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TASK-DEPENDENT VISUAL BEHAVIOUR OF ENGINEERING DESIGNERS – AN EYE TRACKING EXPERIMENT

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1. Introduction

More than 40 years ago Alfred L. Yarbus [1967] conducted a famous eye tracking experiment impressively demonstrating the strong dependencies of human visual behaviour and the task assigned to the observer. In order to better understand the eye movement during perception of complex objects Yarbus confronted a test person with a painting of the Russian artist Ilja Repin. The painting named "Unexpected Visitors" shows a living room of the 19^{th} century, the resident family (women and children) and a recently arrived man entering the room. Yarbus recorded the test person's eye movement first during (1) a free examination of the painting, then after asking the test person (2) to estimate the material circumstances of the family, (3) to estimate the ages of the people, (4) to surmise what the family had been doing before the arrival of the visitor, (5) to remember the clothes worn by the people, (6) to remember the position of the people and objects in the room and (7) to estimate how long the visitor had been away from the family.

The eye tracking analysis revealed that each question influences the test person's gaze path in a different way. Yarbus [1967] stated that depending on the task assigned the visual behaviour varies. For example, in response to question 2 the test person paid particular attention to the clothing and the furniture. In response to question 3 all attention was concentrated on the faces. And in response to the instruction given by question 4 the test person directed his attention particularly to the objects located in the hands or located on the table.

This paper presents an eye tracking experiment transferring the research approach of investigating the dependency of different tasks on visual behaviour into the context of engineering design. In contrast to Yarbus' experiment the stimulus is not a painting, but a 2D sectional drawing representing a technical system. In order to closely analyse the basic question of how different tasks influence the visual behaviour of engineering designers, the experiment is conducted by application of modern remote eye tracking systems and by participation of a larger sample of test persons (n = 26).

The paper proceeds as follows. Section 2 gives a short overview of the basic attention models applied in visual science. In this context Yarbus' research approach and his basic results are briefly introduced. Section 3 presents findings of previous eye tracking experiments in engineering design and, based on this, derives the research questions of the experiment presented in this paper. Section 4 describes the experimental setup including the participated test persons and the applied eye tracking system. In addition to this, the stimulus and the corresponding tasks are introduced. Section 5 presents the quantitative results of the experiments. Here, individual scan paths and sequence diagrams are shown and discussed in the context of task-dependent visual behaviour. In addition to these findings, section 6 presents the results of a quantitative data evaluation taking into account the full data sets of all 26 test persons. Section 7 concludes.

2. Visual behaviour in visual science

2.1 Visual attention models

In visual science two basic groups of models are applied to describe aspects of visual attention: bottom-up models (stimulus-driven) and top-down models (goal-driven). Itti [2000] explains that, when people observe their environment, not all of its components are perceived as being equally interesting. Some objects automatically and effortlessly “pop-out” from their surroundings. These objects attract the people’s visual attention in a bottom-up manner. Bottom-up models base on the assumption that certain aspects of the visual scene inherently draw an observer’s attention to a specific locations. This understanding implies that visual attention is essentially reactive and primarily stimulus driven. Bottom-up models are especially relevant in e.g. advertising research or safety science.

In contrast to bottom-up models, top-down models consider the observer as an active part in his or her visual behaviour. According to Rothkopf et al. [2007] it is well established that an on-going task influences the gaze strategy. As soon as the visual scenes become meaningful, recognized objects are related to the observer’s intentions and experiences and thus determine where visual attention is drawn. Based on numerous research results from both views, Duchowski [2007] comes to the conclusion that, particularly for eye tracking studies, task selection may be the most critical consideration of all. Because eye movements and visual attention are deployed as a combination of bottom-up and top-down cognitive processes, the nature of the task will influence eye tracking outcomes. Consequently, people shift their visual attention depending on the task resulting from the situation they are confronted with.

2.2 Task-dependency

The experiment of Yarbus [1967] was one of the first experiments confirming the task-dependency of visual behaviour and thus, provides a basis for nearly all top-down models. Nevertheless, when evaluating the results, two important points have to be considered. Firstly, in the 1960s eye tracking technology was quite young and thus the eye tracking systems applied were more intrusive than today. In fact, during Yarbus’ recording, the test person’s eyes was anaesthetized and his eyelids were taped open with heated strips of adhesive plaster. Secondly, the results were based on a single test person, whose personal data and previous knowledge were not further described.

Due to these reasons, DeAngulus and Pelz [2009] repeated the experiment with contemporary eye tracking systems and with a larger sample of test persons (n = 17). They found out that the recorded eye movements are remarkably similar to those published by Yarbus. In order to also gain quantitative results, DeAngulus and Pelz segmented the painting into defined areas of interest (AOIs) with associated labels (cf. Figure 1) and calculated the percentage of time spent on viewing each AOI, averaged across all test persons. They could show, for example, that, when asked about the absence of the visitor, 35 % of the time was spend on the man’s face, whereas, when asked to surmise what the family had been doing before the visitor‘s arrival, 30 % of the time was spend on the tabletop.

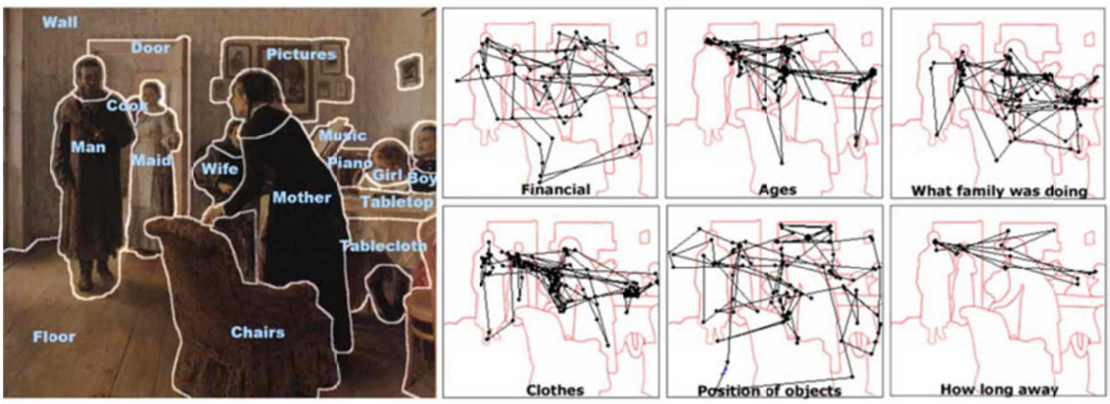

Figure 1. Yarbus’ stimulus with AOIs and resulting scan paths [DeAngulus and Pelz 2009]

3. Visual behaviour in design research

3.1 Initial situation

Research methods such as interview technique, observation or protocol analysis are already well established in design research [Ahmed 2007]. In order to additionally support the research investigating human behaviour in design, these methods recently became more and more supplemented by data gained from physiological measurement techniques [Steinert and Jablokow 2013]. Eye tracking is one of these techniques and it was already exemplary applied by Matthiesen et al. [2013] to investigate the functional understanding of technical systems and by Boa et al. [2013] to compare product preferences to the visual behaviour for product representations.
The experiment presented in this paper bases on the results of a previous eye tracking experiment conducted at ETH Zurich to analyse differences in the visual behaviour of novice and experienced engineering designers trying to understand a technical system represented by a 2D sectional drawing. The basic findings are summarized in the assumption of five visual strategies stating that in contrast to novices more experienced designers tend towards [Lohmeyer et al. 2013]:

- first trying to get an overview before checking the details (overview strategy),
- aligning their search with the load flow (alignment strategy),
- prioritising their search criteria (prioritisation strategy),
- using scan path pattern to check recurring parts or assemblies (pattern strategy),
- imagining the dynamic behaviour of moveable parts (internalization strategy).

Based on the same data set, two basic scan path patterns were identified: Skimming and scrutinizing (cf. Figure 2). *Skimming* describes the visual exploration of a larger area of the stimulus. It is characterized by short fixations and long saccades. *Scrutinizing* implies the accurate investigation of a small area of the stimulus. In contrast to skimming, scrutinizing is characterized by long fixations and short saccades. These patterns have been found in the scan path of all test persons, but the mode and duration of their occurrence varied individually [Mussgnug et al. 2013].

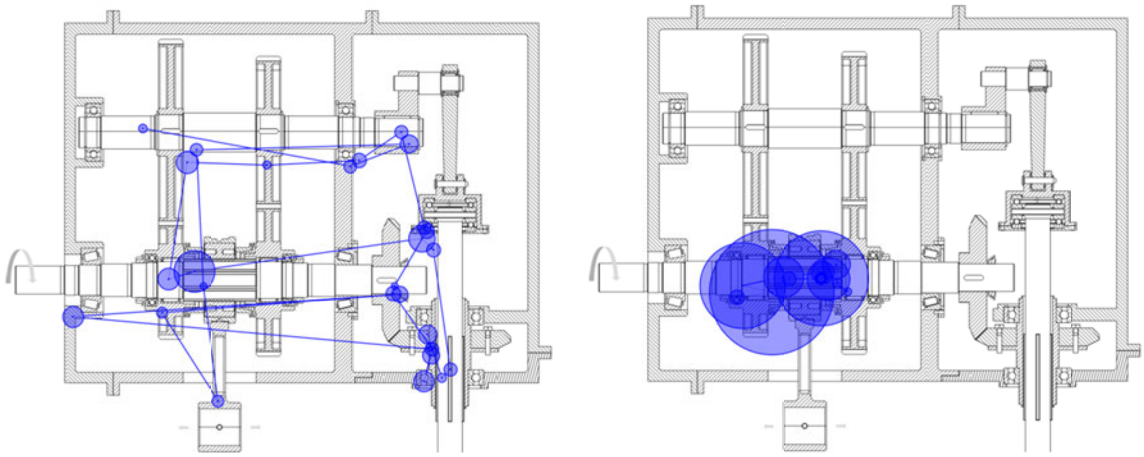

Figure 2. Basic scan path patterns: Skimming (left) and Scrutinizing (right)

3.2 Research questions

The experiment presented in this paper combines previous eye tracking research in engineering design (section 3.1) with recently confirmed results from visual science (section 2.2). The overall objective of the experiment is to find indicators for task-dependencies on the visual behaviour of engineering designers. Due to this the experiment analyses the influences of different tasks on the engineering designer's visual behaviour during the examination of a 2D sectional drawing. Based on this objective, two basic research questions arise: (1) "Are there similarities in the visual behaviour of individual test persons solving the same task?" and (2) "Are there task-dependent differences in the visual behaviour taking into account the data of all test persons, who participated in the experiment?"

4. Experimental setup

4.1 Test persons and eye tracking systems

A total of 26 test persons participated the experiment. All test persons had a bachelor degree in mechanical engineering and were just continuing their studies in engineering master courses. The test persons were from three different technical universities located in different nations: 10 were from TU Athens in Greece (8 male, 2 female), 10 from KIT Karlsruhe in Germany (8 male, 2 female) and 6 from ETH Zurich in Switzerland (6 male).
The experiment was conducted by application of SMI RED 250 eye tracking systems, which are table-mounted systems using a sampling frequency of 250 Hz. These video-based systems record and measure an infrared light reflection of the test person's eyes and, based on this, calculate the point of gaze relative to a stimulus presented on a screen. In the experiment presented here the stimulus was shown on 22'' monitors with a resolution of 1680x1050 pixels.

4.2 Stimulus and tasks

The stimulus was a 2D sectional drawing representing a shiftable gear drive (cf. Figure 3). The system's input is defined by a directed rotation and a constant torque provided by a motor located on the right side of the gear drive. An additional input is realized by the lever above, which allows shifting between two different gears. Due to the design of the gear drive, the system's output is a combined movement of rotation and unidirectional translation.
In the experiment the test persons had to solve three different tasks. These tasks were sequentially assigned by directly fading in the corresponding question (and as far as possible also options for the answer) at the top left corner of the stimulus. The test persons were asked (1) to identify in which direction the output shaft rotates, (2) to find out in which position of the gearshift the output rotates faster and (3) to understand and to explain the complete system's output.

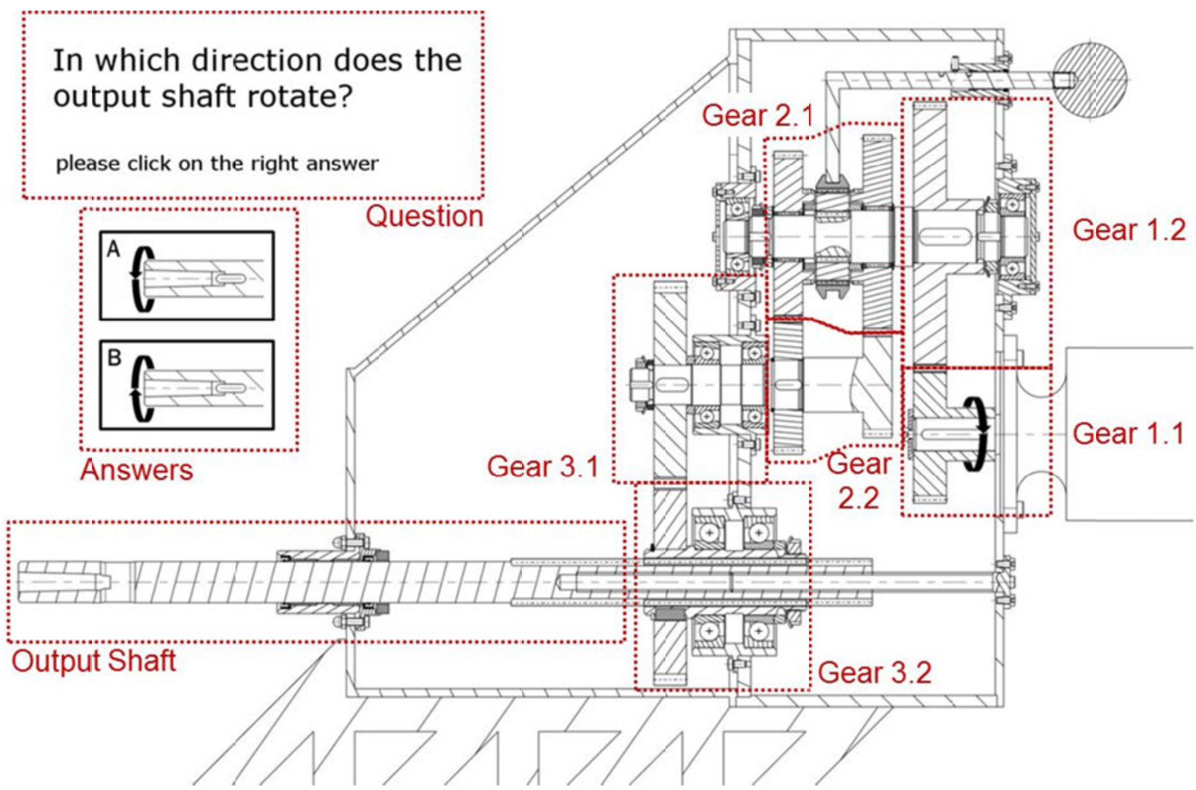

Figure 3. Stimulus with the first task and the definition of nine areas of interest (AOIs)

5. Qualitative results

5.1 Task 1: Direction of the output shaft

When confronted with the stimulus and the first task all test persons started skimming through the drawing individually. The duration of this orientation phase varied from 15 - 70 s. This phase was followed by a systematic search, in which the visual behaviour of all test persons was similar. Figure 4 exemplary shows the last 10 seconds of three individual scan paths just before choosing the answer.

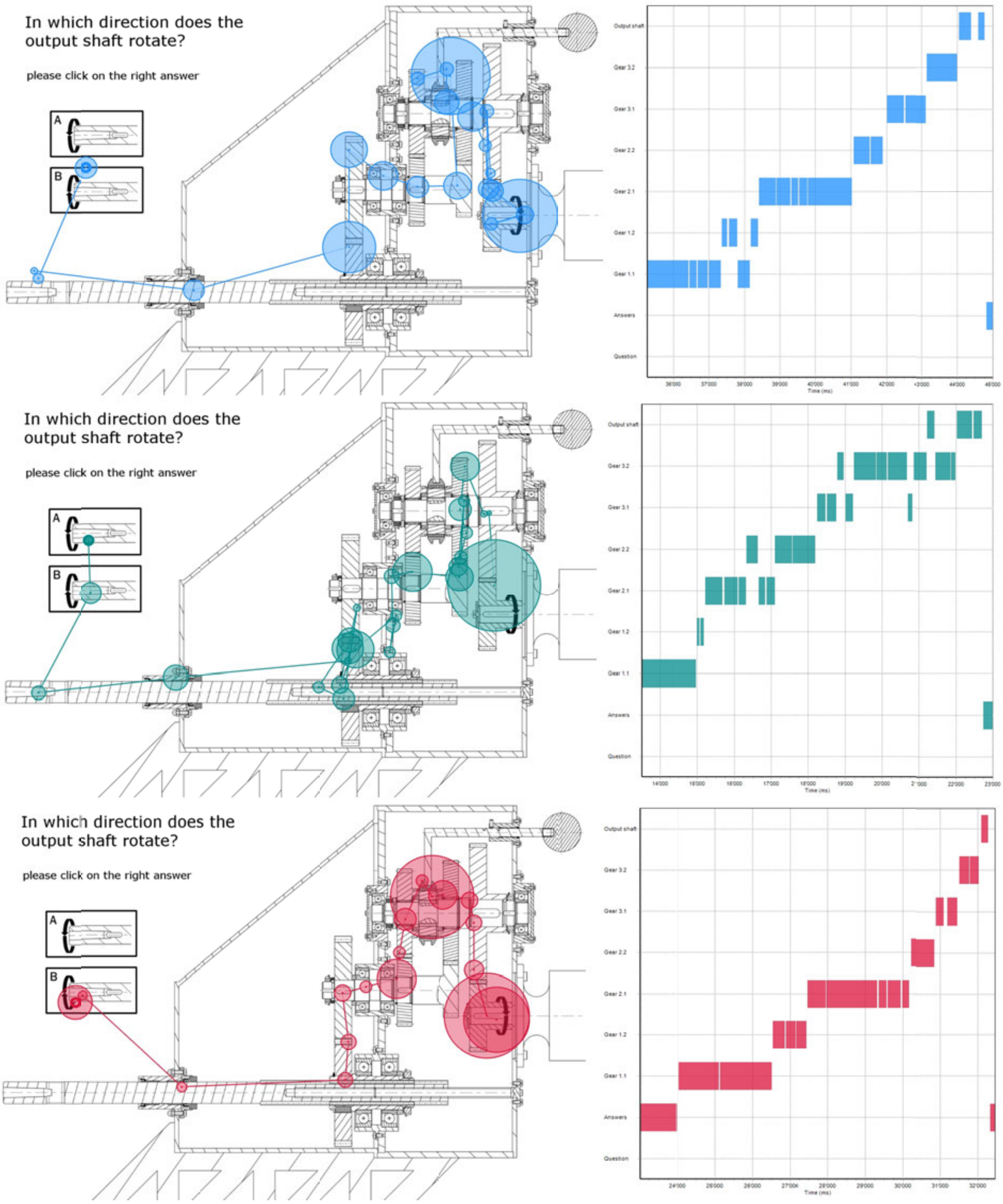

Figure 4. Scan path (10s) and AOI sequence (10s) in solving task 1 tracked from a test person from TU Athens (top), ETH Zurich (middle) and KIT Karlsruhe (bottom)

The scan paths depicted show that the test persons started their search by giving a high amount of visual attention to the gear wheel connected to the motor shaft (gear 1.1) and the curved arrow representing its initial rotation direction. The long gaze fixations in this area indicate a certain cognitive effort to decode and internalise the information provided here. In order to check the number of gearings (the rotation direction changes with every spur gearing), the scan paths of all three test persons similarly continue proceeding from gear 1.1 via the gears 1.2, 2.1, 2.2, 3.1, 3.2 and the output shaft to the answer options. Although the fixation locations and fixation durations varied individually in detail, the scan paths indicate a general visual behaviour.

In addition to the scan paths, Figure 4 also includes the corresponding sequence diagrams illustrating the exact order and duration of fixations on the areas of interest (AOIs) shown in Figure 3. These diagrams confirm the assumption of a similar visual behaviour by revealing a general stairlike course through the adjacent AOIs across these three test persons. Single outliers jumping back to the previous AOI or forward to the next AOI, indicate a brief check of information perceived earlier, e.g. in the orientation phase. This visual strategy of alignment was found in the eye tracking data of all 26 test persons, who participated in the experiment. The strategy was only applied after finishing the orientation phase and it often was followed by finally choosing answer A or answer B.

Besides, Figure 4 presents the results of test persons from three different nations. Due to this, it can be assumed that the visual behaviour in solving this task is mostly independent of local differences in education and thus might be representative for engineering designers in general.

5.2 Task 2: Position of the gearshift

When confronted with the second task all test persons were initially skimming through the drawing again. Due to the fact that the stimulus had not been changed except the task description and the answer options, the orientation phase was considerably shorter than before. Figure 5 presents the adapted stimulus and, analogical to Figure 4, typical scan paths of three (other) test persons close to their final answer.

The results show that the test persons give special attention to the gearshift (gear 2.1) located on the upper shaft. In this area the scan paths are characterized by longer fixations and shorter saccades, which indicates scrutinizing and thus, an accurate analysing of the gearshift and its function. In order to compare the proportion of the gearings connected left hand and right hand to the gearshift (the larger the driving gear wheel/smaller the driven gear wheel, the higher the output speed), the test persons temporarily drew their visual attention to the gear wheels on the middle shaft (gear 2.2).

In addition to this, all three test persons briefly checked the designation of the lever position (left = 1, right = 2) located on the top right of the drawing, before they shifted their attention to the left and marked their answer.

In contrast to the first task, the typical visual behaviour illustrated in the figure and described in this section was not found in all data sets. Just 18 of 26 test persons continuously focused on the gearshift and the connected gear wheels. In this context, it is important to highlight that, in fact, there is no correlation between focusing on the gearshift and choosing the right answer. However, the results of task 2 as well indicate similarities in the visual behaviour of the test persons, which, moreover, are clearly different to those identified in task 1.

5.3 Task 3: Overall system output

In contrast to task 1 and 2 the third task was an open question. In this part of the experiment the test persons were asked to verbally explain the reaction of the output shaft. Before explaining, they were allowed to extensively analyse the drawing once again.

The third question was more difficult to answer due to two reasons. Firstly, the question was open-ended and this caused the test persons to be unsure of the full extent of the right answer. Secondly, the third question included the first and the second one, because rotation direction and rotation speed are part of the output shaft's reaction. Due to this, all test persons checked the correctness of their previous answers by using the typical scan path patterns described above.

An additional part of the output shaft's reaction is determined by the internal thread inside the shaft and the corresponding external thread on the bolt located down to the right of the drawing. In combination with rotation, the threads cause a translational movement of the output shaft. Similar to a screw, the shaft moves either in or out depending on the rotation direction. The scan paths recorded in the experiment show that nearly half of the test persons just skimmed, but not scrutinized this area of the drawing. These test persons literally have overseen the threads and consequently were not able to consider the resulting effect in their answer.

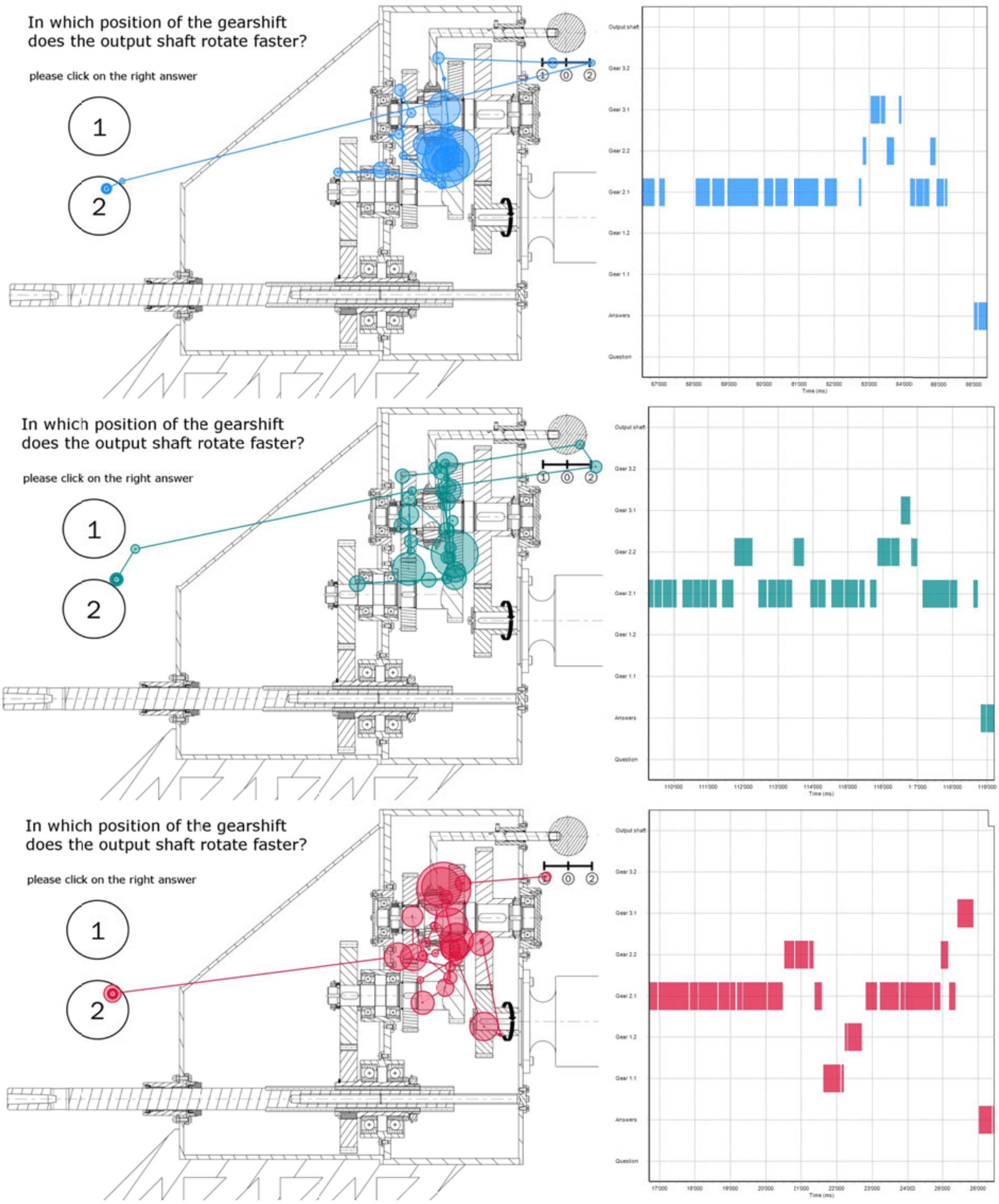

Figure 5. Scan path (10 s) and AOI sequence (10 s) in solving task 2 tracked from a test person from TU Athens (top), ETH Zurich (middle) and KIT Karlsruhe (bottom)

Figure 6 shows the scan paths and the AOI sequences of three test persons just before they started their verbal explanation. All three test persons drew a certain amount of their visual attention to the area the threads are located, but, in contrast to the results presented above, no clear similarities in their scan paths were observed. It seems that the complexity of the task – caused by the level of difficulty and the way the question was asked – activated individual visual strategies. The sequence diagrams show the stairlike course known from task 1, the alternating course also identified in task 2 and even a reverse course that, in this single case, was followed by a correct and complete answer.

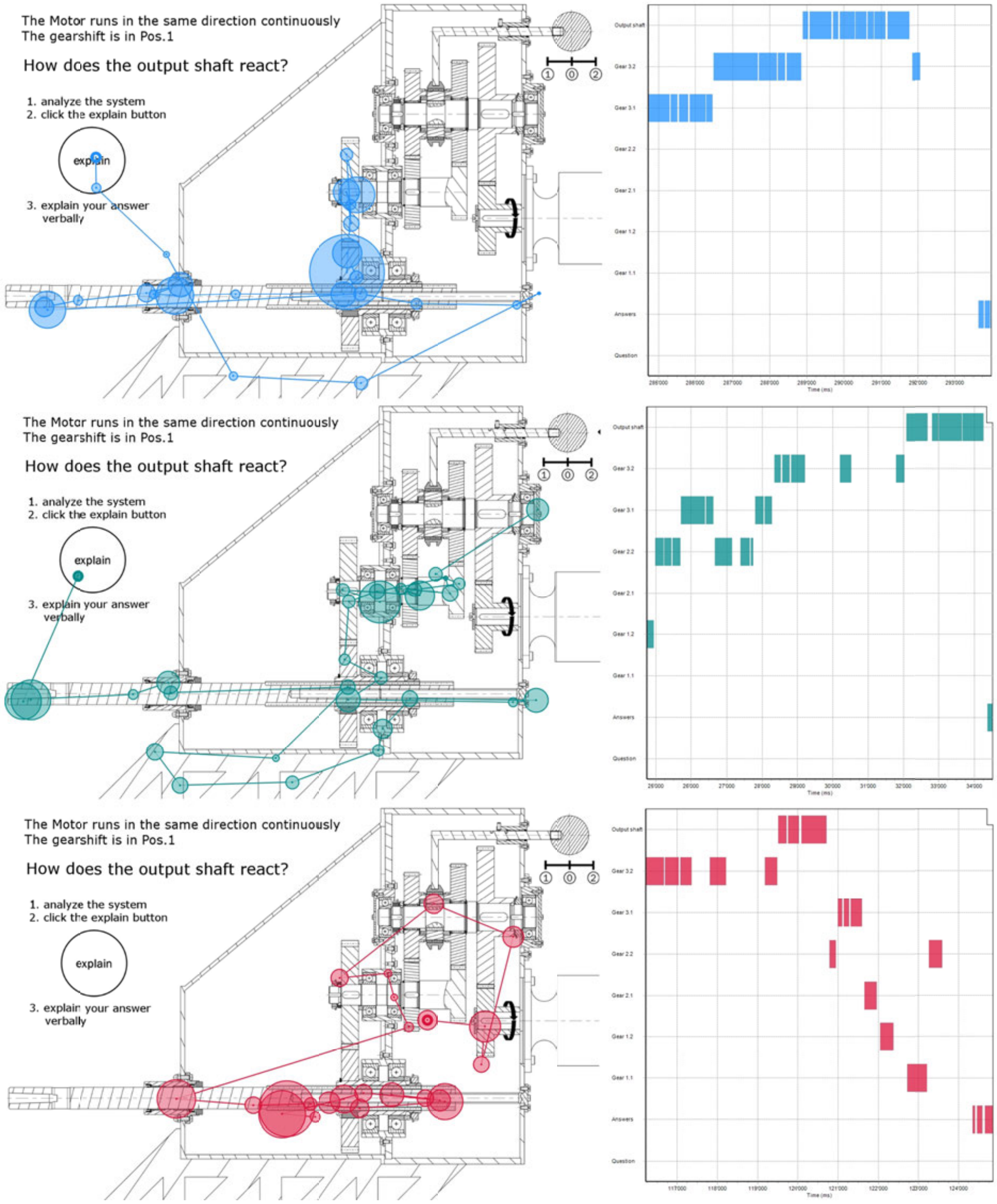

Figure 6. Scan paths (10 s) and AOI sequences (10 s) in solving task 3 tracked from a test person from TU Athens (top), ETH Zurich (middle) and KIT Karlsruhe (bottom)

6. Quantitative results

Section 5 presented results based on the visual behaviour of individual engineering designers. Besides, the scan paths and AOI sequences shown in Figure 4, Figure 5 and Figure 6 are selected cutouts of the full data set recorded during the experiment. This section presents a quantitative evaluation of the data taking into account the eye tracking records of all 26 test persons in total runtime.

6.1 Task duration

A relevant measurement is the time the test persons needed to choose an answer. Table 1 presents the resulting mean task duration. As a matter of fact, the first task was finished most quickly, although the test persons were confronted with the stimulus for the first time and thus needed a certain time for orientation. On average, the test persons only spend a few seconds more on the second task, but to answer the third task they finally took about twice the time. The results indicate an increasing level of difficulty from task 1 to task 3. This assumption is confirmed by the decreasing number of right answer from task 1 (22 of 26) to task 2 (18 of 26). Consequently, it can be assumed that in the experiment the difficulty of the task assigned had an impact on the resulting visual behaviour.

Table 1. Mean task duration and standard deviation in seconds (n = 26)

	Task 1	Task 2	Task 3
Task Duration	55.781 (29.228)	67.282 (44.884)	117.590 (64.234)

6.2 Dwell time

In addition to the qualitative results showing similarities in the order of AOIs the test persons drew visual attention to, the quantitative evaluation can support comparing the attentional dispersion to AOIs. In this context, the relevant measurement is the dwell time, which by definition is the sum of durations from all fixations and saccades that hit the specific AOI. Table 2 presents the mean dwell time resulting from the experiment.

The values indicate that each task is assigned to a characteristic attention profile. For instance, the visual behaviour of task 1 is characterized by a high amount of attention on the AOIs “Answers”, “Gear 1.1” and “Gear 2.1”. Whereas the visual behaviour of task 2 is distinguished by the fact that averaged more than 25 % of the visual attention was given to the AOI “Gear 2.1”. Even task 3 reveals some characteristic values such as the highest level of visual attention on the AOI “Gear 3.2”. These results basically confirm the assumptions made on basis of the qualitative evaluation. A task, its content as well as its formulation, have a detectable influence on the visual behaviour of the person confronted with the task.

Besides the mean dwell time, table 2 also presents the corresponding standard deviation. The measurements reveal that the individual dwell times on the AOIs are widely distributed across the 26 test persons. This result shows that individual visual behaviour depends on more than just the task assigned. How a single engineering designer searches through a technical drawing is, amongst others, also influenced by individual factors such as previous knowledge, personality traits and the level of expertise in the specific subject matter.

Table 2. Mean dwell time and standard deviation in % (n = 26)

AOIs	Task 1	Task 2	Task 3
Question	3.6 (3.8)	3.2 (5.6)	4.6 (3.6)
Answers	15.1 (7.3)	4.2 (3.6)	7.6 (3.6)
Gear 1.1	13.1 (5.1)	3.8 (3.1)	5.8 (4.0)
Gear 1.2	8.2 (3.3)	8.9 (3.6)	7.1 (2.7)
Gear 2.1	10.4 (5.0)	25.5 (11.0)	15.9 (7.1)
Gear 2.2	6.9 (4.0)	11.5 (8.3)	5.0 (3.2)
Gear 3.1	6.3 (2.4)	3.8 (3.0)	6.0 (2.6)
Gear 3.2	6.5 (3.5)	1.3 (1.4)	8.3 (5.4)
Output Shaft	5.2 (2.3)	0.8 (0.9)	4.3 (3.8)

7. Conclusion

The results of the eye tracking experiment distinctly show that the visual behaviour of engineering designers does depend on the task assigned. Following the first research question, the qualitative evaluation of the data exemplary illustrates similarities in the visual behaviour of test persons solving the same task. By comparing the individual behaviour of three different test persons just before they answered, similar scan paths with partly identical AOI sequences could be identified.

The second research question considers the task-dependent differences in the visual behaviour of engineering designers. Based on the assumption that relevant information is provided at different stimulus locations and in different information density, already the qualitative results indicate typical scan paths and AOI sequences for each task. The quantitative evaluation confirms these findings by revealing characteristic attention profiles describing the task-dependent attentional dispersion on AOIs across all 26 test persons.

The experiment presented in this paper shows that Yarbus' research approach is well transferable to design research and that, in fact, the visual behaviour of engineering designers depends on the task, including its specific level of difficulty. Nevertheless, the task is not the only influencing factor in this context. Especially in those cases the task is not described clearly and completely, individual strategies seem to have a higher impact on visual behaviour and thus, need to be extensively analysed in future experiments.

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