

# HOW WE UNDERSTAND ENGINEERING DRAWINGS: AN EYE TRACKING STUDY INVESTIGATING SKIMMING AND SCRUTINIZING SEQUENCES

Lohmeyer, Quentin; Meboldt, Mirko  
ETH Zurich, Switzerland

## Abstract

Engineering drawings representing machine systems are usually sectional drawings showing the inner mechanical mechanisms. A precondition for understanding such a drawing is to be familiar with the notation of its basic elements. However, in order to really understand how a represented machine system works, additional cognitive processes have to be initiated. This paper presents an eye tracking study investigating how engineers behave while trying to understand such a sectional engineering drawing. The eye tracking data collected during the experiment was analyzed by an approach that for the first time combines the evaluation methods of skimming and scrutinizing sequencing and transition matrix analysis. Based on this procedure, three behavioral patterns have been identified that, if found in a person's eye tracking data, allow drawing substantial conclusions about the cognitive processes run through.

**Keywords:** Human behaviour in design, engineering drawings, eye tracking

## Contact:

Dr.-Ing. Quentin Lohmeyer  
ETH Zurich  
Mechanical and Process Engineering  
Switzerland  
qlohmeyer@ethz.ch

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# 1 INTRODUCTION

Engineering drawings are formal representations of product parts or product systems providing geometrical as well as functional information. The drawings are usually created in accordance with national and international standard conventions for layout and nomenclature in order to fully and clearly convey graphically the ideas and information necessary for engineered items (Agrawal and Agrawal, 2013). Consequently, engineering drawings are typically not open to interpretation like works of art such as paintings or photographic pictures. According to Madsen (2012), a successful engineering drawing describes a specific item in a way that the viewer of the drawing understands completely and without misinterpretation.

Engineering drawings representing machine systems are usually sectional drawings showing the inner mechanical mechanisms. A precondition for understanding such a drawing is to be familiar with the notation of its basic elements. However, in order to really understand how a represented machine system works, additional cognitive processes – usually requiring a certain level of spatial aptitude – have to be initiated. Indeed, there are certain studies that found correlations between performances in understanding engineering drawings and scores on spatial visualization tests (Field et al., 2005, Branoff and Dobelis, 2012). They indicate that, in order to make assumptions about a machine system's behavior in operation, the viewer of a two-dimensional engineering drawing firstly has to be able to develop a three-dimensional mental model of the represented machine system and secondly must be able to mentally set this model in motion.

In design research, the results of several recent studies indicate that eye tracking seems to be most suitable to investigate human behavior during interaction with such two-dimensional representations of design information. Boa and Hicks (2014) for example used gaze detection as an indicator of cognitive processes to propose a model for information interaction of engineers with design artefacts. Maier et al. (2014) recorded different eye tracking measurements such as fixation duration and pupil diameter to investigate how the quality of UML diagram layouts impact the viewer's cognitive load. And Eriksson et al. (2014) applied eye tracking to analyze basic visual behavior when interacting with different types of assembly instructions.

In the context of engineering drawings as well first eye tracking experiments have been conducted (Matthiesen et al., 2013, Lohmeyer et al., 2014). The findings of these studies are based on analyzing scan path data, which basically includes an evaluation of the central eye tracking measurements 'fixation duration' (How long did the participant look at a certain location?) and 'saccade amplitude' (From where to where did the gaze jump?). Beside several insights into visual strategies the participants applied to understand a given engineering drawing, the studies revealed the need for a reproducible way to distinguish between sequences of visual overview exploration (skimming) and visual detail investigation (scrutinizing). Based on this need, Lohmeyer et al. (2015) proposed an algorithm using clearly defined numerical criteria for an objective detection of skimming and scrutinizing sequences in eye tracking data. As a next step in this field of research, the present study now addresses the following research question: In which way does the detection of skimming and scrutinizing sequences support the analysis of eye tracking data to describe and to explain the cognitive process of understanding engineering drawings?

This paper presents an eye tracking study investigating how engineers behave while trying to understand a sectional engineering drawing of a machine system. The eye tracking data collected during the experiment was analyzed by an approach that for the first time combines the evaluation methods of skimming and scrutinizing sequencing and transition matrix analysis. Based on this procedure, three behavioral patterns have been identified that, if found in a person's eye tracking data, allow drawing substantial conclusions about the cognitive processes run through.

The paper proceeds as follows. Section 2 illustrates the difference of skimming and scrutinizing sequences and briefly explains how they can be detected in eye tracking data. Further, the basic idea of transition matrices is introduced and clarified by an exemplary application. Section 3 describes the experimental setup including detailed descriptions of participants, eye tracking system, stimulus, task and procedure. Section 4 presents the results of the study with a special focus on the three behavioral patterns identified. It is described in what way each pattern is characterized by a certain combination of skimming and scrutinizing sequences and transition matrices, and under what circumstances participants have used these patterns in examining and understanding the engineering drawing.

## 2 DATA ANALYSIS METHODS

Data obtained from eye tracking experiments contains several measurements that can be processed and visualized in multiple ways. This section gives an overview of the data analysis methods applied in the present study.

### 2.1 Skimming and Scrutinizing

A common way to illustrate the visual behavior of a person relative to a stimulus is the scan path visualization, which depicts fixations by circles and saccades by connecting lines. Here, the diameter of each circle represents the fixation duration and the length of each line represents the saccade amplitude.

Figure 1 shows two exemplary scan paths of one person during the examination of an engineering drawing. The scan path on the left side shows a typical skimming sequence, which is characterized by short fixations and long saccades. It is assumed that skimming is applied, when a person aims to get an overview of a system and tries to identify relations between single elements from a high-level perspective. The scan path on the right side shows a typical scrutinizing sequence. In contrast to skimming, scrutinizing is characterized by long fixations and short saccades and it is applied when a person tries to understand certain details of the stimulus.

These basic types of visual behavior have already been found and described decades ago. Based on an eye tracking experiment with about 200 participants investigating how people look at pictures, Buswell (1935) reported that he found two general patterns of perception. He described that “one of these patterns consists of a general survey, in which the eye moves with a series of relatively short pause over the main portions of the picture” and that “a second type of pattern was observed, in which a series of fixations, usually longer in duration, are concentrated over small areas of the picture, evidencing detailed examination of those sections”. However, although skimming and scrutinizing are well known in research and although they describe basically different cognitive processes, their differentiation usually still bases on personal judgment. So far, only little research has aimed to quantify their characteristics (Unema et al., 2005, Holmqvist et al., 2011a).

In the present study a numerical data analysis method is applied, which detects skimming and scrutinizing sequences directly from eye tracking data without an intermediate step of graphical scan path representation. For the analysis an algorithm is used that basically works by checking each pair of a fixation and its subsequent saccade (Lohmeyer et al., 2015): The start of a scrutinizing sequence is defined by the criterion that two pairs in a row are characterized by fixation durations above 240ms and saccade amplitudes below  $0.5^\circ$ . As soon as the fixation duration of a following pair decreases (once lower than 180ms or twice lower than 200ms) or the saccade amplitude increases (once higher than  $1.2^\circ$  or twice higher than  $0.8^\circ$ ), the scrutinizing sequence ends and a skimming sequence starts. This skimming sequence continues until the next scrutinizing sequence is detected.

Due to this method, a whole scan path can be subdivided into sequences of skimming and scrutinizing including the exact points in time, where one type of visual behavior is displaced by the other.

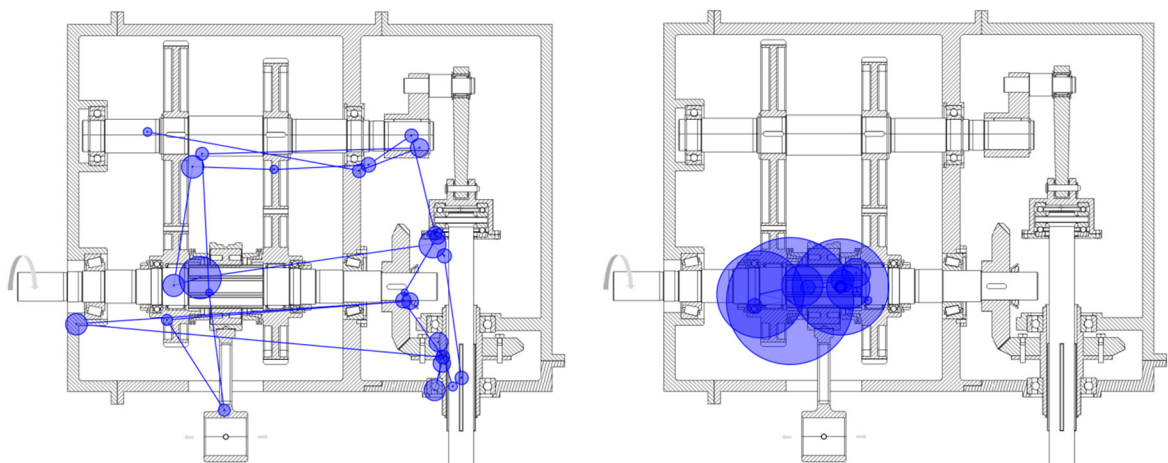


Figure 1. Basic types of visual behavior: skimming (left) and scrutinizing (right) in 7 second scan paths of one test person trying to understand an engineering drawing

## 2.2 Transition Matrix

An engineering drawing usually contains relevant information distributed at different locations. In order to track at which point in time a person draws his or her visual attention to these locations, it is necessary to define so-called areas of interest (AOIs). Figure 2 shows the exemplary engineering drawing including three AOIs, which have been defined in accordance with the subsystems of the represented machine system. This approach now allows calculating the gaze's dwell time within each AOI and furthermore, measuring the number and the direction of all transitions.

A transition is defined as a saccade from one specific AOI to another (Holmqvist et al., 2011b). If a scan path involves multiple transitions, these can be represented in form of a matrix. The cells of such matrices contain the frequencies of direct transitions between AOIs (Hooge and Camps 2013). Although the cells on the diagonal by definition should be empty, they are often used to report the number of saccades within an AOI (Wickens and McCarley, 2008).

Figure 2 gives two examples. On the left side the recorded eye tracking data is represented graphically in form of a scan path. Due to the definition of the three AOIs, it can be seen that during the presented skimming sequence (top), there are several transitions and also multiple saccades within AOIs. The corresponding transition matrix on the right side provides detailed information by showing the exact numbers and directions. In sum, there are seven transitions (three from AOI 3 to AOI 1, two from AOI 1 to AOI 2, one from AOI 1 to AOI 3 and one from AOI 2 to AOI 3). The cells on the diagonal give the number of saccades within the AOIs (three in AOI 1, six in AOI 2 and eight in AOI 3). Taking into account that this example only covers 7 second eye tracking data, it can be assumed that for longer sequences the graphical scan path representation becomes increasingly confusing, while the transition matrix remains valid. The second example shows the transition matrix of a scrutinizing sequence (bottom). The result shows no transition at all, which is typical for scrutinizing sequences. In fact, a scrutinizing sequence containing transitions might even indicate the definition of inappropriate AOIs.

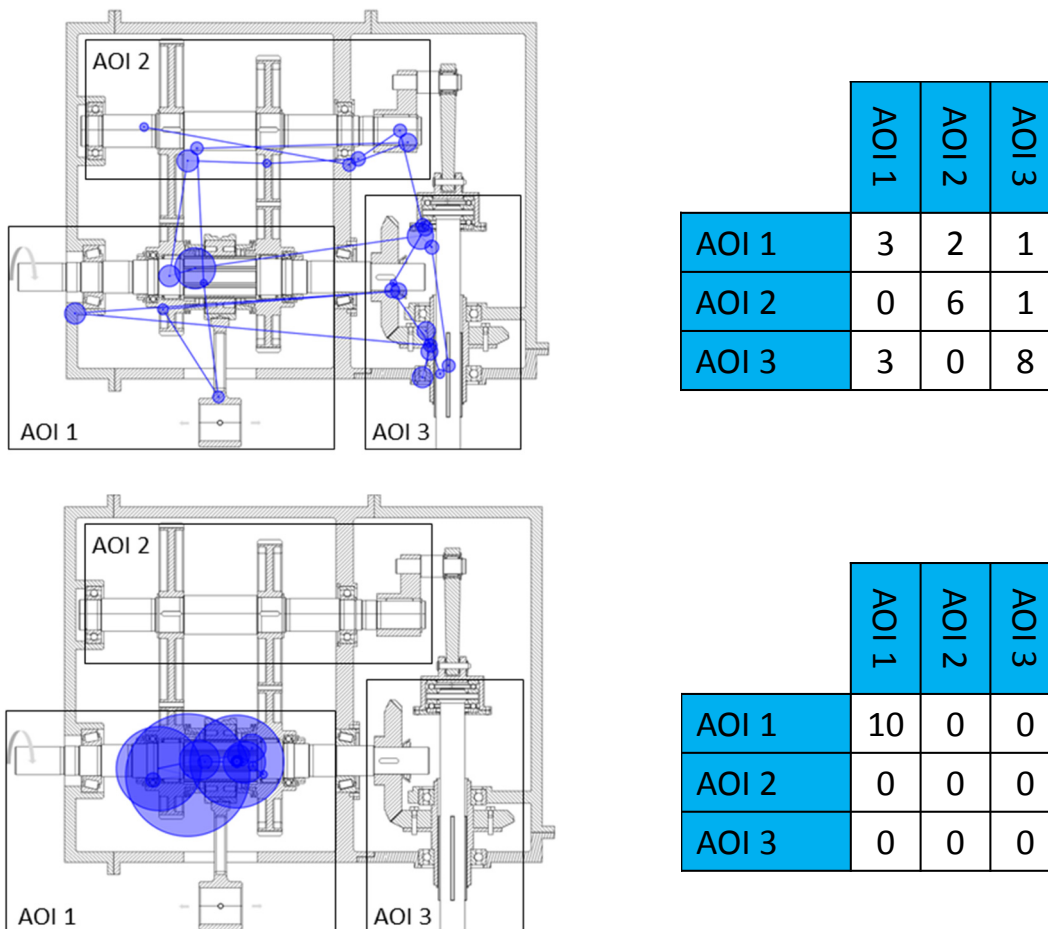


Figure 2. Eye tracking data related to areas of interest (AOIs) represented graphically by scan paths (left) and numerically by the corresponding transition matrices (right)

### 3 EXPERIMENTAL SETUP

#### 3.1 Participants

Twenty-six students (22 male, 4 female) participated in the experiment. All participants had a bachelor degree in mechanical engineering and were just continuing their studies in engineering master courses. Ten of these students were from TU Athens in Greece, ten were from KIT Karlsruhe in Germany and six were from ETH Zurich in Switzerland. The participants ranged in age from 20 to 31 years. All participants were English-speaking and had normal or corrected to normal vision.

#### 3.2 Apparatus

The experiment was conducted by application of the remote eye tracking system SMI RED 250 (sampling rate: 250Hz, position accuracy:  $0.4^\circ$ , tracking resolution:  $0.03^\circ$ ). The stimulus was shown on a 22" flat screen (solution: 1680 x 1050px, operating distance: 70cm). Eye tracking data was analyzed by using SMI BeGaze 3.5. Event detection was defined after fixation duration criterion ( $\geq 80$ ms) and fixation dispersion criterion ( $\leq 100$ px).

#### 3.3 Stimulus and Task

The stimulus was an engineering drawing (cf. Figure 3) representing an axial piston pump by a longitudinal (left) and a transverse sectional view (right). The stimulus also showed the task the participants had to solve (top) and two given answer options (bottom) referring to the transverse sectional view. Furthermore, the rotation direction of the input shaft was visualized by two curved arrows at the very left side.

Eckert et al. (2011) already used this stimulus in an experiment investigating different notions of function. They selected the pump as an example of a design that is highly optimized for robustness and durability and has sufficient complexity to reflect components designed by teams in industry. In the present study the engineering drawing of the axial piston pump is suitable as stimulus, because solving the task requires multiple cognitive abilities to identify the relevant components and to imagine how these components will move in operation.

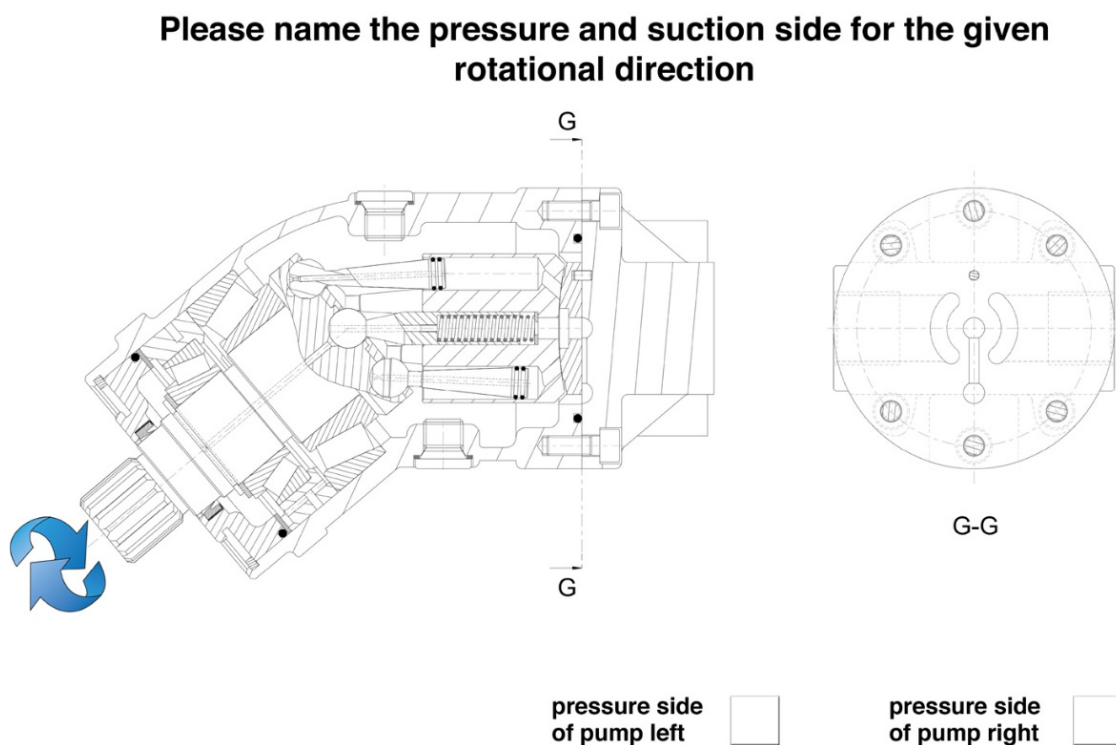


Figure 3. Stimulus: Engineering drawing representing an axial piston pump by a longitudinal (left) and a transverse sectional view (right)



### 3.4 Procedure

The participants were tested individually. Before assigning the task all participants were confronted with the engineering drawing of the pump and asked whether they knew what it represented. Participants, who were not able to identify the system, were informed about what the drawing showed. Furthermore, all participants were asked to think aloud while solving the task assigned. During the experiments individual eye tracking data as well as audio data were recorded. The time of each recording was limited to five minutes.

The detection of skimming and scrutinizing sequences was conducted as described in section 2.1 by evaluation of all pairs of a fixation and its subsequent saccade. Disturbance events such as blinks (and their subsequent saccades) have been excluded from evaluation.

In addition to the analysis of eye tracking data, the participants' performance was evaluated by the following three criteria: (1) Did he or she choose the right answer? (2) Did he or she explain correctly how the rotation direction affects the pressure side of the pump? (3) How quickly did he or she solve the task?

## 4 FINDINGS

The first confrontation with the stimulus revealed that 15 participants recognized the represented system as a pump. Consequently, 11 participants needed to be informed about what the engineering drawing was showing. In the end, 8 of the 15 participants, but only 3 of the 11 participants chose the right answer (pressure side of the pump left).

The analysis of the eye tracking data showed that the participants' visual behavior can be accurately described by means of skimming and scrutinizing and the corresponding transition matrices. The approach further allows to compare skimming and scrutinizing sequences across participants and to search for common behavioral patterns. Based on the results of the present study, three of these patterns have been identified.

### 4.1 Orientation Pattern

The orientation pattern was found in the scan path of nearly every participant. As illustrated in Figure 4, it is characterized by alternation of short scrutinizing sequences (500-2000ms) and rather long skimming sequences (>3000ms). During skimming several AOIs are hit, but the number of transitions are very low (usually 0 or 1 per cell).

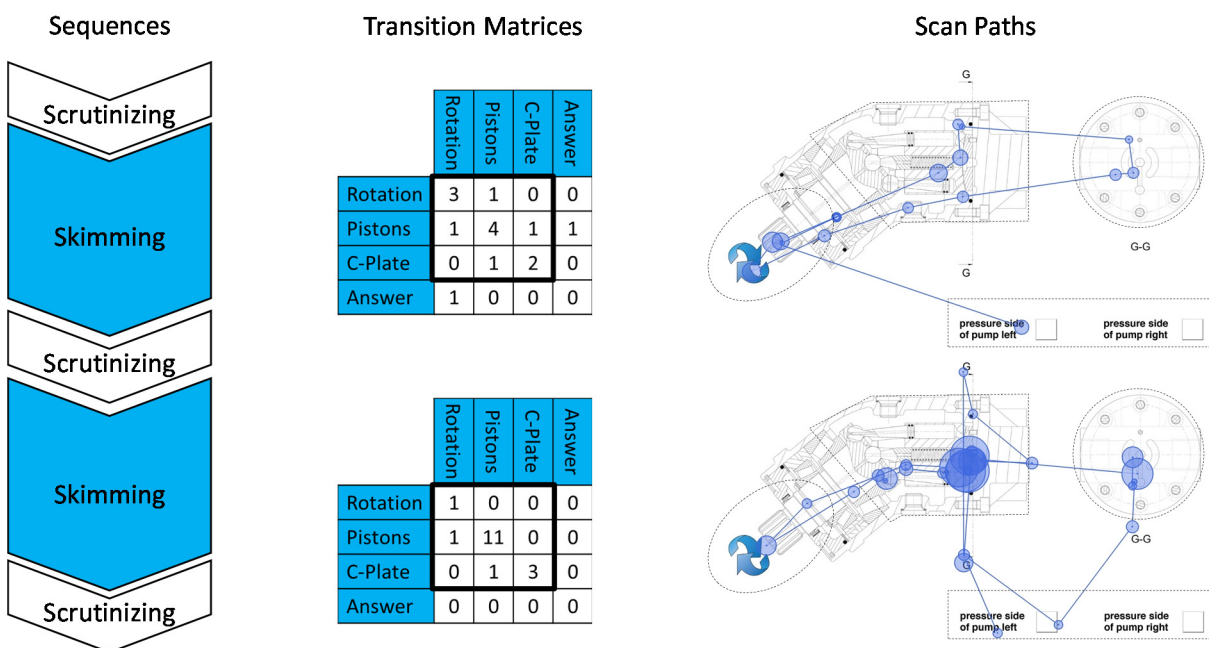


Figure 4. Orientation Pattern: Alternation of short scrutinizing sequences and long skimming sequences characterized by a low number of transitions

Finding this pattern in eye tracking data indicates that at this point in time a person is looking for locations where he or she can gather relevant information. Figure 4 presents the examples of an orientation pattern from the experiment. The upper scan path shows a skimming sequence where a participant quickly shifted his attention from the rotating input shaft on the left side to the control plate on the right side and back. This kind of scan path was often found within the first twenty seconds of examining the engineering drawing. It can be assumed that this behavior is required to basically recognize which elements are represented and where they are located. The lower scan path shows a similar behavior. Only a few seconds later the participant again skims from the left to the right, now more extensive skimming through the middle AOI, which in fact contains essential information to answer the question correctly.

The study revealed that high performing participants only needed a short time of orientation, whereas low performing participants continuously repeated different versions of orientation patterns, sometimes even for several minutes.

## 4.2 Comprehension Pattern

The comprehension pattern is characterized by alternation of skimming and scrutinizing sequences of approximately the same duration (1000-4000ms). Their corresponding transition matrices only have a single entry in one cell of the diagonal. This means that all skimming and scrutinizing took place within a single AOI.

Finding this pattern in eye tracking data indicates that a person has assessed the information within one specific AOI to be highly relevant and now aims to establish a deeper understanding about its content. An example of a comprehension pattern is presented in Figure 5. It shows the visual behavior of a participant, who tried to understand the movement of the pistons, which is triggered by the incoming rotation. During the application of this behavioral pattern, the participant was able to recognize that due to the rotation and the angle between the axis of the pistons and the axis of the input shaft, pistons rotating upwards are drawn out of the piston drum, whereas pistons moving downwards are pushed into it.

In the present study, comprehension patterns have been found in the scan paths of participants, who initially were not familiar with the pump shown on the engineering drawing, but were able to use their mechanical comprehension skills to deduce how this system works. However, no comprehension patterns were found in the scan paths of extremely high and extremely low performing participants. It can be assumed that high-performers already knew how the pistons move in operation. They simply had no reason for an extensive examination. In contrast, low-performers seemed to be unable to identify locations of relevant information and thus, they got stuck in orientation.

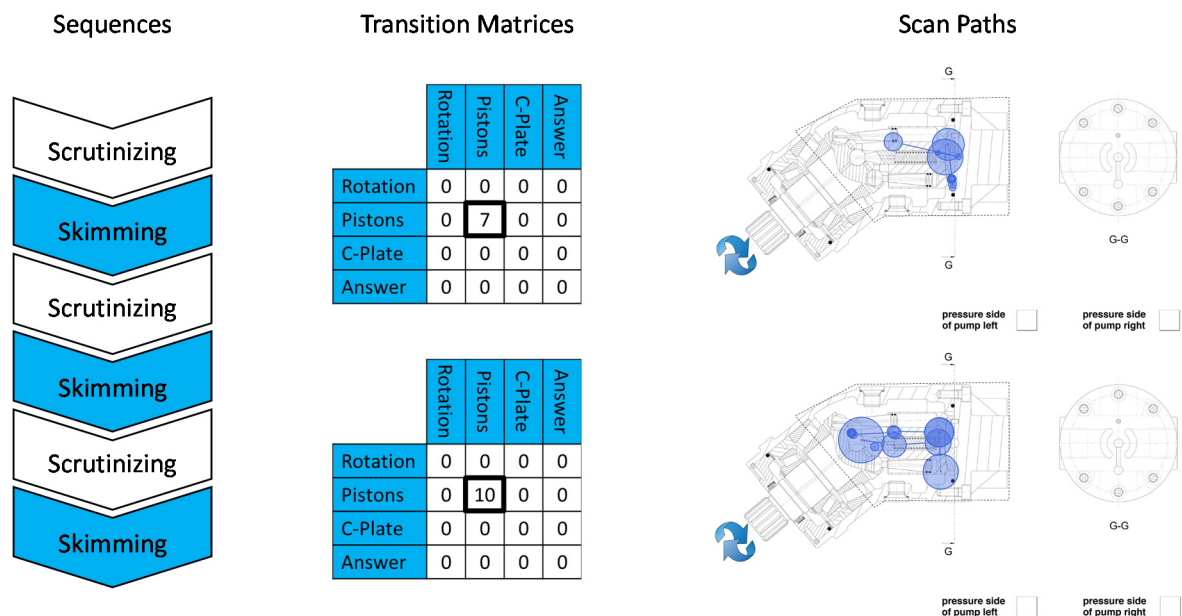


Figure 5. Comprehension Pattern: Alternation of scrutinizing and skimming sequences of approximately the same duration within a single area of interest (i.e. no transitions)

### 4.3 Conclusion Pattern

Just as the orientation pattern, the conclusion pattern is characterized by alternation of short scrutinizing sequences (500-2000ms) and rather long skimming sequences (>3000ms). Consequently, these patterns cannot be differentiated by just a sequence analysis. However, comparing the transition matrices clearly shows that, in contrast to orientation, the skimming sequences of a conclusion pattern contain multiple transitions between only two specific AOIs.

Finding this pattern in eye tracking data indicates that a person is connecting pieces of information located in different AOIs in order to draw conclusions about possible relations. Figure 6 presents the example of a conclusion pattern from the experiment. The upper scan path shows a skimming sequence, in which a participant shifted his attention from the notation of rotation direction to the ring of pistons and back. The corresponding transition matrix gives the frequency of transitions, which in this case is five in each direction. This means, that the participant repeated shifting between the hit AOIs five times within only seven seconds. It can be assumed that this behavior allowed him to transfer the information of rotation direction from the first AOI to the ring of pistons located in the second AOI and thus, enabled him to draw and to double-check conclusions of how the single pistons are affected.

The lower scan path shows a following skimming sequence, which is also characterized by multiple transitions now connecting the second and the third AOI. Here, information of the pistons' movement is related to the design of the control plate. Similar to the previous scan path this skimming sequence includes four to five transitions in each direction. The scan path also shows that the participant skimmed through the annotations specifying the position and the direction of the transverse sectional view (G-G). In the end, exactly these two pieces of information are required to draw the fact-based conclusion that the pressure side was located on the left side.

In the present study, conclusion patterns have been found especially in the scan paths of participants, who either had applied several comprehension patterns before or who already had acquired in-depth knowledge of the pump and how it works. In this context it is indispensable to highlight that extremely high performing participants nearly exclusively applied conclusion patterns that furthermore were characterized by a very high number of transitions. These finding suggests strong correlations between performance and conclusion pattern frequency as well as performance and conclusion pattern intensity.

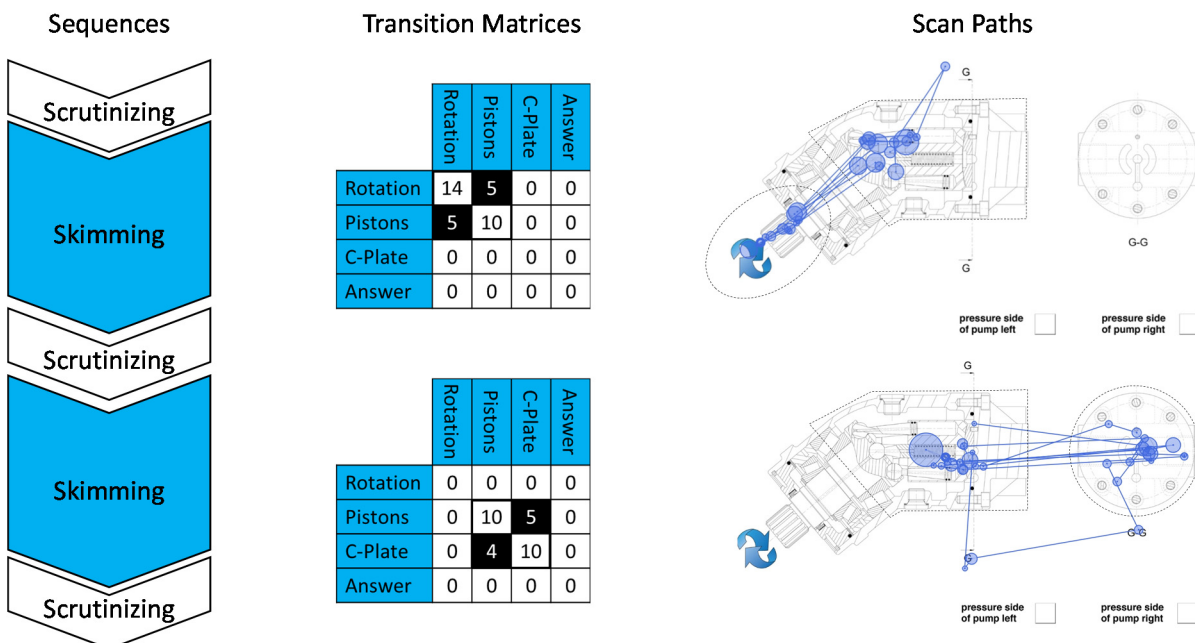


Figure 6. Conclusion Pattern: Alternation of short scrutinizing sequences and long skimming sequences characterized by a high number of transitions



## 5 CONCLUSION AND OUTLOOK

The aim of the study presented in this paper was to investigate how the detection of skimming and scrutinizing sequences supports the analysis of eye tracking data in order to describe and explain the cognitive process of understanding engineering drawings.

The study results showed that by usage of numerical detection criteria the exact starting and ending points of skimming and scrutinizing sequences within a scan path can be clearly identified. Due to this, the data analysis method allows to describe and to compare scan paths by resulting sequence diagrams, which provide valuable information of skimming and scrutinizing durations and the frequency of alternation. The present study revealed that at least two different patterns can be found in sequence diagrams: One pattern is characterized by alternation of short scrutinizing sequences and long skimming sequences, the other by alternation of scrutinizing and skimming sequences of approximately the same duration. However, although the results indicate that during the application of these two patterns basically different cognitive processes have been run through, it was also shown that the detection of skimming and scrutinizing itself is not sufficient to explain differences in the participants' performances.

The problem was solved by combining skimming and scrutinizing sequencing with the evaluation method of transition matrix analysis. This new approach relates identified sequences to defined AOIs and due to this, it allows a considerably more specific characterization of skimming and scrutinizing sequences. Based on this approach the classification of behavioral patterns found in the collected eye tracking data could be improved to a level that allows distinguishing the cognitive processes of (1) orientation, (2) comprehension and (3) conclusion during the examination of an engineering drawing.

A key finding of the experiment is that in general all three patterns are required to knowingly choose the correct answer. Orientation allows a person to search the engineering drawing for locations of relevant information, comprehension allows to extract the corresponding pieces of information from these locations and conclusion finally allows to put the pieces together and to build up an overall understanding of the represented system. However, this finding is based on only the present study. In order to test whether the patterns identified by skimming and scrutinizing sequencing and transition matrix analysis can be confirmed, additional experiments using various engineering drawings as stimuli are required.

In context of this finding, it is also important to emphasize that few extremely high performing participants, who had already been familiar with the axial piston pump and its functionality before the experiment, skipped the patterns of orientation and comprehension and directly applied the conclusion pattern to solve the task correctly. This result indicates that expertise might have a substantial impact on the way we understand engineering drawings. Consequently, the aim of future studies will also be to further investigate these correlations of engineering expertise and visual behavior.

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