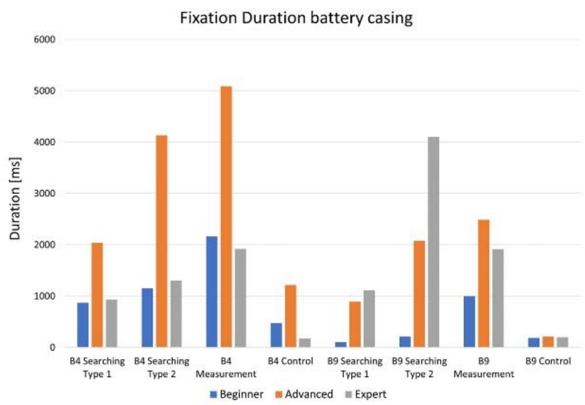

Figure 7: Fixation battery casing

In Figure 5 the average fixation durations for the assistance system shows that beginners have a high fixation duration in the beginning sequence and related tasks, especially for the tasks: B4 Searching type 2 and B4 Measurement. In the sequence B9 and related tasks, the average fixation duration is lower for the tasks B9. For the expert level there are only values for the tasks B9 Searching type 2 and B9 Measurement. In Figure 6 the average fixation durations for display of the digital twin are presented. It shows that beginners show the high fixation duration in B4 Searching type 1 and B9 Searching type 1. The fixation duration values for expert level are zero and values for advanced level are low. Figure 7 shows that advanced level has the highest fixation duration for B4 Searching type 2 and B4 Measurement. Overall, the fixation duration of beginners is comparable low in tasks of sequence B9. A particularly clear result is that the experts do not use any support from the digital twin. Advanced users also interact extensively with the battery casing. By far, beginners use the digital twin most often. We expect that the cognitive load for beginners is especially high and decreases with increasing skill level of the participant. For this purpose, a csv file containing the pupil diameter was created from the Tobii Pro Lab analysis software. Based on the results, it was not possible to differentiate the user groups based on pupil dilation and therefore cognitive load.

3.6.4. Heatmaps and gaze plots

The two most common methods for visualizing gaze data are heatmaps and gaze plots. By heatmaps, it can be assessed whether the relevant information is receiving enough attention or whether there are distracting variables, see Figure 8.

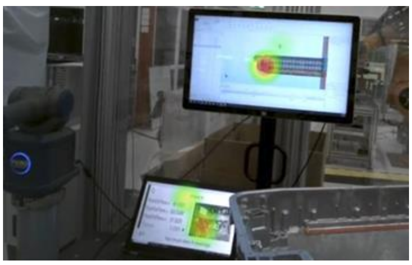

Figure 8: Heatmap of measurement sequence for search type 1

4. Discussion and limitations

This article proposes an approach to integrate eye tracking in the human-centered design of digital assistance systems for manual inspection process in a smart factory. This is done to systematically explore the interaction with a digital cognitive assistance system based on a user needs evaluation with eye tracking technology. In doing so the article highlights the different eye tracking analysis options with their potential benefits and challenges as summarized in Table 1. Based on our empirical research with different candidate groups of skill levels, we were able to gain user group specific insights for the design optimization of the original system and to develop adaptive cognitive assistance concepts for different skilled users.

Table 1. Potential benefits and Challenges for eye-tracking analysis.

Type of analysis	Potential benefits	Challenges
AOI	•User attention distribution when using multiple systems •Identification of user needs during task	•Manually processing times-of-interest •Time allocation of the fixations to the tasks •Manual fixation mapping
Pupil diletion	Identification of tasks with high cognitive load	•Allocating reliable pupil measures in a dynamic work process •Data loss due to varying light conditions
Scan path	•Identification of different problem-solving strategies •Identification of distractions in the provision of information with multiple systems	•Manual mapping of fixations •Creating multitude of gaze plots due to the dynamic work process •Manually processing times-of-interest

To support the design of digital assistance systems using eye-tracking technology, we recommend focusing on development steps where there is a high degree of end-user involvement in the process, as shown in Figure 1. This applies to both the specification of usage requirements (second development step) and the testing and evaluation of design solutions (fourth development step). The AOI analysis of gaze behavior was best suited to the process presented, as it allowed the user groups' gaze patterns on the various AOIs to be identified immediately. The combination of TOI and AOI made it possible to study user's gaze behavior in detail for the individual tasks of several measurement sequences. In the fourth development step, prototypes of the assistance system are tested and evaluated directly by the future end users. The AOI analysis can be used to check whether end users pay the expected amount of attention to relevant areas of the information provided. This is a good way to identify misuse, whether the information presented is useful to the end user, and whether the optimal amount of information is displayed in the task steps. In our work system, we found that expert level users do not use the digital twin. Future adaptive solutions could therefore be designed to display the digital twin only for training purposes.

The cognitive assistance system will be presented at eye level on the large display, rather than on the workstation screen. For the next iteration of the system's development, we have designed an adaptive feedback system that can provide user skill level specific feedback to the process after all tasks have been completed. Limitations of our research are that the eye-tracking-based design approach was only applied to one manual inspection process. Therefore, the generalizability of the approach is therefore limited and should be repeatedly tested in future studies. The number of participants was limited, expert level participants were not available or were excluded due to wearing visual aids. In addition, the results are not compared with other methods of user-centered analysis. Eye-tracking analysis is time consuming, and the interpretations are based on individual knowledge and experience. Further research should be conducted to automate the analysis process to make it easier to use and more efficient. Therefore, future technological improvements in this direction and error prevention strategies may help to increase the acceptance among developers and designers.

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