Visualization of production area information: How important is a 3D-Visualization?

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Abstract

A key objective in designing human-computer interfaces in the field of industrial manufacturing should be the dynamic visualisation of manufacturing processes with help of innovative visualisation elements. This article describes a comparative evaluation study of two ways of visualising complex shop floor activities in real-time: a traditional two-dimensional, windows-based form of visualisation and an innovative three-dimensional, realistic interface, the so-called Virtual Shop Floor (*VISOR*). In order to evaluate both visualisations, an experimental investigation with 20 test persons and the application of different evaluation methods (eye mark registration, key stroke recording, video-taped observation and interviews) was performed at the ifab-Institute of the University of Karlsruhe. One result of this investigation shows, that the cognitive strain of the test person is high-significantly lower when using the realistic interface in comparison with the traditional visualisation.

Keywords: human-computer interaction, information visualisation, software-ergonomics, eye mark registration, evaluation

1 Introduction into Shop Floor Controlling Systems

1.1 Visualization Forms for Shop Floor Controlling Systems

Shop floor controlling is defined as the short-term controlling and monitoring of shop floor processes. It is responsible for the planning compatible execution of shop floor orders while considering human, economic, quality and deadline demands. In order to execute shop floor orders in a planning compatible manner the appropriation of personnel, equipment, material and other necessary resources, as well as the execution of work tasks, are initiated, surveyed and secured by the shop floor controlling system.

The goal of the current work is to provide a contribution to the experimental analysis and configuration of computer supported, process-orientated visualization forms using the example of enterprise shop floor processes within the operative shop floor controlling. Various research studies have found that the available, shop floor controlling systems, usually window-based, have deficits with respect to their user-friendliness and information transparency (see Greenough, Kay, Fakun & Tjahjono, 2000; Kasvi & Vatiainen, 2000; Stowasser, 2002).

1.2 Today's Shop Floor Controlling Systems

The window technique has been established as a standard in all enterprise application areas. In the window technique the entire screen surface is divided into individual logical groups. One differentiates between information, controlling, processing and notification parts. A perception psychologically suitable arrangement of these groups serves to ease the registration of information as well as its quick interpretation.

The control stations implemented up until now are more data orientated and are thus less suitable for the process-orientated planning and controlling of a production shop floor. As for the functionality of the control station systems, in which orders are "shoved" through the plant, the appearance of unexpected changes to the status of the shop floor objects (e.g. products, materials, resources) are often only secondary. As a resulting consequence thereof one can observe incomplete data and an insufficient transparency of shop floor operations.

2. Cognitively-orientated Investigation of the visualization *FEWER* and *VISOR*

The ifab-Institute of Human and Industrial Engineering at the University of Karlsruhe is occupied with the structured development and the cognitively-orientated experimental evaluation of user interfaces for the shop floor. Two process-oriented human-computer interfaces supporting the shop floor workers are the basis for the recently performed comparative investigation: a traditional two-dimensional, standard windows-technique based visualisation and an innovative three-dimensional, realistic interface, the so-called Virtual Shop Floor.

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2.1 Objects of the Experimental Evaluation

The basis for the comparative investigation study are two forms of visualizing industrial manufacturing information on the shop floor: a traditional window-(text-)based visualization *FEWER* ("Fensterbasierte Werkstattsteuerung") and an innovative realistic form of visualization called Virtual Shop Floor (*VISOR*) (see Stowasser 2002).

2.1.1 Window-based shop floor visualization FEWER

Within the context of this work, the shop floor system *FEWER* bases on text formulas, masks and dialogues. Text or graphic information as well as interaction possibilities are provided to the user within the structure. Figure 1 clarifies the structure of the user interface *FEWER*.

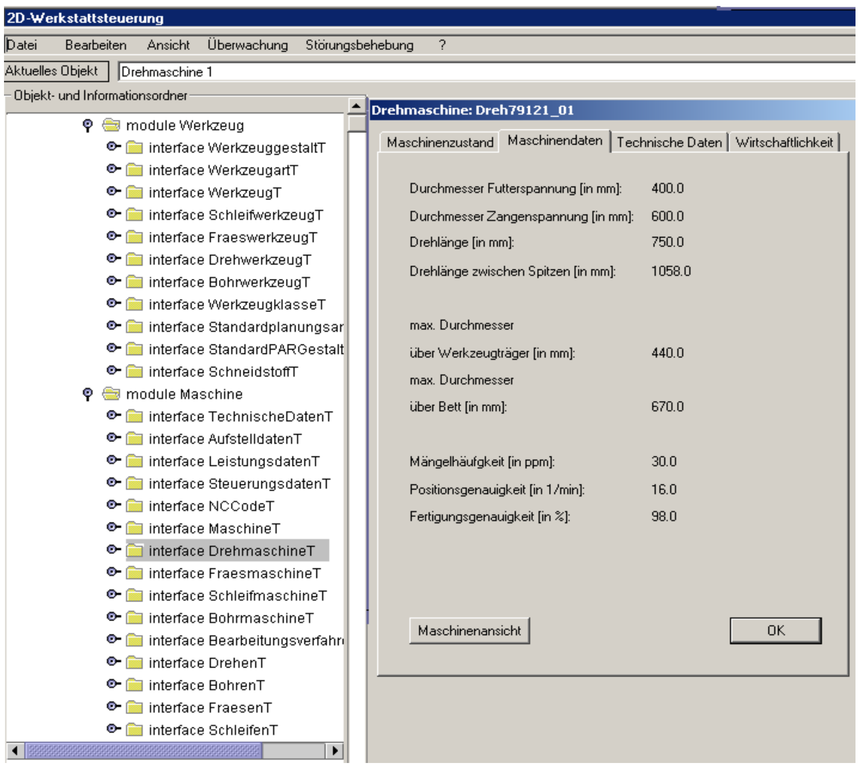


Figure 1. Window-based visualization *FEWER*

The processing part of the screen mask offers a workspace for the execution of the operative shop floor controlling tasks needing to be dealt with, namely: Surveillance of preparation, quantities and deadline monitoring, quality controlling, tracing breakdowns, determining the causes for disturbances as well as intervening in the manufacturing procedure. The processing part in *FEWER* contains a list of the shop floor objects (e.g. machines, orders) and their possible attributes. Using these lists, the user can find the objects required for the control and surveillance of the shop floor.

2.1.2 Virtual Shop Floor Visualization VISOR

VISOR (Virtual Shop Floor) is a realistic representation form based on the use of the graphic, multimedia possibilities of current computer systems. The realistic visualization is, in the context of this work, defined as a spatial-perspective model of a three-dimensional scene, which can be considered from varying views. The model is visualized using graphic computer support. The degree of the visualization reaches an accurately detailed, objective (photographic) level. The dynamic shop floor environment is represented with *VISOR* in a spatial-perspective manner. The user can "place" himself in the realistic shop floor and move about in all three directions by using the spacemouse.

For operative shop floor observation, meaning the surveillance of appropriation (of e.g. resources, personnel), quantities, deadlines and quality, the user requires information about the current shop floor events. Such information is displayed in *VISOR* as text or graphics, whereby the information subject matter plays an important role in the conception (cf. figure 2). The data to be visualized can refer to abstract as well as to concrete circumstances.

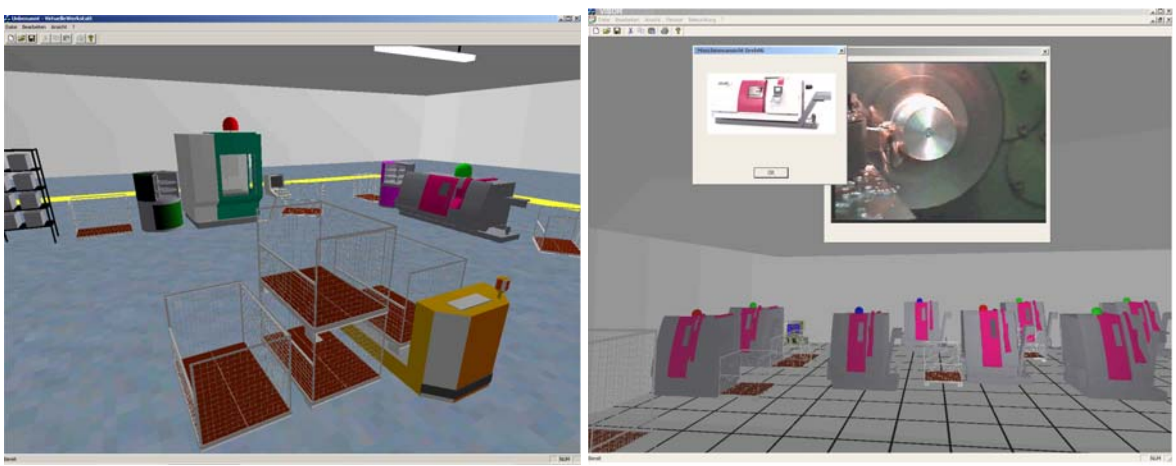


Figure 2. Realistic shop floor visualization *VISOR*

Generally, the choice of representation in *VISOR* can be derived from the results of previous examinations as well as from cognitive psychological insights. According to Buziek (2000) the cognitive perception of images is easier than the production of a conception from language and text information; thus, graphically represented information is usually superior to other forms of coding.

2.2 Methods of the Experimental Evaluation

In the examination various empirical evaluation methods have been implemented for the assessment of the visualization forms *FEWER* and *VISOR*. The interview methods come into play for the assessment of the user interfaces from the subjective perspective of the user and for the recording of demographic data of the test subjects. Since test persons have more difficulties naming their approaches during the task processing, the questioning was used only as a supplement, at the end of the test.

Other (objective) methods are more suitable for the gathering and assessment of test task processing. From the objective evaluation methods, computer protocolling (logfile recording) and eye-mark registration were implemented as a particular method of behaviour observation. The following section describes the experimental evaluation methods of eye-mark registration more detailled.

2.3 Registration of Eye Movements

In order to register and measure eye movements, various methods which exploit the anatomical-physiological characteristics of the eye can be applied. Comprehensive overviews of the various methods are provided by e.g. Young & Sheena (1975).

2.3.1 Point of Regard Measurement

The eye-mark registration system used in this work is based on the method of point of regard measurement. In this method the difference vector between a certain fixed point of the eye and the light reflection of an artificial light source, attached to the head, onto the human point of regard is inferred. Generally, (also in the measurement system used here) the location difference between the mid-point of the pupil and the light reflection of the light source on the cornea is used.

The determination of the location of both reference points is carried out in the current system using the procedure of video-based image processing. The video camera is hereby used to record an image of the eye. The recorded image is subsequently prepared using computer supported image processing and the reference points are filtered out. Detailed specifications regarding the technical realisation of the video-based image processing and the filtering of corneal reflections and pupils are provided by Stampe (1993) as well as Mulligan (1997).

2.3.2 Insights Gained Through Eye-mark Registration

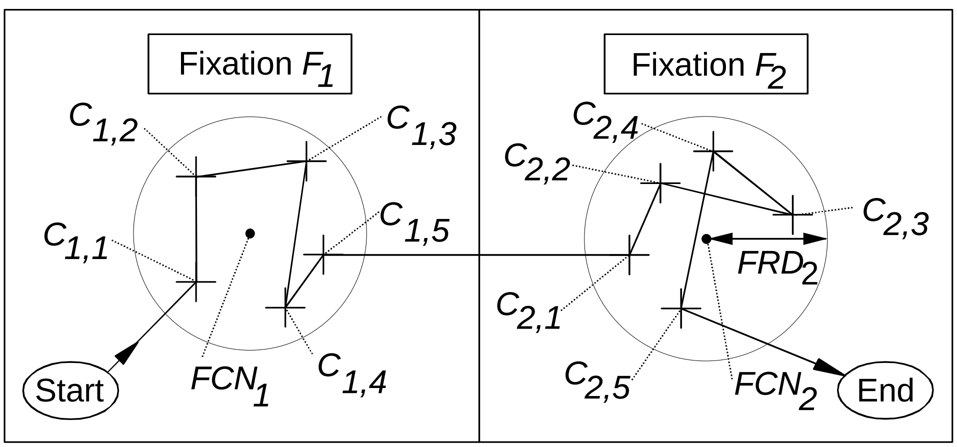
Generally, eye movements can be seen as global indicators for human information input, as long as the attention is directed toward objects in the surroundings. Eye-mark registration can record perception processes, with concrete measurements, which regularly, and often occur subconsciously. Insights about mental procedures, which can not be collected using traditional empirical methods, can thus be gained:

- A erroneous appraisal of their own approaches lead to incorrect or incomplete statements in the written and oral questionings of the subjects. The self-appraisal often does not correspond with the objectively recorded measurement data. Inappropriate actions are often subjectively rated contrary to that which is determined in objective analyses.
- With highly automated actions which are already strongly trained, a stored action programme replaces a conscious execution of the individual actions. Skill-based behaviour (cf. Rasmussen´s Model, e.g. Rasmussen 1986) is unconscious and can usually not be expressed verbally in the interviews.

- Due to the inaccuracy of the direct observations of the eyes by an observer, only rough insights can about the test person's eye movements can be gained.
- During an interview with a test subject, conducted upon completion of the examination, behaviour patterns can only be reconstructed in detail up until 20 seconds since the capacity of the short-term memory only allows for such a short-lived retention. Temporally preceding operations can only be reproduced in vague fragments and no longer allow for a detailed description and analysis of the operations.

2.3.3 Measurement and evaluation methods

In order to record numerical data of view positions on an object online, some definitions are necessary. First of all, this concerns the definition of a fixation (figure 3). A fixation may consist of a number of view positions. If there are more than 5 view positions in a circle with a radius of 7 mm we count them as 1 fixation. All distances between fixation points are measured from the centre of this circle. In order to exclude view positions without any mental information processing, a fixation must have a minimum duration of 200 ms.



Legend:

$C_{i,j}$	View position *j* of fixation *i*
FCN_i	Centre of fixation *i*
FRD_i	Radius of fixation *i*

Assumptions:

Radius of fixation *FRD = 7 mm*

Minimum duration of fixation *= 200 ms*

Figure 3. Definitions of fixations for eye movement registration

In order to evaluate user interfaces it is necessary to define areas of interest. This refers to those parts of a screen in which a defined class of information is placed. Thus, several fixation points can be found in one area of interest. Fixations in one area of interest following one after the other is called a gaze. For certain applications, in particular when monitoring technical systems, sequences of screens or screens with dynamically changing information items are to be observed by the user. For this purpose, scenes have to be defined, including the transition from one scene to another. One specific measure of this is the initial fixation in a scene (Stowasser 2002). It numerically describes the extent to which orientation in the scene is required from the user.

From the eye tracking device itself, only the view points of a user are recorded. From this raw data, the fixation and gazes are calculated using special evaluation software. This data can be further processed (figure 4). For example, view paths for a certain time period of the observation can be traced. A so-called Sankey-diagram may show the strength of gazes between the areas of interest. This kind of diagram is well known from material flow investigations.

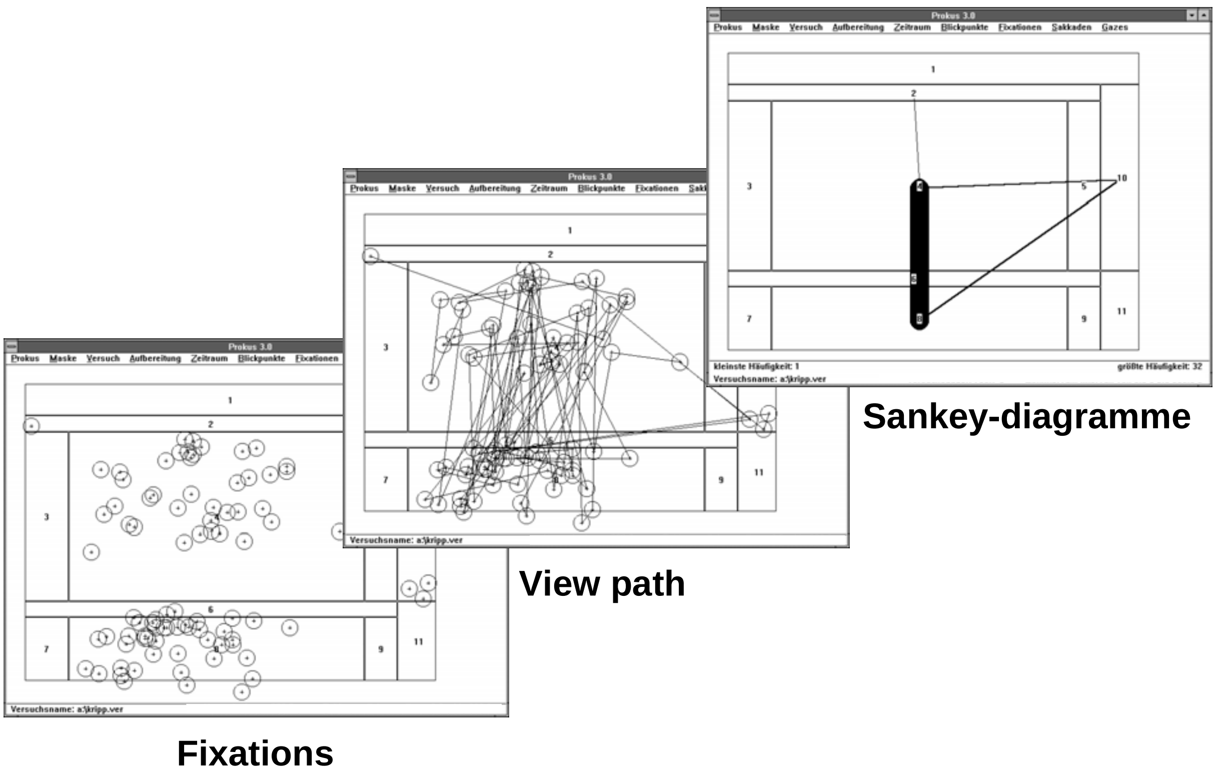


Figure 4. Evaluation methods for eye movement registration

The following are among the most important eye movement registration variables which can be recorded with the described procedure (see Stowasser 2002):

- Total processing time
- Number of fixations
- Average number of fixation per unit of meaning
- Average length of the fixations
- Total fixation duration
- Fixation rate

- Average initial fixation duration
- Average saccadic length
- Total view path
- Average saccadic maximum velocity
- Average saccadic maximum acceleration

2.4 Investigated Shop Floor Tasks and Test Persons

Twenty test persons took part in the test series, of which 10 test persons (average age of approximately 38 years) are active in the area of industrial planning and controlling. The test persons from this target group are referred to as "industrial practitioner" in the following. Furthermore, 10 students (average age of approximately 26 years) from the mechanical engineering, economic science and electrical engineering branches also took part.

In order to evaluate the aforementioned working hypotheses experimental examinations, using the evaluation methods mentioned before, will be carried out. The tasks to be executed by the test persons are derived from operative shop floor controlling, meaning from the surveillance and securing of dynamic shop floor processes. In the examination each test person must complete six test tasks in a predetermined order. Each test task z is comprised of a series of operative shop floor controlling tasks. Figure 5 shows, as an example, the sub-tasks of the test task 4.

Task 4

Sub-task 4-1 (provided time: 3 min)

Familiarize yourself with the shop floor (orders, machines, etc.)! Explore the shop floor and its objects!

Sub-task 4-2 (time limit: 30 s)

Check the quality of the products in orders O4 and O7!

Intermediately UNPREDICATABLE EVENT:

Tool breakage at lathe 4.

Sub-task 4-3

Assign the order A3 to lathe 7!!

Sub-task 4-4 (time limit: 90 s)

Surveil the states of all 10 machines and label these states!!

Intermediately UNPREDICATABLE EVENT:

Disturbance at lathe 3.

Figure 5. Sub-task sequence exemplified with test task 4

3. Results of the Evaluation Study

3.1 Subjective Assessment of Strain

Figure 6 shows the average subjectively perceived strain *SPS*, dependent upon the respective test task *z*. The ascertainment that the subjectively perceived strain, averaged for all test persons, increased highly significantly with an increase in the test complexity, verified by the non-parametrical Kruskal-Wallis-Test $\chi^2 = 49{,}412; df = 1; p = 0{,}000$.

The fact that the test persons' subjective strain perceptions were influenced significantly by the visualization form ($\chi^2 = 5{,}178; df = 1; p = 0{,}023$) is relevant for the evaluation of the visualization forms. The average subjectively perceived strain increases with increasing task complexity from "minimal" to "moderate" to "strong" with the use of the window-based visualization form. Averaged for all test persons, the test persons perceived a "moderate" level of strain when using the window-based visualization form.

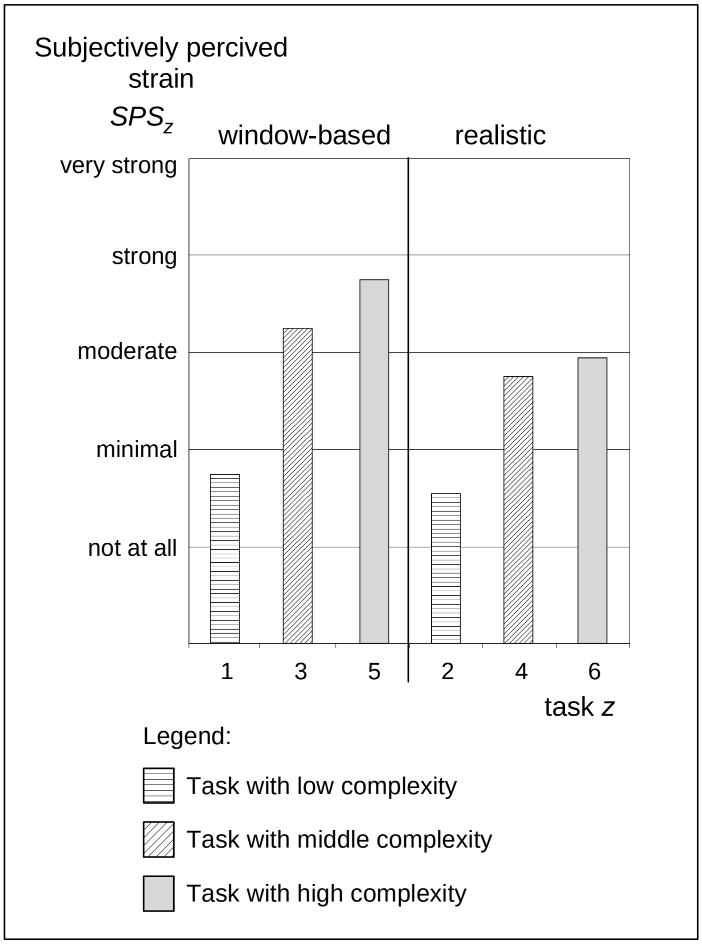


Figure 5. Average subjectively perceived strain SPS_Z

The average subjectively perceived strain roses from "minimal" to "moderate" (with increasing task complexity from low to middle) with the use of *VISOR*. In contrast to *FEWER*, the average for all test persons was rated as "moderate", even with higher task complexity. The processing of the shop floor controlling tasks using *VISOR* was averaged for the scenarios 2, 4 and 6 and were rated as "minimally" strenuous. The Kruskal-Wallis-Test which was carried out lead to the statement that no significant differences between the answers from the industrial practitioners and the students were present ($\chi^2 = 3{,}435; df = 1;\ p = 0{,}064$). Thus, the test person type had no influence upon the subjectively perceived strains.

3.1 Influence of the Visualization upon Eye-mark Registration Variables

The performed analysis of variance shows that the visualization form (window-based or realistic) has significant or ever highly significant influences upon the parameter values of numerous eye-mark registration dependent variables. Figure 6 summarizes the intra-subject effects of the visualization form upon eye-mark registration dependent variables. It lists the arithmetical means of the dependent variables (for all test persons) for a comparative assessment.

The average total processing time *TPT* is higher in the window-based visualization forms. The average fixation duration *ANF* is the most frequently used eye-mark registration key figure for the assessment of the visual information uptake. The evaluation of the examinations shows that the average fixation duration is considerably higher when the window-based visualization form is chosen for the operative shop floor controlling. The prolonged fixation duration in comparison with *VISOR* is a clear indication of a higher cognitive strain for the test person when using the traditional, window-based visualization form. According to Unema (1995, p. 161), the increased fixation duration is a result of the increased cognitive performance in information processing caused by a lower compatibility of the visualization form with the user's mental model.

Considering the topology form Lochner and Nodine (1987) in which searching and processing fixations are differentiated, it can be seen that the generally, cognitively less strenuous searching fixations play a major role when the reality approximation visualization form is used (average fixation duration 256 ms). According to Zülch, Fischer and Jonsson (2000) the searching process is comprised of the steps "recognition of an object", "comparison with a mental pattern" as well as "decision as to whether or not the considered object is the object sought". When the mental pattern of the considered and sought object do not correspond a further object is focused upon. This process is repeated continuously until the mental pattern corresponds with the considered object, meaning the searching process becomes longer.

In contrast, the fixations analysed during the use of the window-based visualization can better be classified as processing fixations (average fixation duration 330 ms), requiring more cognitive performance from the user when compared with searching functions. The user is continuously thrust into new situations in the window-based visualization form, for which often no practical action guidelines for the use of the shop floor controlling system are available. Even though the basic graphic structure of the window technique generally remains constant, new situations mainly result from the fact that the user is constantly required to reinterpret and reprocess the information, predominantly represented as text.

Dependent variables			Arithmetical mean		Signifi-cance
Notation	Formula symbol	Unit	Window-based	Realistic	*p*-value
Total processing time	*TPT*	s	353	341	0,010 *
Fixation related variables					
Number of fixations	*NFX*	1	918	1170	0,000 **
Average number of fixation per time unit	*ANF*	1	30	32	0,077
Average fixation duration	*AFD*	ms	330	256	0,000 **
Total fixation duration	*TFD*	s	267	275	0,175
Fixation rate	*FIR*	1/s	2,6	3,4	0,000 **
Average initial fixation duration	*MID*	ms	330	258	0,001 **
Saccades related variables					
Average saccadic length	*ASL*	°	19,7	22,9	0,000 **
Total view path	*TVP*	mm	132.665	173.160	0,000 **
Average saccadic maximum velocity	*ASV*	°/s	328	561	0,000 **
Average saccadic maximum acceleration	*ASA*	$°/s^2$	42.542	94.947	0,001 **
Legend: * significant influence of the visualization with *p < 0,05* ** highly significant influence of the visualization with *p < 0,05*					

Figure 6. Intra-subject effect of the visualization on the eye-mark registration dependent variables

The key figure fixation rate *FIR* is tightly connected with the average fixation duration and is used to determine how many fixation are registered per unit of meaning. The fixation rate provides insights regarding the frequency of glance jumps. The use of the realistic shop floor results in a considerably higher fixation rate of 3.4, compared with 2.6 in the window-based visualization. The exploration of the realistic shop floor representation tends to result in the need for a greater number of shorter fixations. In contrast, the processing of shop floor controlling tasks using the window-based system leads to a smaller number of longer lasting fixations.

The visualization form also has a highly significant influence upon the average initial fixation duration *MID*. The initial fixations indicate the first cognitive access of a new impulse situation: the average initial fixation duration *MID* tends to be longer the more complex a new situation is for the user. The examination shows that that the recognition of a new scene in the window-based visualization form produces a greater strain upon the user's cognitive system. The user must produce a higher performance intensity in order to recognize information on the user interface as is the case with the realistic visualization form. The correlation can be explained by the fact that the window-based user interface masks generally remain unchanged (information, control, processing and notification sections), is however not mentally compatible with the user's spacial, geometrical conception of the shop floor. Thus, "new" scenes must first be interpreted by the cognitive system. In contrast, the realistic shop floor visualization distances itself from such pre-defined mask structures; the shop floor is thereby represented in a manner which is compatible with the user's mental model. This results in less strain to the memory when exploring new scenes and can thus lead to performance advantages (Dutke 1994).

The analysis of the saccades related key figures leads to the following comparisons: The realistic visualization leads to a larger average saccadic length *ASL*, a longer total view path *TVP*, a higher average saccadic maximum velocity *ASV* as well as a higher average saccadic maximum acceleration ASA than the window-based representation. The reasons for the larger saccadic length and thus the longer total view path are possibly:

- The use of the realistic visualization form leads to larger glance leaps (saccadic lengths) since the entire user interface is taken up by the realistic representation of the shop floor. In the window-based representation the information is represented in relatively small window areas and thus require no glance leaps.
- Various investigations (cf. e.g. Williams 1982; May et. al 1990, pp. 75) show that the saccadic length is reduced with a higher stimulus complexity and strain to the cognitive system by the user interface. This supports the results derived from the analysis of the average fixation duration which states that the user strain is higher when using the window-based visualization form than when using the realistic form.

The strikingly low average saccadic maximum velocity and acceleration can also be interpreted as an indicator for a higher cognitive strain to the user when processing shop floor controlling tasks with the window-based visualization form.

4. Discussion and Consequences

4.1 Window-based versus Realistic Visualization

The evaluation of the experimental examination shows that the average fixation duration is, with high significance, lower when the realistic shop floor visualization form *VISOR* is used than with the window-based visualization form *FEWER*. Spatial-graphical representations thus lead to a faster processing of shop floor information, in turn lessening user strain. The process-orientated information for operative shop floor controlling can be perceived more quickly with realistic forms of visualization. Accordingly, the interpretation of information upon the respective cognitive action level is simplified for the user. This can be seen in particular through the orientation of the user in less complex tasks. The user's mental model is represented suitably with the realistic shop floor representation, which can then be seen in the performance enhancement (lower total processing times, shorter total mouse paths).

The assessment of the average initial fixation duration *MID* supports the assumption of the working hypothesis. The average initial fixation duration, referring to the average time required for user orientation within a new scene, is highly significantly shorter when *VISOR* is used than is the case with the window-based representation. Apparently the new impulse situations in the operative shop floor area can be perceived and processed, at cognitive levels, more quickly when realistic representations of the shop floor are used.

This ascertainment can be supported, in particular regarding tasks with higher task complexity, by that Keystroke Recording key figure, which can sometimes be interpreted as equivalent, the time until the first user action. Correspondingly, less time passes before the first user action in the realistic visualization form.

The results of the experimental examination clearly show that the form of visualization is markedly important for the cognitive performance of and the strain to the user during the execution of shop floor controlling tasks. Shop floor controlling systems should reflect the user's individual mental model of the shop floor to be controlled. The compatible representation of mental models, upon which the shop floor worker's cognitive operation planning is based, is suitably supported by the realistic visualization. The realistic visualization also supports the transparency of the shop floor events, in a user-friendly manner, in the configuration of Human-Computer-Interfaces. In particular the dynamic sequences (such as e.g. processing sequences on an order at a machine) can be surveyed using realistic elements. Particular attention must be paid to this circumstance, especially when the user is only very infrequently confronted with the shop floor controlling system, which is oftentimes the case.

4.2 Task and Information Dependent Visualization

The examinations also show, however, that the realistic visualization is not preferred for all operative shop floor controlling tasks. The choice of information coding and visualization is thus dependent upon the type of task and the information required for it.

The window-based visualization was preferred in:

- Location of concrete order, personnel, and customer data, as well as
- Tasks with highly sequential procedures which are based on text information, such as e.g. the execution of disturbance eliminations according to work instructions.

The test persons preferred the realistic visualization mainly for the execution of those tasks for which a spatial perception of the shop floor and of the object arrangement must be supported and for those for which a general overview of the shop floor is advantageous, e.g.:

- industrial resource surveillance,
- order tracing,
- recognition of the shop floor process status,
- registration of errors arising in the shop floor process, as well as
- controlling tasks.

4.3 Hybrid Visualization of the Shop floor

The advantages of both forms of navigation, in other words the realistic and window-based forms, can be combined in a hybrid visualization form using multiple information coding. Order and organizational principles, meaning a hierarchical structuring and semantic grouping of the shop floor objects, can thereby be achieved. Additionally, already present, realistic perception experience, stored in the form of a mental model, can be supported by the realistic representation.

Figure 7. Hybrid visualization of the shop floor

The hybrid shop floor visualization thus takes the cognitive psychological position, that human thought processes are marked by concentration on local detail and by a global overview of important information, into account. This should make it possible for the user to apply the visualization form most suitable for him and to dynamically vary it depending on the task, information needs, individual preferences and personal abilities. This requirement is also fulfilled by adaptive visualizations.

Figure 7 provides, as an example, the vision of a hybrid shop floor controlling visualization. The text-based, hierarchically arranged object list allows for a quick object-orientated access to a sought shop floor element. A realistic animation of shop floor occurrences, through the effect of immersion, and the visual-spatial representation would enhance this even further. Disturbances in the shop floor process, error messages and alarms would have to be shown repeatedly and coded in various forms. (e.g. pop-up disturbance dialogue).

In the future, such systems must be further developed, whereby the consideration of software ergonomic insights is imperative. Prospective research work should determine the degree of detail, between realistic (photographic) illustrations and abstract (sketches), which is reasonable within a given application context. Furthermore, it must be evaluated to what extent the application of Augmented Reality, meaning the Human-Machine-Interaction without the use of monitors, is task suitable and functional for use within the area of shop floor controlling.

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