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STRUCTURED EYETRACKING-BASED REQUIREMENTS VALIDATION WITH THE HELP OF VIRTUAL PROTOTYPES

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ABSTRACT

Customer requirements form the basis of every product development project. Incomplete requirements and lack of involvement of customers are the main factors for the failure of a product at the buyer's market (Hull et al. 2011). The Quality Function Deployment (QFD) describes a common method for translating customer requirements into product features. For this purpose, the QFD provides various matrices for the prioritization and quantification of the requirements, through the various phases of the product development. The first customer tests are carried out with physical prototypes in the later phases of the PEP. These allow the validation of the customer requirements and the verification of the fulfillment of the customer requirements by the product characteristics (Rupp 2014). This occurs at a time when the influence on the product to be developed becomes smaller. Virtual product presentations provide an opportunity to simulate the first findings about the product characteristics and functions early in the product development process. Due to the functional support, the virtual prototypes allow a real-time interaction by the test persons. Thus, it becomes possible that digital images of products can be interactively experienced. Operating units of technical devices and their operating concepts can be analyzed early on their intuitive use. Product features of virtual prototypes can be analyzed in a highly immersive stereoscopic virtual space. The generated virtual prototypes could query the actual areas of interest of the customer in connection with an eye-tracking system.

It is unclear whether the various visual perceptions of the prototypes differ between the virtual and the real world and thus unsatisfactory validation results can occur. A study already planned by the department will reveal possible differences in perceptions. Two-dimensional (2D) monocular eye trackers already allow to analyze the focus of attention and the perception of the customer (Duchowski 2007). By measuring the fixation points (particular sighted point in space), fixation duration, saccade (short jumps from one fixation to the next) and the fixation order, conclusions about the attentional processes of the subjects can be drawn (Rey, 2015). In the three-dimensional simulation, the estimation of binocular eye-tracker still poses major challenges, as with the third dimension the stimulus now will be extended to another level, the depth.

In this context, it should be discussed whether the perception of virtual prototypes can be equated with physical prototypes. The necessity and characteristics of a comparative study to investigate the perceptions of both 3D VR and the reality is derived and described. The test objectives and test design are explained.

Keywords: Customer requirements, product development, QFD, virtual prototype, 3D virtual reality, eye tracking

INTRODUCTION

The trend to ever more customized products has a big influence on modern quality management. In particular, the focus on customer requirements to date has clearly gained in importance (Crostack, 2011). The quality of a product by now is regarded as one of the main factors for the market success of a company (Brüggemann, 2012). The term "quality" describes how much a product fulfills its requirements (ISO 9000, 2015). For a high quality thus the knowledge of customer requirements and their weighting is indispensable.

The needs of customers and stakeholders are the basis for product development. Based on this, the properties of a product are derived. The Quality Function Deployment describes a procedure for this purpose (ISO 16355, 2015). In spite of the use of this method there is often a deviation from the requirements of the customers of the developed products and therefore definitively a lower quality. This is due to a multiplicity of uncertainties and assumptions concerning customer requirements because of hidden (unconscious) needs of customers (Cooper, 2005; Jockisch, 2009) and the "translation errors" from the developers. These hidden requirements cannot be consciously articulated by the customer (Jockisch, 2009) and therefore are very difficult to define. In addition, all contexts of the requirements must be known in order to fully describe a system (Rupp, 2014). Missing interdependencies lead to uncertainties and misinterpretations in the product development. Today's products are subject to many complex connections, therefore it requires special efforts to clearly illustrate the requirements structures.

A success factor of a company becomes the consideration of current customer requirements and needs. These requirements must be checked systematically with the developed product characteristics in the early stages of product development. As a result it is necessary to involve the customer as early as possible in the request validation. Thus, misunderstood or misinterpreted requirements can be detected at an early stage and low product quality can be avoided.

STATE OF THE ART

A key factor is to involve the customer in the product development to produce high-quality products. In the early stages of the product development process the possibility to take influence on the product is very large (see figure 1). That is why it is important to involve customers in the early phases. However, the customer requirements can currently be validated mostly not until real prototypes are available (Rode, 2011). This takes place at a time when the influence on the final product is lower. Virtual product presentation, offers the possibility to yet simulate first initial findings on the product features and functions.

Virtual prototypes describe digital mock-ups and expand these to functions and physical properties. It is possible to carry out analysis and simulations with the virtual prototypes, which are comparable to those of real prototypes (Tiainen, 2014). Due to the function support the virtual prototypes allow a real-time controlled interaction by test persons (Wang, 2002). The necessary data for the creation of virtual prototypes are already qualitatively developed in the design phase and thus are available at an early stage. If it is possible to use the virtual prototype to check the customer requirements, this information could be evaluated in the product development process much earlier.
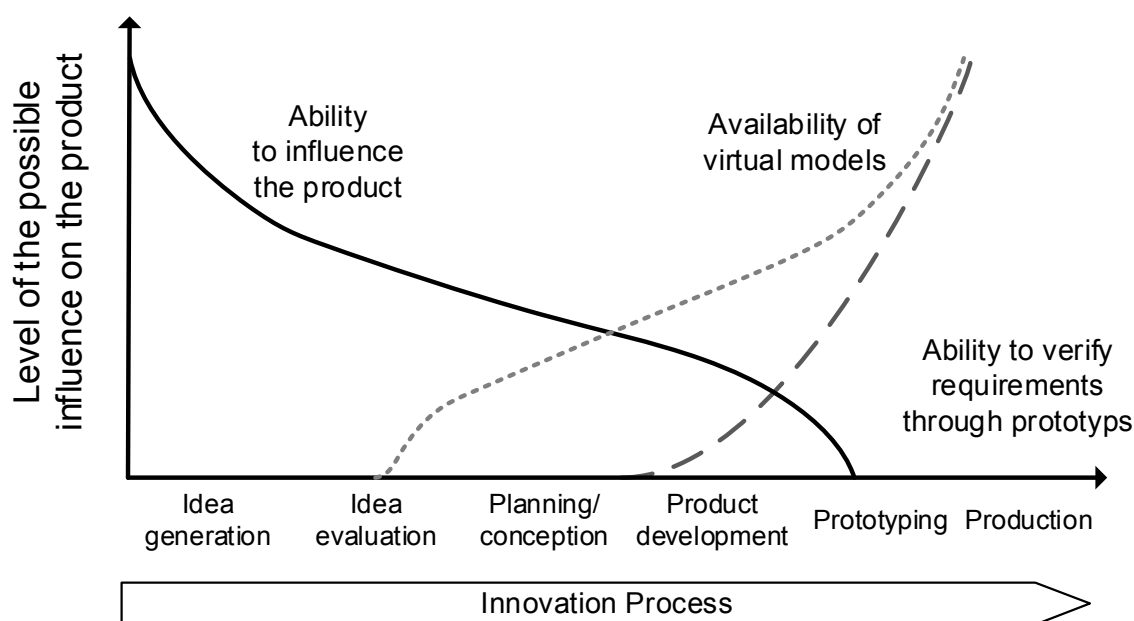
Fig. 1 - Optimization potential with early requirements validation in the innovation process (Rode, 2011)

The final product design has not yet been fully developed in the concept phase. Nevertheless, the customer can already give valuable feedback with the available information. By creation of the virtual prototypes it must be taken into account that mainly the visual perception of the test person can be addressed. Although the visual sense is the most important sense in the human perception (Fels, 2015), it restricts the virtual prototype testing. Product features can only be described optically. For successful use of virtual prototypes uniform design guidelines must be also followed, in order to improve the close-to-reality models (Bordegoni, 2013). Then designers, engineers and end users could use a virtual prototype for evaluating the aesthetic quality, its functions and its usability aspects.

A solution space to identify the customer requirements virtually, could be found in the combination of different methods and tools. Below existing approaches are explained which cover several areas of the problem.

The three dimensional virtual reality (3D VR), in which stereoscopic three-dimensional models can be shown, are already used in big companies for product development (Huber, 2014). By means of the depth effect and a high interaction radius through a simulation of the product model in real-time the degree of immersion increases. The high degree of immersion of such interactive systems allows the user a very accurate perception of the product model represented and a good understanding of product features and functions of virtual prototypes. Up to now tools are missing for the evaluation of main areas of interest of customers in the three-dimensional virtual space. Research results have shown that the visual perception and eye-movement strongly correlate with each other (Fels, 2015). Eye tracking allows to record the eye movements of test persons. Thereby recorded fixations, saccades and binocular movements can be evaluated. Two-dimensional (2D) monocular eye trackers already allow to analyse the focus of attention of the customer (Duchowski 2007; Pfeiffer, 2008). By measuring the fixation points (particular sighted point in space), fixation duration, saccade (short jumps from one fixation to the next) and the fixation order, conclusions about the attentional processes of the subjects can be drawn (Rey, 2015).

Heat maps for instance visualize the focused points and thus permit statements about the customer interest (see figure 2). Gaze plots describe besides the fixation duration the look-saccades in the form of lines. Thereby numbers describe the view sequence.

Fig. 2 -:Exemplary illustration of a heat map on the left and a Gaze plots right (Strandvall 2017; Rey, 2015)

The three-dimensional (3D) representation is still a challenge for the evaluation of binocular eye trackers. With the third dimension, the stimulus is extended by a new level, the depth. Furthermore, eye-tracking studies prove that the human perception changes with increasing closeness to reality. The scenery is looked at differently, the view in the 3D environment is less focused than on a 2D screen, which is also reflected on the heat map in figure 3. A larger area is scanned with the eyes, but with significantly shorter fixation times. In the 3D environment more easily shaded areas are found, while in the 2D environment the intensive areas dominate. Hence, it can be seen that the fixations are more intense and longer on the 2D screen (Häkkinen, 2010). The reason is that in the 3D environment significantly more eye movements take place, because the eyes fixate more on objects than in 2D. By the depth effect objects that are usually in the background and are usually ignored as far as possible, occur in the attention span of the viewer. The number of individual fixation points becomes larger, the fixation duration less. This fact must be taken into account in customer studies.
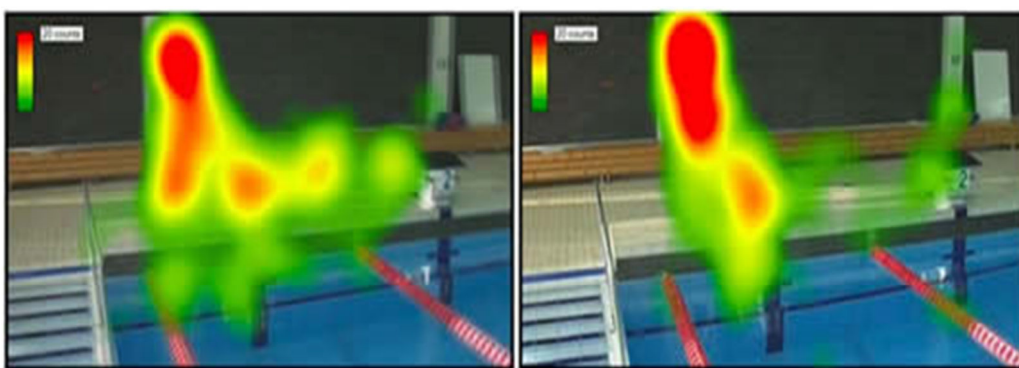
Fig. 3 - Perception in 3D (left) und 2D (right) (Häkkinen 10)

Eye tracking explorations on virtual prototypes are not comparable with real physical prototype tests. The perception differences between highly immersive stereoscopic 3D representations of products and physical products are studied in an undetermined way. Because of this it is necessary to develop a study, with which the comparability of virtual and real prototype tests for the customer requirement analysis may be examined.

Eye-tracking studies alone, without a subsequent detailed interpretation analysis cannot explain why the test person is focusing on a particular screen element or not. The method of eye-tracking is limited, it does not give an answer to the real intention of a viewer's gaze.

The quality management provides several methods to adjust the product development process systematically to the won customer requirements. For the customer orientation within the product development process in particular the Quality Function Deployment (QFD) is suitable (Pahl, 2013). The QFD is an approach for ensuring quality over the product development process (ISO 16355, 2015). The ISO 16355 -1 *Application of statistical and related methods to new technology and product development process* describes the principles.

The basic approach of the QFD is the combination of the different languages (customer, developer) about the product characteristics in terms of matrices with the aim of assuring customer satisfaction regarding new and existing products. The voice of customer (VoC) - defined as communications from the customer - continuously shall serve the company as orientation (Ehrlenspiel, 2003). QFD can use different types of matrices for prioritizing and quantifying different requirements during the various phases of product development. One instance of such a matrix that serves as a communication medium is the House of Quality (HoQ). In the House of Quality matrix, weights quantify the relationship or contribution between customer needs and functional requirements (ISO 16355, 2015). This matrix enables the implementation of both functional requirements and customer needs into structured and technically feasible features (see figure 4). In the first instance the question "WHAT does the customer want" should be translated into "How can the company resolve the requirements?" (Brüggemann and Bremer, 2012).

Fig. 1 - House of Quality

The QFD process includes a classic sequence of steps, which are stated differently in various literatures. The QFD Institut Deutschland describes this sequence as followed:

1. Estimation of customer requirements

2. Competitive comparison by customers

3. Development of constructional interpretation requirements and product characteristics from customer requirements

4. Determine the correlation between customer requirements and product characteristics.

5. Determination of customer-oriented technical importance of the individual product characteristics

6. Determination of the correlations between the product characteristics

7. Analysis of the HoQ (QFD-ID, 2016)

If this standard is realised consistently, it rudimentarily can be ensured that customer requirements are implemented and remain comprehensible in the product development process (Ehrlenspiel, 2003). The modern QFD after ISO 16355 -1 combines the steps with quality and product development methods, which accomplished the approach. Thereby is the modern QFD custom-tailored to find the minimum effort. The flow of methods may vary according to the organization requirements (figure 5).

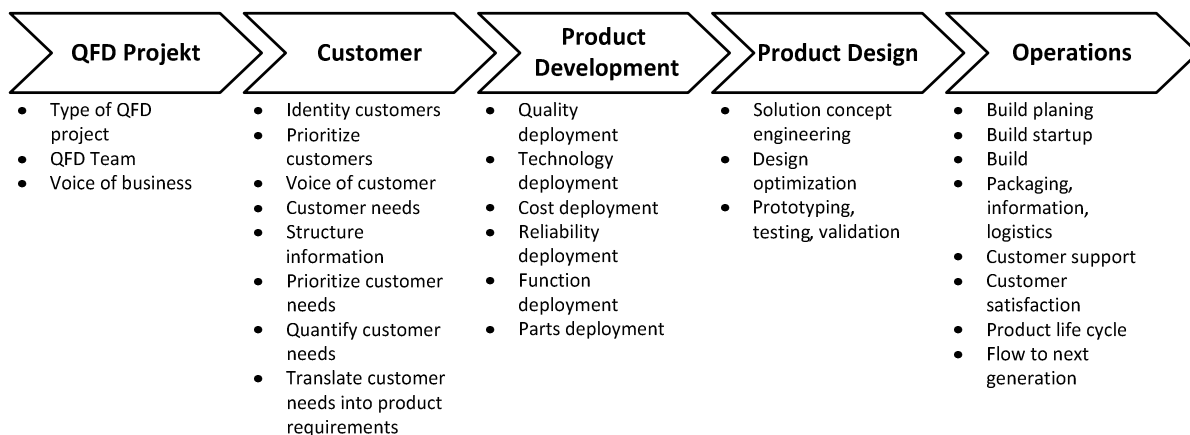| QFD Projekt	Customer	Product Development	Product Design	Operations
• Type of QFD project • QFD Team • Voice of business	• Identity customers • Prioritize customers • Voice of customer • Customer needs • Structure information • Prioritize customer needs • Quantify customer needs • Translate customer needs into product requirements	• Quality deployment • Technology deployment • Cost deployment • Reliability deployment • Function deployment • Parts deployment	• Solution concept engineering • Design optimization • Prototyping, testing, validation	• Build planing • Build startup • Build • Packaging, information, logistics • Customer support • Customer satisfaction • Product life cycle • Flow to next generation

Fig. 5 - Flow chart of product development with QFD (ISO 16355, 2015)

The choice of methods is orientated on the respective product development process. The German QFD institute describes a best practice flow diagram (figure 6). In the graphic meaningful links of modern development techniques are presented with the QFD process. The rigid use of the HoQ is equalized by various matrices too.
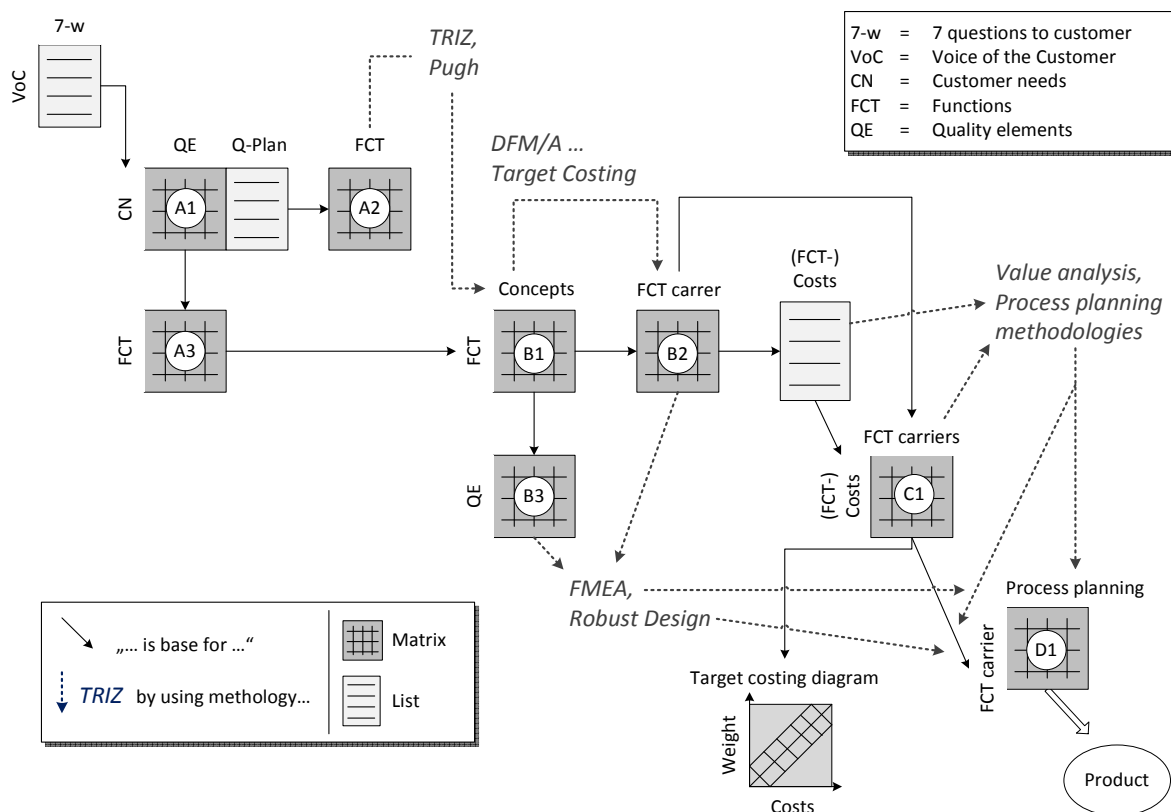
Fig. 6 - German QFD institute best practice flow diagram (ISO 16355, 2015)

Although the requirements in the modern QFD can only be brought to the first matrix, an iterative examination is not provided. But if there is a misunderstanding in the emphasis of the requirements, the development can fail the customer requirements.

From these considerations, the following challenges for early validation of customer requirements can be derived:

1. Virtual prototypes in conjunction with binocular eye-tracking will probably provide an opportunity to determine the customer interests. The analysing of customer requirements inside three-dimensional virtual space is technically still in the research stage and not to solve without appropriate methods.

2. Virtual prototypes must be simulated very realistically. Therefore a high degree of immersion is required which must be generated by a three-dimensional virtual reality.

3. The suitability of stereo three-dimensional eye-tracking studies has to be compared with studies of physical prototypes to guarantee comparability.

CONCEPT

The motivation of this research is to solve the described challenges to enable the early requirements' validation by means of virtual prototypes. Therefore the urgency of a study, which examines the differences of perception in 3D VR and the reality, will be explained. The stereoscopic virtual reality enables users to experience products in digital form (Huber, 2014). Thus, the process of customer requirement validation can be successfully brought forward in the product development process, the presentation options have to be determined by

conceptual characteristics. As CAD data are already made in the design phase and have different parameter values, the focus can be placed on their involvement. For use and interaction with virtual prototypes a software needs to handle 3D CAD data and additionally calculate the simulation in real time. Engines like Verosim, Unity or Unreal are suitable for this purpose. This would allow the application of virtual prototypes in the early stages of the product development process. By integrating into the QFD a classification is created, which could make it possible to analyse the focus of interest of the customer based on the conceptual features of the virtual prototype (see figure 7).

Requirements are correlated with quality features in the first HoQ. Thereby the characteristics of the product features can be determined based on customer requirements. Based on these characteristics, the first conceptual 3D models can be created. By linking with physical properties virtual prototypes are generated. This can be simulated with the appropriate software in the 3D VR. When customers now interact with these virtual prototypes, their focus of interest may possibly be pursued by the eye-tracking. Thereby the methods of the classic requirements management (interview, observation) help to classify the respective focuses. So it might be possible to adjust the emphasis of the requirements from the HoQ with the actual emphasis of the characteristics of the eye-tracking analysis.

This extra loop allows an agile approach with the QFD. This adjustment of the focuses would allow to transfer a product model influenced by the developer point of view in a customer-oriented way into the next phase of the components planning.
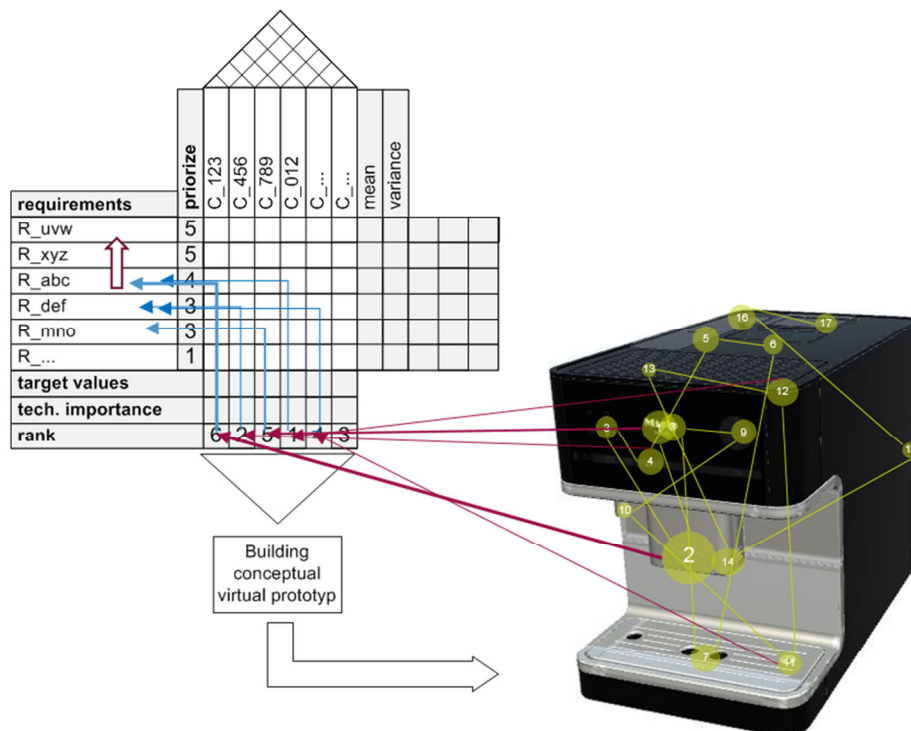

Fig. 7 - Schematic representation of a VR extended QFD

The added value is a product development which is geared more closely to customer requirements, which can react much earlier to changes. The aim is a high quality product and with it an increased customer satisfaction. The essence of the success of this approach is the evaluation and interpretation of eye-tracking in 3D space. This means that the eye movement of both eyes must be recorded. Accordingly, the depth could be analysed and thus the spatial

preposition (before vs. after) could be determined. 3D plots could be generated, in which also the view direction is considered (Uni Magdeburg, 2015), which would result in more meaningful eye-tracking data, and thus more accurate insights into the interests of customers.

It remains unclear whether the increased significance, is analog to the physical prototypes. This circumstance is to be analyzed by a comparative study. The following process chart (figure 8) describes the theoretical course of the study. In this study, test persons will be faced with corresponding physical and virtual products. Here the focus is on visually perceptible product characteristics. A binocular eye-tracking shall record the eye movements of test persons. This enables developers to draw conclusions from perceptions and preferences. Further comparisons of the virtual und physical studies will give a statement about the accordance.
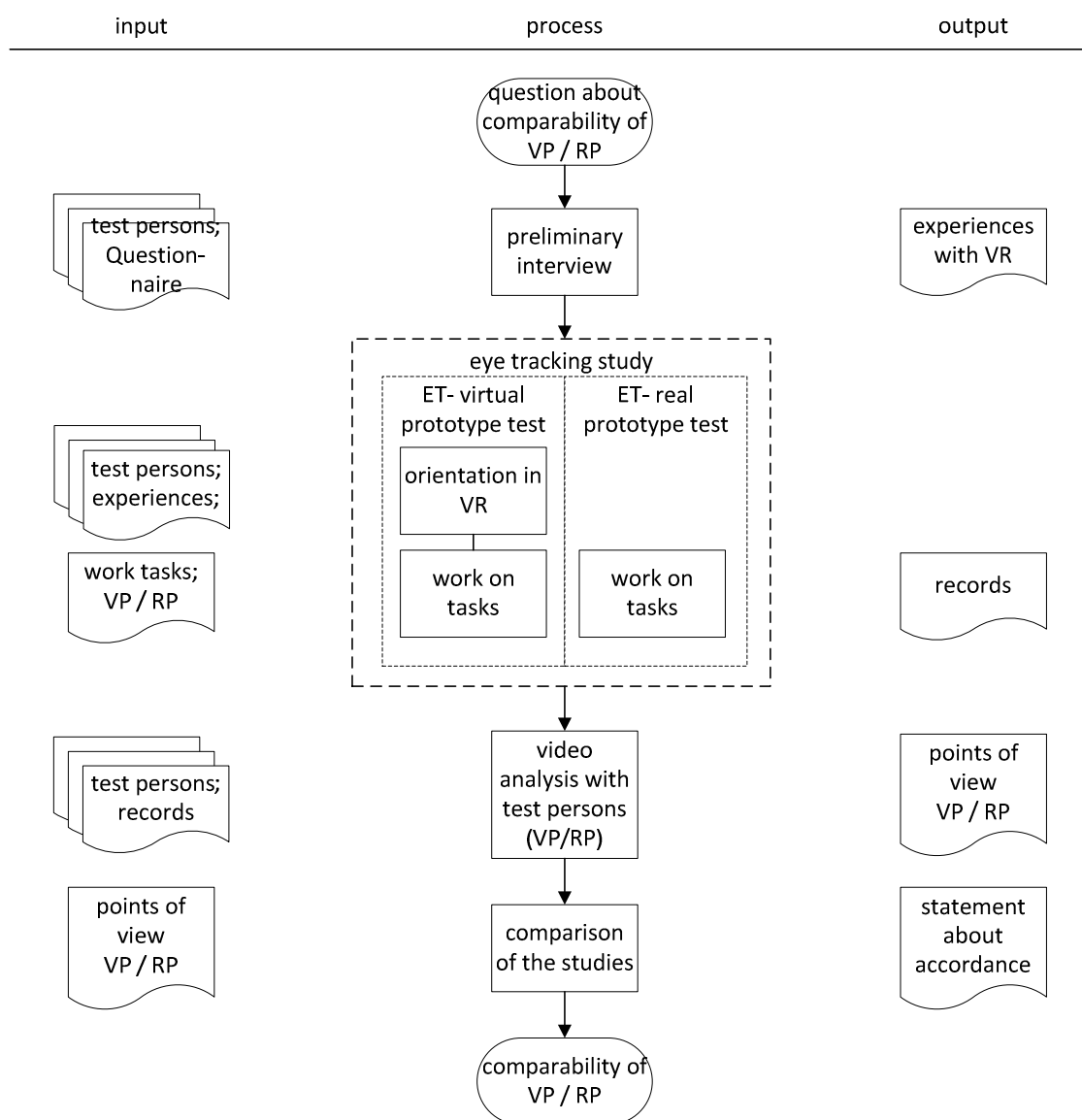

Fig. 8 - Process chart regarding the course of the study

For this study standards need to be developed for comparable results, which can be described as follows.

Set-up of the product model (virtual prototype)

The aim is to assure that the general appearance of the virtual product model matches the real product. Size conditions must be adapted 1:1 in order to ensure a high immersion. Colours must match so that there cannot be unwanted distractions. Functions must be deposited and able to be used interactively in real time. When selecting the product it is important to make sure that this will not pose problems in a 100" power wall. A fully automatic coffee machine meets these requirements and can be well simulated. The operating concept varies between models and can be used for this study. The virtual reality technology serves as a tool to carry out experiments as well as exploratory tests and to collect data. (Di Gironimo et al. 2013, p. 361) Repeatable, valid data, in order to gain connections and insights, serve to reduce the difficulties of understanding within the product development process. They therefore promote risk minimization within development.

Set-up of the test environment

The virtual test environments should match the real test environment, potential distractions must be eliminated. The input devices to interact with the virtual prototypes play an important role. Rademacher describes an attribution of input devices to the specification of VR-work systems. Here, the power wall creates a highly collaborative environment, a joystick/gamepad for intuitive input is recommended (Rademacher, 2014). A gesture control could make input more intuitive. For the planned series of tests a gamepad is used as many test persons have previous experience with this input device.

Choice of the test persons

The people need to be clustered according to their previous knowledge. A different level of experience of the users with the VR can lead to various scene evaluation. Initial tests have shown that the experience of using a gamepad allows a completely different interaction with the virtual prototypes and thus provokes different results. Experience in the use of S3D models also significantly contributes to the acceptance in handling virtual prototypes. For clustering the test persons in advance short questionnaires are issued, in which the handling of input devices and the experiences are requested using virtual reality. On the other hand, the demands of the ISO 16355 must be considered to the customer selection of QFD projects. In the ISO 16355-2:2016 various methods and tools are presented, how customers and their voice can be determined.

Set-up of the test procedure

Essentially, two different approaches can be used. On the one hand it is possible to set features specifically in scene and consciously scrutinize requirements on the other hand product models can be used to detect unconscious areas of interest and to derive new requirements. In this case, an operating concept should specifically be tested on intuition. The test persons are given clear tasks, which are independently processed by them and analysed by eye-tracking. The test periods should not exceed 5 minutes. For comparable records the tests must be completed both in the virtual and the real environment. To filter a learning curve in the use of the operating unit, two groups are divided. Both groups pass through the series of tests in different order.

Assessment flow

In the evaluation of the tests, a two-stage approach is recommended. Here, the eye-tracking data are recorded and stored. Following the tests, the test persons face their recorded eye-tracking data. The test person has the opportunity to comment on his intentions during the test and equalize this with the recorded aspects. Thus, deviations of the eye movement can be determined. Thereby the flow of the core study can be described as follows:

1. Preparation of the study: Within the preparation of the study, test scenarios are defined at the beginning. Then, the methods to be used in the integration concept will be selected and adapted the test concept. The scope of the experiment and the selection of the necessary documents are the main component of this point.

2. Introduction: At the beginning of the study, the goal of the study is presented and the user is instructed in the course of the workshop. In addition, the participants will be presented with the basics in the form of a presentation. In addition, data protection must be provided. This consent allows data processing, collection and storage of the personal data.

3. VR Introduction: An introduction to the use of the VR system is provided for each participant. Individual components such as the input devices are displayed to the user, explained and handed over to the use of an analog model. For this purpose a task, similar to the real test conditions, is formulated. This gives the user a good overview of the required degree of interaction with a virtual prototype and the expiration of the upcoming test. In this step, compatibility with perception and interaction within a 3D environment is also considered. A questionnaire is intended to clarify the previous experience with the VR and the technical affinity of the participants.

4. Main study: In this step the main study is taken. The user is presented with a standard task and has the time to read and understand it. Eyetracking is set up and calibrated. The eyetracking shots are started and the prototype to be evaluated is displayed and handed over to the user. All conditions are controlled and recorded. The user tries to edit the work task, in this case eye tracking video, audio and screen recordings are collected and short notes are created. These help to clarify questions in the follow-up meeting and to gain more understanding of the user's expectations in order to be able to transfer them to new requirements for the product.

5. Data collection by means of questionnaires: After the main study and the product interaction, a questionnaire evaluation takes place. The survey allows comparable assessments to be obtained. General impressions about the test object can be determined by standardization.

6. Retrospective evaluation: Individual conspicuous features collected by the Eye tracking studies should be followed and interpreted by the user. It is also possible to request evaluations from the user and to specify specific system components that are linked to the evaluation targets in detail. A data collection using a partially structured interview can generate additional information at this point.

7. Completion of the study: To conclude the study, a sociodemographic questionnaire is to be completed in order to be able to classify the subjects groups. Finally, the

participation in the study will be appreciated and, if necessary, a confirmation of participation will be issued.

8. Data evaluation and report: In this step the analysis, statistical analysis and preparation of the data are carried out. Thus, comparable results can be generated. These results should be summarized in a report.

With these preparations it will be possible to carry out the studies.

CONCLUSION

The concept described here, helps to optimize the product development process. The development is more focused on customer requirements and changes are detected more early. Virtual prototypes are intended to prepone, replace and complement the physical tests. Eye tracking analyses are intended to capture the perception of the customers in the various test series and thus generate information about the actual customer requirements. This will also be used to check whether unknown customer interests can be shown up to now. In addition, early validation of requirements has the potential to shorten the product development process, since an early query of customer acceptance is possible. If there are any change requests or inconsistencies in the customer requirements, this could be reactivated even more flexibly.

However, it is unclear whether a comparability of the virtual and physical eye tracking analyzes is given. The study described in this paper is intended to clarify this fact. It is expected that the evaluation of the three-dimensional eye tracking data allows a similar statement about the customer preferences, as the physical prototypes. The virtual prototypes have to be simulated with a high degree of understanding. Today's standards of a three-dimensional virtual reality offer a high degree of immersion and are therefore suitable for the simulation of virtual prototypes.

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