Faculty II – School of Computing Science, Business Administration, Economics, and Law

Dissertation

Supporting Supervisory Control of Safety-Critical Systems with Rationally Justified Information Visualizations

A dissertation accepted by the School of Computing Science, Business Administration, Economics and Law of the Carl von Ossietzky University Oldenburg (Germany) to obtain the degree and title

Doctor of Engineering (Dr.-Ing.)

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Date of Dispuation: 19.02.2019

Abstract

The degree of automation in technical systems—for instance, autonomous driving or automatic anomaly detection in control rooms—is continually increasing. Monitoring a high amount of information in these systems becomes a major task of the human operator. Owing to the rising quantity of information, this task is becoming increasingly complex. Especially in case of safety-critical systems, supervisory control can become critical as overlooking or misinterpreting important information can easily cause serious impacts.

The information to be monitored is communicated to the human operator via the human machine interface (HMI). In this aspect, it should be ensured that the supervisor can perceive information elements indicating critical system states as fast and accurately as possible to initiate possible countermeasures in time. For systematically deriving HMIs for safety-critical systems, the state of the art lies in the application of human factors (HF) methods as well as of task analysis or ecological interface design (EID). The available methods can extract the information a supervisor needs to know (**what** has to be shown on the HMI) and deduce a structure for the HMI (**where** to show the information). However, actual HF methods do not offer a systematic approach to determine a concrete visualization of the information (**how** the information should look like). In the dissertation, a method has been developed that allows systematic derivation of information visualizations for monitoring tasks in safety-critical systems. This method is called Konect and combines scientific knowledge of perceptual skills of humans, the application of HF methods and the model-based design of HMIs. The dissertation builds upon the state of the art for designing an HMI for monitoring safety-critical systems and links HF methods to the concrete visualization of information. This systematic engineering approach is evaluated in different domains: In the automotive domain, it is evaluated to increase the reaction times for detecting automatic cruise control (ACC) failures, thereby preventing accidents in truck platoon scenarios, while it is evaluated in the maritime domain to improve vessel performance monitoring efficiency. The results reveal that the designs created with Konect performed significantly better than the non-Konect designs.

Zusammenfassung

Der Automatisierungsgrad in technischen Systemen steigt aktuell kontinuierlich an: Dabei sind autonomes Fahren oder die automatische Erkennung von Anomalien in Kontrollräumen nur zwei Beispiele. Diese Systeme müssen dabei immer noch von Menschen überwacht werden und in Zukunft wird diese Überwachungsaufgabe immer stärker zur Hauptaufgabe des Menschen werden. Aufgrund der steigenden Informationsmenge wird diese Aufgabe jedoch immer komplexer. Insbesondere in sicherheitskritischen Systemen kann die Überwachung riskant werden, da das Übersehen oder Fehlinterpretieren wichtiger Informationen schnell zu ernsthaften Auswirkungen führen kann.

Die zu überwachenden Informationen müssen dem Menschen über die Mensch-Maschine-Schnittstelle (HMI) mitgeteilt werden. Dabei muss sichergestellt werden, dass der Mensch Informationen über kritische Systemzustände schnell und korrekt wahrnehmen kann. Nur so können mögliche Gegenmaßnahmen rechtzeitig eingeleitet werden und schlimmere Auswirkungen verhindert werden. Für die systematische Ableitung von HMIs im sicherheitskritischen Bereich liegt der aktuelle Stand der Technik in der Anwendung von Human Factors (HF) - Methoden wie beispielsweise Aufgabenanalyse oder Ecological Interface Design (EID). Diese Methoden sind in der Lage die Informationen systematisch zu erheben, die ein Operator in einer bestimmten Aufgabe wissen muss (**was** muss angezeigt werden). Zudem kann eine Struktur für die Informationen abgeleitet werden (**wo** müssen die Informationen angezeigt werden). Aktuelle HF-Methoden bieten jedoch keinen systematischen Ansatz, um eine konkrete Visualisierung für die Information abzuleiten (**wie** müssen die Informationen dargestellt werden). In der vorliegenden Dissertation wurde eine Methode entwickelt, die in der Lage ist, Informationsvisualisierungen für Überwachungsaufgaben in sicherheitskritischen Systemen systematisch abzuleiten. Diese Methode heißt Konect und kombiniert wissenschaftliche Erkenntnisse aus dem Bereich der Wahrnehmungsforschung, über die Anwendung von HF Methoden und über modellbasiertes Design von HMIs. Die Dissertation baut dabei auf dem aktuellen Stand der Technik auf und verknüpft HF-Methoden mit der konkreten Visualisierung von Informationen. Dieser ingenieursmäßige Ansatz wird in verschiedenen Bereichen evaluiert: Im Automobilbereich zur Erhöhung der Reaktionszeit bei der Erkennung von ACC-Ausfällen und damit zur Vermeidung von Unfällen und im maritimen Bereich zur Verbesserung der Effizienz des sogenannten *Vessel Performance Monitoring*. Die Studienergebnisse zeigen, dass Designs, die mit

Konect erstellt wurden, signifikant schneller und korrekter wahrgenommen werden als Designs, welche mit konventionellen Methoden entworfen wurden.

Acknowledgement

In the last four years, several people have accompanied and supported me to prepare this work. At this point, I would like to express my deepest thanks to these persons:

I would like to thank my supervisor, Dr Andreas Lüdtke. Not only did he give me important advice on all aspects of my dissertation, but also taught me that one should always put people with their abilities and individual personalities first in all our activities – and that does not does not only apply to the creation of an efficient human-machine interaction. This has shaped my professional career as well as influenced me on a personal level. Furthermore, I would like to express my deepest gratitude to my supervisors Prof. Dr Axel Hahn and Prof. Dr Martin Baumann for their valuable guidance. I also thank Prof. Dr Martin Fränzle and Dr Marco Grawunder for their contributions as members of my disputation committee.

The work was developed in close cooperation with the Human Centered Design group at OFFIS. I would like to thank all my colleagues for supporting me, keeping their ears open for any questions I came up with, improving my presentations after rehearsals, and always providing an excellent and relaxed working atmosphere. I would especially like to emphasize the support of Dr Sebastian Feuerstack and Dr Bertram Wortelen with whom I discussed the scientific topic of my dissertation. They supported me in the elaboration. Without you this work would not have become what it is today.

Finally, I would like to thank my family members who had my back throughout this period. Particularly noteworthy is my husband Andreas, who was always by my side and encouraged me throughout the whole creation and writing process of my dissertation. Thank you very much!

Marie-Christin Harre

Oldenburg, 26.02.2019

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1 Introduction

In March 1979, the United States (US) faced the most significant accident in the US commercial power plant operating history [Commission, 2013]. The accident took place at the Three Miles Island Nuclear Power Plant in Pennsylvania. Owing to a chain of events, a part of the nuclear core was damaged, radioactive gases and iodine were released, and thousands of residents had to be evacuated.

Today, we are surrounded by complex technical systems in which one failure can have severe implications on human health, life, and the environment. These systems are characterized as „safety-critical systems": „Safety-critical systems are those systems whose failure could result in loss of life, significant property damage, or damage to the environment"[Knight, 2002]. This definition for safety-critical systems apply to a broad range of systems coming from various domains like medical care, nuclear power systems such as the Three Mile Island Nuclear Power Plant, aircraft, and automotive or maritime. In the last few decades, the level of automation in these systems has continually increased and the task of the human operator has changed from being the active controller to a passive supervisor. Bainbridge revealed that there are two general categories of tasks left for an operator in such a system: „to monitor that the automatic system is operating correctly, and if it is not he may be expected to call a more experienced operator or to take-over himself" [Bainbridge, 1983]. The underlying work focuses on the first category – the monitoring. The monitoring takes place to ensure that the system under supervisory control is functioning as expected and no problems or malfunctions occur. Quite early in 1983, Bainbridge revealed the often-cited *ironies of automation* that the irony of an increased level of automation lies in higher demands for the human operator in the monitoring task instead of replacement of the human by automatic devices: „The increased interest in human factors engineers reflects the irony that the more advanced a control system is, so the more crucial may be the contribution of the human operator." [Bainbridge, 1983].

1.1 Motivation

The shift from active control to passively supervising a system implies that the amount of human monitoring tasks of safety-critical systems increases. To maintain the safety of the whole system, this monitoring activity has to be supported: To monitor the state of the system, the human operator is supported by a human machine interface (HMI) on which necessary information to assess the current system state is represented visually. In case of the Three Miles Island accident, the major problem lied in this representation: Later investigations revealed problems with the reactor control system's user interface. The status of a valve was displayed in a misleading way and the visualization for a level probe control was missing. As a result, operators monitoring the system could not diagnose the problem [Norman, 2002] and behaved incorrectly. Had the interface visualized this information in a manner to enable the operators recognize the problem fast and accurately, this accident could have been prevented.

The Three Mile Island incident clarifies what has to be considered when looking at the so-called „human factor" in the field of safety-critical systems: „We human beings have design flaws. [...] Some of the qualities that make us efficient also make us error-prone. We learn to move rapidly through the world, quickly recognizing patterns but overlooking details" [Hallinan, 2010b].
In case of the monitoring task, this applies for different sides: On the one hand, we have the *human operator* conducting the monitoring task. He/she might overlook important information or recognize information too late to be able to execute countermeasures in time—e.g. in case of autonomous driving cars, the driver must react in seconds, given a sensor or other technical equipment failure, so that he/she is able to break immediately to prevent an accident. On the other hand, we have the *human machine interface designer* who decides which information needs to be shown on the HMI, how this information should be structured, and how the exact graphic representation should look like. During HMI design, the HMI designer can already overlook certain information elements and might visualize a piece of information in an inefficient manner (so that it cannot be seen fast enough or can even be overseen in the monitoring task). One might argue that the HMI designer is an expert, but even expert knowledge has been shown to be error-prone by empirical studies [Hegarty, 2011]. This is further emphasized by the fact that the HMI is situated in the safety-critical domain. Empirical studies testing HMI solutions should be conducted with expert users, who are rare and expensive. Thus, the amount of empirical studies needed to ensure the quality of the resulting HMI should be reduced.
To improve the safety of the whole system, both human sides must be recognized—the human operator and the designer.

When looking at history, developing that kind of system is a typical problem that could be resolved from an engineering perspective: „It is the job of the engineer to find solutions to technical problems. He [or she] relies on natural and engineering knowledge and takes into account material, technological, and economic conditions as well as legal, environmental, and human-related restrictions. The solutions must fulfil the given

and self-recognized requirements. After clarification, initial problems become concrete subtasks that the engineer handles in product creation" (*translated according to* [Feldhusen & Grote, 2013]).
The underlying dissertation looks at the described problem from this engineering perspective and proposes a constructive method to reduce the risk of overseen or inefficiently visualized information (in a timely manner) on both sides—the HMI designer perspective and the human operator perspective.

The Three Mile Island accident has already caused basic changes in the design of such HMIs and added an engineering perspective to the HMI design task for safety-critical systems. The upcoming scientific field was called *human factors engineering* (HFE) in which the dissertation is positioned in. In the late 1980s, ecological interface design (EID) was introduced as a human factors engineering method and has its origin in nuclear power plant system design. EID is used for systematically deriving a satisfactory HMI for safety-critical systems [Burns & Hajdukiewicz, 2013]. Besides EID, there exists a broad range of further human factors (HF) methods [Stanton et al., 2006] like the task analysis (TA). Each method can extract the information a supervisor needs to know in a particular situation and can deduce a structure for the HMI—e.g. information that belongs to the same task should be grouped together in order to avoid extensive search for information within one task. Hence, one is already able to make the right information accessible in the right place to the human controller by applying an engineering approach. But each HF method stops at this point and does not offer a systematic approach to determine a concrete visualization of the information. The visualization is quite an important aspect as there is much evidence that task performance can be dramatically different with different visual displays of the same information (e.g. [Breslow et al., 2009] [Hegarty et al., 2010] [Novick & Catley, 2007] [Peebles & Cheng, 2003]). This evidence argues for the importance of the visual display design" [Hegarty, 2011]. Hegarty summarized the main advantages of visualization in displays for cognitive tasks: external storage of information, organization of information, offloading of cognition on perception („when non-visual data are mapped onto visual variables, patterns often emerge that were not explicitly built in, but which are easily picked up by the visual system." [Hegarty, 2011]) and offloading cognition on action—e.g. offload internal mental computations on external manipulations of the display itself. This is, for instance, done while playing Tetris and rotating the cubes directly instead of thinking how to rotate them. Owing to the fact that visualizations are currently not systematically derived within the state-of-the-art application of HF methods in a step-by-step procedure [Tory & Moller, 2004] [Stone et al., 2017], a lot of potential for the resulting HMI is lost: „On the one hand, we have the human visual system, a flexible pattern finder, coupled with an adaptive decision-making mechanism. On the other hand are the computational power and vast information resources [. . .]. Interactive visualizations are increasingly the interface between the two. Improving these interfaces

can substantially improve the performance of the entire system" [Ware, 2004].
When dealing with the problems identified in the monitoring tasks of safety-critical systems, the previously described factors are of outstanding importance—the time needed to perceive critical states and the assessment failures of the system's criticality [Gruhn, 2011]. Thus, summarizing, it can be said that the dissertation is situated in the domain of **monitoring** information that represents the actual state of an underlying safety-critical system. So, the focus lies in preventing severe accidents that are caused by **assessment failures** in case of overlooking important information that reflect a critical system state or recognizes the system's critical state **too late to execute countermeasures in time**.

1.2 Challenges

The latest trends emphasize the need for a systematic engineering method for deriving visualizations that would allow fast and accurate assessment of criticality [Brazier, 2010]: One supervisor is confronted with a continually increasing amount of information. While the data to be monitored grows successively, the number of people monitoring this data is reduced due to economic needs. To cope with this problem, the HMI designer must be supported by a constructive engineering method that can reduce the risk of wrong design decisions and facilitate the findings of an optimal design solution in a systematic manner [Feldhusen & Grote, 2013]. On the other hand, the human operator must be supported in his or her monitoring task. In this regard, it is again helpful to have a deeper look into the visualization of data on the HMI: „One of the greatest benefits of data visualization is the sheer quantity of information that can be rapidly interpreted if it is presented well"[Ware, 2010]. The emphasize here lies on the words „if it is presented well.". The question that arises in this context is: What does a *well* presentation look like? Regarding the main dissertation aims (prevent the two monitoring failures—overlooking of information and slow perception of critical states), a *well* graphic form presentation allows fast and correct perception of relevant information and meets the cognitive and perceptual skills for fast and accurate perception of the human operator in the best possible manner. In this respect, the HMI design problem can be seen as a kind of specific search problem that has to be solved: „UI optimization is an application of engineering optimization for discrete design problems, where a task consists of a finite set of candidate designs, an objective function, and constraints"[Oulasvirta, 2017]. A major challenge lies in opening up the search space for efficient design solutions and the best „combination of design decisions". This search space for optimal solutions will be part of the engineering method to be specified in this dissertation. Therefore, the main requirements for a constructive design method have to be considered. According to Feldhusen et al. [Feldhusen & Grote, 2013], a constructive design method should:

- make it possible to work in a problem-oriented manner and thus be industry-independent in every construction activity
- promote invention and knowledge to facilitate the finding of optimal solutions
- be compatible with terms, methods, and findings of other disciplines
- not create solutions by chance
- allow transferability of solutions to related tasks
- be teachable and learnable
- correspond to the findings of the working sciences, thus facilitating work, saving time, avoiding wrong decisions, and ensuring active motivated participation

Thus, the major challenges lie in:

***C1* – How does an appropriate search space for *efficient*[1] visual forms look like with correspondence to the findings of previous scientific work?**
The careful definition of an appropriate search space will ensure that solutions are not created by chance, but instead a reason for each decision will be given. This reason should be achieved on a problem-oriented manner so that it is industry-independent and transferable to related tasks. Furthermore, this search space should be built upon a scientific basis and consider prior findings about human perceptual skills. So, it will be compatible with the findings of other disciplines. Additionally, it will promote invention and knowledge to facilitate the finding of an optimal design solution, thereby decreasing the probability for wrong design decisions.

***C2* – How does an engineering procedure for selecting visual forms for monitoring HMIs in the safety-critical domain look like?**
This engineering procedure should help the HMI designer to open up the design search space in an engineering manner and stepwise analyse and synthesize options for the graphical appearance of the HMI. So, the designer can come up with a profound solution that will guarantee a high quality of the HMI design regarding the suitability to the human operator's monitoring task. This procedure should further facilitate the finding of an optimal solution, make the reasons for taking certain decisions transparent, and should be teachable and learnable. According to Feldhusen et al. [Feldhusen & Grote, 2013], it is important to „foster the constructor's individual skills through guidance and assistance, to increase his willingness to be creative while understanding the need for an objective assessment of the outcome. This will generally increase the level of design". Furthermore, this procedure should be compatible with the terms, methods,

[1] *Efficient* means in the underlying dissertation that the visual form serves the purpose of allowing fast perception and avoid overlooking relevant information for assessing critical system states)

and findings in the field of HFE and bridge the gap between the actual existent methods (as EID or task analysis approaches) and the actual graphic form representation. The orderly procedure will not only avoid the possibility that important information is overseen during design activity or that coincidentally taken design decisions will result in inefficient working conditions of the human operator, but has another important advantage: An orderly procedure on a partially abstract level creates generally valid reusable solution documents [Feldhusen & Grote, 2013]. This is essential for easy transferability to related tasks, but also for a sound V&V (Verification & Validation), which is part of the system's engineering procedure in the development of such systems. In this regard, it should be considered that the aim of the dissertation is not to totally replace the user's evaluation of HMI solutions in such a V&V activity. Rather, the engineering procedure is intended to support a goal-oriented way of designing an HMI, confine the search space for the visual appearance of optimal HMI solutions, and hence reduce the needed amount of user evaluation iterations.

1.3 Objectives & Contribution

To cope with the previously described problems and challenges, the underlying dissertation has the following objectives:

***O1* – Establish a theoretical framework that provides knowledge of the relevant perceptual and cognitive skills of a human operator as input for the HMI design search problem**: This theoretical framework addresses C1.

***O2* – Establish a systematic procedure that allows the applicability of the theoretical framework**: This procedure closes the gap between the actual state of the art and a systematic way to derive a graphic form and addresses C2.

The provided contribution is called the **Konect method**. Konect consists of the **Konect procedure**, which is built upon a scientific basis (**the Konect theoretical framework**). So, the method represents an engineering design method for constructing graphical forms on monitoring HMIs in safety-critical systems optimized for fast and accurate detection of critical system states to allow fast execution of appropriate countermeasures.

1.3.1 Terminology

As the dissertation is situated in the engineering domain, the term „*method*" should be understood as it is common in this area: *Method* is seen as a manner or mode for doing something, especially in accordance with a definite plan and a systematic way of instruction [Beer, 2008] [Oswald, 2006]. The word stems from the Greek term *methodos* that can be translated as *path of pursuit* or *the way of doing something* [Oswald, 2006]. According to Balzert [Balzert & Balzert, 2004], a method consists of concepts, notations, and a methodological procedure that proposes the steps to follow to achieve an underlying aim. This is shown in Figure 1.1. The underlying dissertation contributes the so-called Konect method and the corresponding subparts (concepts (*Konect theoretical framework*), notations (*Konect Idea Box*), and a methodological procedure (*Konect Procedure*). The Konect method is applicable in the context of existing methodologies for deriving an HMI design (e.g. software development methodologies such as agile development or waterfall development, or human factors methodologies such as EID). In this regard, it is important that the dissertations' aim is **not** that the method guarantees that no empirical evaluation of the HMI is needed. Rather, the method should narrow the search space for optimal HMI design solutions (related to fast and correct perceptions of critical situations) and offer objective reasons for the choice of visualizations, thus increasing the probability that the solution fits the task optimally and reducing the number of necessary evaluation iterations.

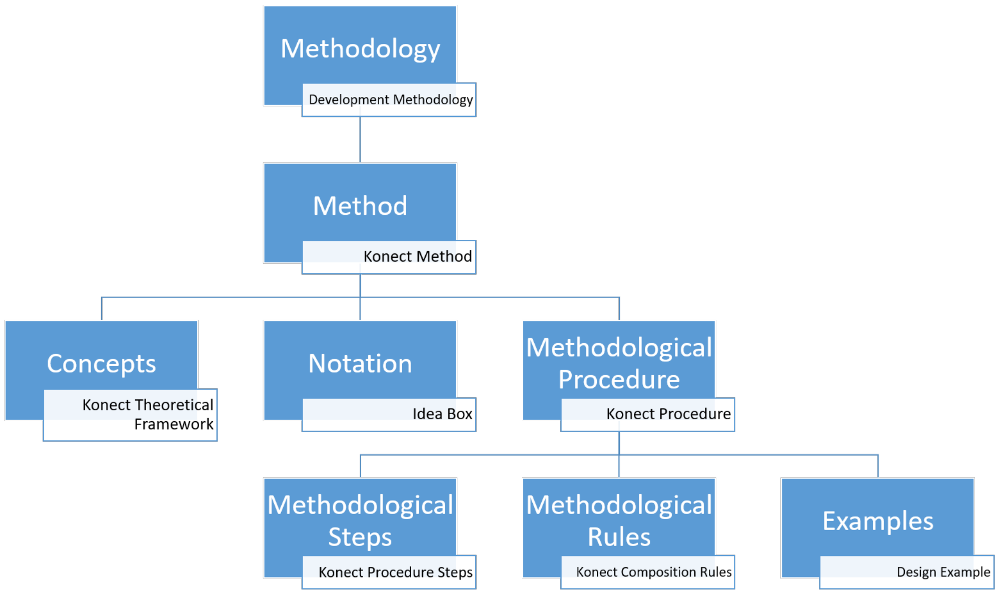

Figure 1.1: The term *method* as applied in the underlying dissertation (according to Balzert [Balzert & Balzert, 2004].

1.3.2 Scope

The underlying dissertation focuses on the **monitoring task** of safety-critical systems and optimization of HMIs for **fast and correct detection of critical system states**. The focus is on the graphical forms and thus on the visual component—more precisely on focal vision. Other components such as audio, haptics, etc. are not considered. However, it is considered that the method is extensible so that further human senses can be integrated in future work. Regarding the optimization goal, aims such as usability, intuitive understanding of visualizations, simple learnability of the HMI, or that the

HMI is graphically appealing might be conceivable. As the aim of the dissertation is that the method provides rational justifications for visualizations that can increase safety of the system, fast and accurate perception was chosen as the optimization goal. Other aspects like usability can be even contrary and therefore were beyond the scope of the dissertation: „safe HMI principles may accord with usability principles, but may also conflict with usability" [Rae, 2007].

1.4 Research methodology

„Research is creating new knowledge." -Neil Armstrong

The overall goal of research is to achieve new knowledge. In this aspect, two quite different branches of research exist: empirical research and constructive research [Hinkelmann, 2015]. In empirical research, new knowledge means new understandings about reality. This can be achieved via empirical studies to test the hypotheses of how the reality and world around us is working. In constructive research, new knowledge represents a new artefact (e.g. a method, procedure, concept) that solves a problem.
In the underlying dissertation, the object of research is problem-centred and initiated as a systematic procedure, which is needed to ensure the quality of the HMI design solution. This problem can be solved by constructing the artefact (systematic procedure on the basis of a theoretical framework), as described in the objectives section 1.3. Thus, the dissertation is placed in the scientific area of constructive research.
To establish the scientific quality of the resulting contribution, the dissertation follows an engineering approach, starting with problem identification followed by the definition of the requirements. Based on the requirements, a reflection of related work is conducted to identify the research gap in a better way and allow a target-oriented way of working for developing a solution. Finally, the solution is evaluated in two different domains. What has been done in detail is described in the upcoming section in the chapter's overview and visualized in Figure 1.2.

1.5 Chapter Overview

The dissertation is subdivided into eight chapters: The introduction described a first overview of the motivation and problem identification. Furthermore, a first overview of objectives is given. This is emphasized and specified in greater detail in Section 2 (State of the Art). For this, the domain, in which the dissertation is situated, is analysed in greater detail. This includes the task (2.1 The Monitoring Task in Safety-Critical Systems), the actual state of HMIs for monitoring in the safety-critical domain (2.2), and how the actual state and basics for designing such types of HMIs look like (2.3). This results in a more detailed problem identification (2.4). Based on this, the requirements are specified (3). With this definition of the requirements, a deeper look into current related works can be carried out to see to what extent problems are already solvable with similar approaches in the scientific domain. This analysis of related works further identifies the current gaps in the scientific domain.

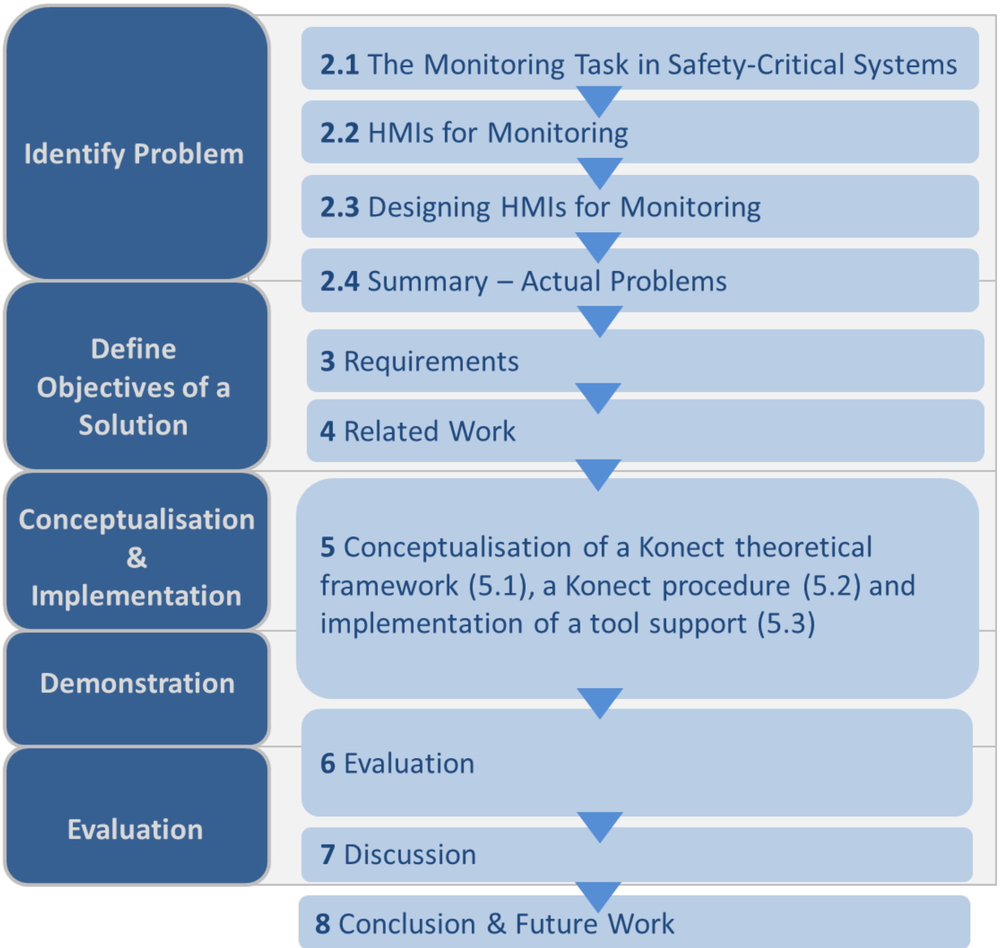

Figure 1.2: Chapter Overview with relation to research methodology.

After this step, the dissertation enters into the conceptualization & implementation step: In Chapter 5, the conceptualization of a theoretical framework (5.1) and a systematic procedure (5.2) is described and demonstrated according to an engine monitoring use case. For being able to apply the method, a tool support was implemented in Java FX. The tool support is described in Section 5.3.

In Section 6, the Konect method is evaluated. Therefore, the Konect method is applied in different domains and examined in empirical studies. The paper presents the automotive domain for offering a support for truck platooning and the maritime domain to support vessel performance monitoring.

In Section 7, a detailed discussion of the achievements acquired with reference to the definition of the requirements and a discussion of limitations is presented. The dissertation closes with a conclusion summarizing the work presented in the underlying dissertation and presents an outlook of future scientific investigations (section 8).

The results and works related to the dissertation have been communicated via publications. Hence, parts of the following text have already been published. A full list of publications is given in the appendix.

2 Monitoring in Safety-Critical Systems

Every scientific work needs to establish its context. Therefore, this chapter looks deeply into the state of art and basic principles involved in the domain in which the dissertation is situated: HMIs for monitoring safety-critical systems. The introduction outlined the central question of the dissertation. When having a look at the basic principles and the state of art, this question can be detailed and broken down into further concreted problem statements. These are needed to be solved in this dissertation. For this, the following aspects are taken into consideration:

- section 2.1 gives a definition of the monitoring task
- section 2.2 describes the state of art of actual HMIs that exist for conducting the monitoring task
- section 2.3 describes the state of art for designing HMIs for monitoring of safety-critical systems

This further clarifies the gap that needs to be solved in the underlying dissertation and leads to a more concrete formulation of actual problems to be solved. These are outlined in Section 2.4.

2.1 The Monitoring Task in Safety-Critical Systems

As described before, „safety-critical systems are those systems whose failure could result in loss of life, significant property damage, or damage to the environment" [Knight, 2002]. The human operator is still responsible for ensuring safe operation of these systems. In case of any anomaly, the operator should take countermeasures as fast as possible to restore a stable state of the underlying system. To assess an anomaly, the operator monitors a broad range of relevant parameters: In this respect, to monitor a system is „to examine the displayed status information, both formal (control panel displays) and informal (sounds, vibration, smells etc.), to decide whether or not the system is in a normal state and under control" [Boff et al., 1986]. For this reason, the human operator looks at the information and draws conclusions about the system state. Monitoring does not include any control or actions taken for running the system: „An operator monitors a system when he or she scans an array of displayed

Figure 2.1: Typical control room with operators sitting in front of a range of monitors.

information without taking any action to change the system state. The purpose of monitoring is to update the operator's knowledge of the system state and accordingly to permit decisions as to whether the system would be functioning normally or whether some intervention by the operator is required." [Boff et al., 1986]. An example of human operators monitoring a safety-critical system is shown in Figure 2.1, in which two human operators monitor an industrial heat and power combined plant. The control room displayed in this Figure was introduced in 2014 and represents the state of the art for the actual environment for the monitoring task. A lot of different information elements have to be monitored. Currently, there exists no official limit for the number of monitored information elements per operator [Kockrow & Hoppe, 2014]. In industrial plant operations, 80%-95% of the time the human operator is in the monitoring mode, while 1% - 5% are characterized by high demands due to process disturbances or unforeseeable operating events [Kockrow & Hoppe, 2014]. Manual interventions are rather rare and unpredictable, but usually have large impacts and are often subject to high time pressure as these systems work in real time. In case of any process deviations or malfunctions, the operator has to act quickly and perceive the critical system state as fast as possible.

Prior work has shown that the monitoring task is mainly visual, as empirical studies have revealed quite early that visual performance is superior to auditory performance [Kennedy, 1971]. This is the reason why the dissertation focuses on a method for deriving visual forms—this is the preferred medium for the task looked at.

2.2 HMIs for Monitoring

For analysing the state of the art of HMIs for supervisory control in the safety-critical domain, the analysis was twofold: On the one hand, the knowledge presented in the following text is based on latest surveys published in books and literature. On the other hand, the knowledge was acquired in case studies conducted with industry partners involving HMIs that are actually in use. This included the HMIs used by flight controllers monitoring the Environmental Control and Life Support System (ECLSS) of the ISS, the HMIs used by operators monitoring the electricity grid, and the HMIs for monitoring autonomous underwater vehicles. The case studies are described in detail in the upcoming subsection.

2.2.1 Case Studies

Three case studies were conducted to assess the state-of-the-art HMIs currently used by industry partners in the monitoring task of safety-critical systems. The analysed HMIs are:

(C1) HMI for monitoring the ECLSS: The first HMI was situated in the space domain and supported the monitoring of the ECLSS of the Columbus Module on ISS. The ECLSS is a subsystem „typical of crewed space vehicles which provides necessary conditions in order to make life in space possible" [Messerschmid et al., 2013]. This includes several subsystems that ensure living conditions of the crew on board—e.g. temperature and humidity control, atmospheric composition and pressure, cabin ventilation and air filtration, generation of O_2 and N_2 and CO_2 removal, and fire detection and suppression. The correct functioning of the ECLSS is monitored from the ground in the Columbus control room. The room is divided into six working areas. One of these areas—the so-called STRATOS—is responsible for monitoring the ECLSS system.

(C2) HMI for monitoring electricity grid: The second HMI was energy-related and used to monitor the electricity grid. In this case, the control room operators have to ensure the correct functioning of the distribution of energy from energy supply to energy consumption. So, it has to be ascertained that the allowed limits for voltage and power are not exceeded to avoid damage of the technical equipment.

(C3) HMI for monitoring AUVs: The third HMI was situated in the maritime domain and used to monitor autonomous underwater vehicles (AUV). AUVs are used, for instance, to inspect the state of tunnel systems for drinking water. In this regard, relevant parameters as heading, speed, or the depth under water and distance to the ground have to be monitored. Furthermore, the operator has to monitor the path followed by the AUV to ensure that the vehicle follows the desired trajectory [Sahu &

Subudhi, 2014].

To establish the state of the art of these HMIs, semi-structured interviews were conducted with relevant partners. The procedure followed in the interviews is described in more detail in the following subsections.

Interview Preparation

Before the interviews were conducted, a familiarization with the domain and the HMIs was carried out. This was necessary to ensure proper communication with the interview partners in the technical language and to guarantee that the interview partner could be understood without problems.
The familiarization was done by reading manuals about the HMI designs in the different domains and manuals about the task of the interview partners.

As part of the preparation, task models were created to allow a structured and complete way of conducting the interviews later on. So, the support for each task offered by the HMI was discussed systematically. This not only ensured a certain degree of completeness, but also a fluent conversation.

Interview Partners

In all three case studies, the interview partners were operators of the monitoring system.

In case of C1, the so-called flight controller is the main operator: The flight controller monitors the real-time telemetry to ensure that all functions (temperature and humidity control, fire detection and suppression, atmosphere and pressure control, and air revitalization) are working correctly. In case of anomalies, he/she is responsible for rapidly putting the system into a stable state. Two flight controllers participated in the interviews. Furthermore, a columbus instructor participated to provide further background knowledge about the technical background and the astronauts' perspective.

In case of C2, the interview partners were operators monitoring the electricity grid of a region in northern Germany. These are so-called „Schaltmeister". Three Schaltmeister attended the interview.

In case of C3, there were three different interview partners (two users operating the AUV and one user testing the AUV for research purposes and to establish future usage scenarios). All of them were well acquainted with the HMI.

Interview Procedure

For each interview, a process protocol was created to ensure a structured procedure. Each interview began with a short welcome and a subsequent explanation of the main aims of the interview to enable a focused conversation.
After this first introduction, the HMI was discussed in a semi-structured way based on the previously conducted task analysis. For each HMI, the advantages and disadvantages were discussed and problems of actual HMIs regarding optimal task support were reported.
In case of C3, the interview was further structured by applying the human efficiency evaluator (HEE), a tool for rapid and early efficiency evaluation of HMIs [Feuerstack & Wortelen, 2017].

The results of the interviews are described in detail in the upcoming section.

2.2.2 State of the Art of Monitoring HMIs in Industry

The case studies as well as the literature analysis led to consistent results regarding actual state of the art of HMIs for supervisory control: The current HMIs often suffer from a lot of textual information and numbers with which anomalies can easily be overlooked. An example can be seen in Figure 2.2. The shown HMI is still in use to monitor different parameters of the ECLSS system.
The case studies revealed that the reason for text-laden HMIs can be found in history: Before 1980s, supervisory control often involved physical gauges as pressure gauges, analogous, or temperature indicators placed on a wall. Additionally, the operators were supported by an annunciator panel that showed all alarms. „Operators had fewer instruments to monitor, and instruments were grouped on the wall based on operator's tasks." [Opto22, 2014]. With growing innovation, the processes to be monitored became more complex, and computer systems were introduced to help handle this complexity. The early computer systems were subject to some technical restrictions. Instead of visualizing information via gauges, only text was available and the use of colors was rather limited: „Many of poor designs are holdovers due to the limitations of early control systems and the lack of knowledge of system designers" [Gruhn, 2011].
With technological progress of the computer systems, new possibilities for visualizing information have arrived [Olshannikova et al., 2015]. Interface designers often turned to so-called piping and instrumentation drawings (P&IDs), which are exemplarily shown in Figure 2.3.
P&IDs focus on the process hardware and show a representation of the alignment of physical entities of the system to be supervised. In the example of HMI in Figure 2.3), one can see overuse of colors and shadows to present the P&ID in a more realistic way: „When computer graphics became really detailed and thousands of colors were available, they were mostly used to make the same P&ID representations look more

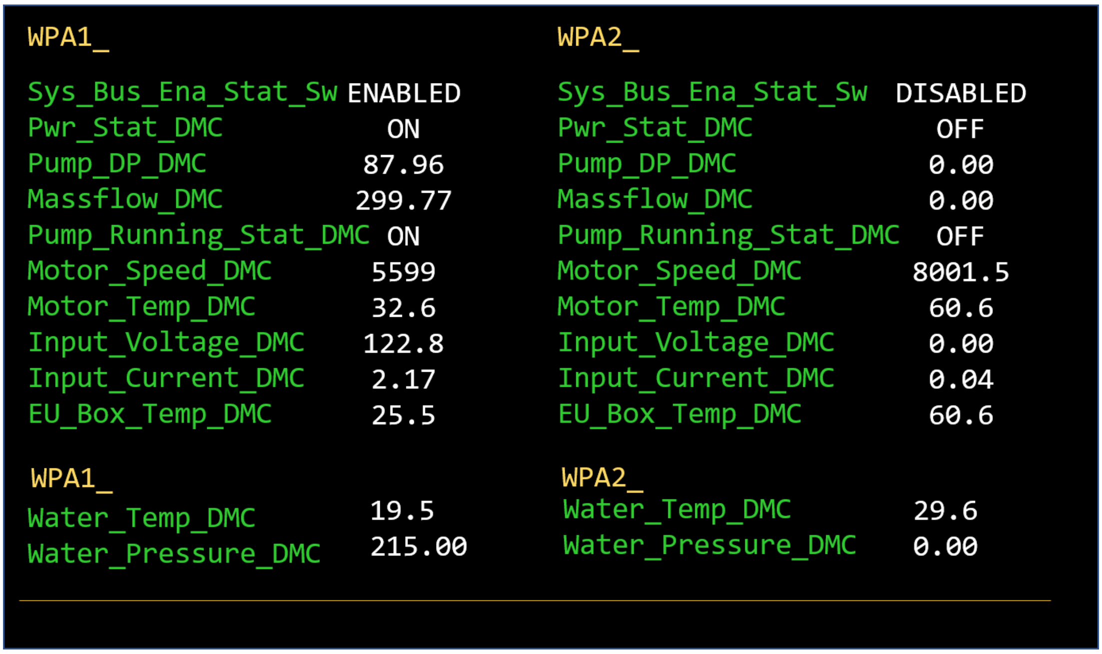

Figure 2.2: Exemplary Extraction of HMIs for monitoring parameters of the ECLSS system (based on [Transportation & A/S, 2007]).

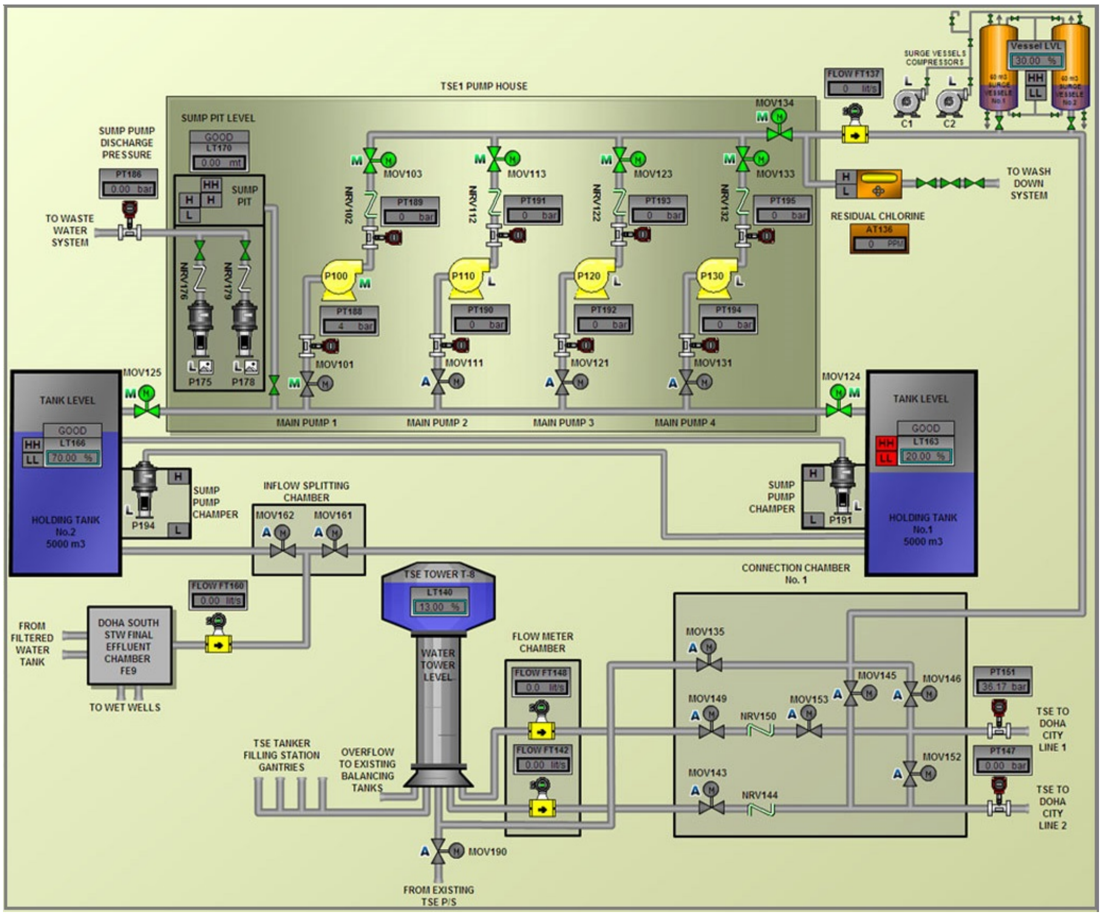

Figure 2.3: Example of typical poor HMI.

realistic, not to change the HMI to better suit operator's tasks. Furnaces with dancing flames and detailed floors and walls don't provide useful control information; they only serve to distract the operator on the job" [Opto22, 2014]. The information necessary to monitor the underlying system as actual temperature or pressure values are only shown via small text elements positioned next to the visualization of physical elements. Even though this kind of HMIs show a physical arrangement of technical equipment, this view is quite static and variable parameters are still visualized as text fields. This generates the problem that important information can easily be overlooked and the detection of problems or anomalies is impeded. This problem is even aggravated if overuse of animation and color exists as this results in misplaced salience [Gruhn, 2011]. The overuse of color and the choice of text for encoding variable parameter values could be observed in all three case studies. In C3, the position of the AUV and tracking was offered in a visual form, but further parameters, such as heading or speed, were still provided as textual information.

Besides the fact that information is strongly shown quite inefficiently via text fields, actual HMIs also suffer from the structure: „They have no hierarchy, and are intentionally a very 'flat' view of every element of the process rather than supporting 'drill down' for additional information" [Nimmo, 2012] [Opto22, 2014]. An aggregation of information to visualize the overall system state is often missing [Burns & Hajdukiewicz, 2013]. This missing overview could also be observed in all three case studies. Thus, the operators have to search quite extensively and during this search process may even have to switch between different HMI views (observed in C1 and C2). This missing overview of the parameters and the telemetry causes a high workload of human operators. This leads to the fact that „increasingly, ineffective or misleading human-machine interfaces (HMIs) are being cited as causes in industrial accidents" [Opto22, 2014]. This aspect shows that the HMI is not optimally adapted to the operators' tasks.

In all the three case studies, the characteristics of poor HMIs, according to Gruhn [Gruhn, 2011], were existent. These are presentation of raw data like numbers (temperatures, pressures etc.), no trends, flashing and spinning graphics, use of bright colors and 3D-shadows, color coding of piping and vessel contents, lots of crossing lines, alarm-related colors for non-alarm related elements, and inconsistent color usage [Gruhn, 2011]. This can lead to major problems: Still today, „poor HMI designs have been identified as factors contributing to abnormal situations, billions of dollars of lost production, accidents, and facilities. Many HMIs actually impede rather than assist operators" [Gruhn, 2011].

2.3 Designing HMIs for Monitoring

As stated in Section 2.2, the currently used HMIs for conducting supervisory control of safety-critical systems are suffering from different aspects: HMIs are often text-laden, presenting raw data, such as temperature or pressure, as numbers. Visuals as graphics and bright colors are used for styling purposes instead of showing information and are often used inconsistently [Gruhn, 2011].
This aspect could be attributed to the state of the art of procedures or approaches of the designers to come up with an HMI: „In fact some designs are actually *worse* than older designs! Just as a computer is not a typewriter, new HMI designs should not mimic those of old. The problem is that many designers often simply don't know better." [Gruhn, 2011].

Analogous to the currently used HMIs (2.2), the state of the art of the procedure applied to designs, such an HMIs, is also based on the literature and knowledge acquired in the three case studies described previously.
The state of the art for designing HMIs for supervisory control in the safety-critical domain can be subdivided into two different approaches, which are shown in Figure 2.4.

The **first approach** lies in adding *ad hoc* the whole user interface at the end of the software engineering process by applying creativity and vague guidelines. The case studies revealed that the designs are often done by engineers who are in most cases also in charge of implementing the design solutions. The information shown on the HMI, the structure of this information, and the graphic form design of the information is based on a vague way of proceeding rather than on sound engineering methods. So, the result is strongly influenced by the intuitions of the engineer and in this case the designer who developed the HMI: „Empirical studies have made clear that one should not rely on intuitions alone to judge the effectiveness of visual displays, as people's intuitions about displays are not necessarily a good indication of their effectiveness" [Hegarty, 2011]. The case studies revealed that no evaluation with users (as it is quite common in user-centred designs) takes place in most cases.
The **second approach** applies the so-called human factors (HF) method for systematically deriving the information elements to be shown on the HMI as well as the structure for these information elements in accordance with the operators' tasks (Task analysis) or the systems structure (ecological interface design). Task analysis (TA) analyses the tasks a human operator must conduct while supervising a safety-critical system. Ecological interface design (EID) analyses the functional purpose of the system to be supervised and the functioning and operating principle in the form of a systematic, structured work domain analysis. In this case, the information shown on the HMI as well as the structure of this information can be derived systematically following a sound engineering method. But regarding the graphic form design, creativity and vague

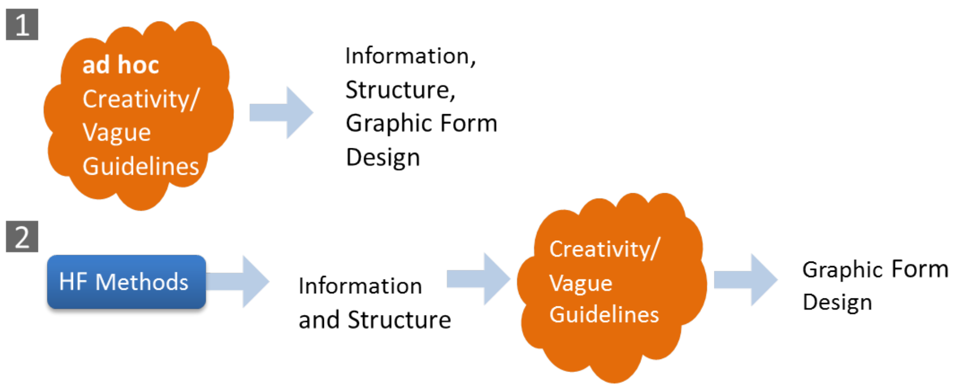

Figure 2.4: State-of-the-art for designing HMIs for supervisory control in the safety-critical domain.

guidelines are utilized for designing the visual appearance of the HMI.
The current approaches for designing HMIs can be roughly subdivided into four main categories: *guidelines*, *procedures*, *standards*, and *patterns*. The details are described in the upcoming subsections.

2.3.1 Guidelines

Guidelines give advices in the form of a list of rules or best practices applicable in the design phase. These guidelines are often not ordered in a way that they could be applied stepwise for systemizing the design activity. Instead, they represent general guidance via aspects to be considered during the design phase. The examples of guidelines actually applied for creating HMI designs are the following:

Shneiderman's 8 Golden Rules for Display Design: Shneiderman's 8 Golden Rules for Display Design represent well-established rules to be recognized during designing [Shneiderman et al., 2016]. These rules represent a generic guide to good interaction design applicable to most interactive systems. According to Shneiderman, a good user interface design for effective interaction should: *strive for consistency*, *enable frequent users to use shortcuts*, *offer informative feedback*, *design dialogue to yield closure*, *offer simple error handling*, *permit easy reversal of actions*, *support internal locus of control*, and *reduce short-term memory load.*

Nielsens 10 Usability Heuristics: Similar to Shneiderman, Nielsen presented broad principles for interaction design and aspects that need to be minded during the design phase. These are *visibility of system status*; *match between system and the real world*; *user control and freedom*; *consistency and standards*; *error prevention*; *recognition rather than recall*; *flexibility and efficiency of use*; *aesthetic and minimalist design*; *help users recognize, diagnose, and recover from errors*; and *help and documentation* [Nielsen, 1994, Nielsen & Molich, 1990].

Tognazzini's List of basic principles for interaction design: Compared to Shneiderman and Nielsen, Tognazzini presents the longest list of guidelines. The principles are compatible with the principles of Shneiderman and Nielsen; they can be used as a kind of checklist to ensure that the different aspects (e.g. consistency) were minded during the design phase [Tognazzini, 2016].

While the previously presented guidelines are strongly situated in the generic field of usability engineering, some guidelines have a stronger focus on safety-critical systems:

Practical Human Machine Interface Principle for Safe Computer Controlled Systems: Rae [Rae, 2007] addresses design principles for safety-related computer systems. The principles provide general aspects to be minded during the design phase of HMIs specifically addressing safety-critical systems. These are, for instance, that *the HMI should make the operator aware of the current state of the controlled system, as it relates to safety*, or that *the HMI should alert the operator to consequences of potentially unsafe actions* [Rae, 2007]. These principles provide a generic overview and no hints of any visual representation are given.

EEMUA 191 Alarm Systems: The EEMUA is the Engineering Equipment & Materials Users' Association, which is a non-profit distributing industry association and considered as „the leading source of good practices with respect to alarm management techniques" [Fiset, 2009]. The EEMUA 191 was released in 1991 and represents the basic guidelines of how to improve alarm management systems, especially in industrial processes. The guidelines provide well-established rules on how to set alarm parameters, alarm constraints, and provide standard texts for alarm messages [Equipment & Association, 2007].

NUREG–0700: NUREG–0700 provides guidelines for the human interface design for nuclear power plants [Commission, 2002]. The guidelines embody 18 principles to be considered when creating the HMI for such systems. These are *personnel safety*, *cognitive compatibility*, *physiological compatibility*, *simplicity of design*, *consistency*, *situation awareness*, *task compatibility*, *user model compatibility*, *organisation*, *logical/explicit structure*, *timeliness*, *controls/display compatibility*, *feedback*, *cognitive workload*, *response workload*, *flexibility*, *user guidance and support* and *error tolerance and control* [Rae, 2007]. In actual practice, these guidelines are mainly applied for reviewing after the design phase instead of constructing the HMI.

Gnome Human Interface Guidelines: The Gnome Human Interface Guideline [Day, 2016] offers assistance on how to design effective window applications. While

EEMUA 191 focuses specifically on the surrounding aspects for alarm management, the Gnome Human Interface Guideline provides, for instance, more specific guidelines for the visual appearance of alert messages—e.g. that an alert window should be raised above an application and it should have no title. These guidelines are quite specific for typical WIMP[1] applications and represent a kind of more generic style guide.

In the previously mentioned guidelines, the focus does not lie on the visual representation of such HMIs, but provide rather generic guidance for the interaction design. The highest focus regarding the graphic form representation is contributed by Hollifield et al. [Hollifield et al., 2008]:

Basic Principles for High Performance HMIs: Hollifield et al. [Hollifield et al., 2008] presented a comprehensive guide to design, implement, and maintain effective HMIs for industrial plant operations. These guidelines offer the highest amount of principles addressing the graphic form design. Examples are, for instance, that the *amount of text should be minimized* and that *all display screen lettering should be in non-serif fonts*. Furthermore, the HMI should strive for a *limited use of color* and that *display elements have consistent visual and color coding*.

Most guidelines focus on the usability (Shneiderman's 8 Golden Rules, Nielsens Usability Heuristic) of the systems. In this regard, „learnability is in some sense the most fundamental usability attribute, since most systems need to be easy to learn and since the first experience people have with a new system is that of learning to use it"[Nielsen, 1994]. So, usability has a strong focus on supporting end-users or novice users rather than expert users. Nielsen presented the learning curves and the usage efficiency for the two different kind of systems (see Figure 2.5): A hypothetical system that focuses on novice users should be easy to learn. But as a consequence, it is often less efficient to use compared to a system designed for expert users which is hard to learn but highly efficient to use. This is emphasized by Rae who is situated in the safety-critical domain and described that „safe HMI principles may accord with usability principles, but may also conflict with usability" [Rae, 2007]. This is the reason why the Konect method developed in the underlying dissertation aims for fast and correct perception of critical system states and will not focus on usability. This is further underlined when comparing guidelines specifically positioned in the safety-critical domain, such as NUREG-0700, to the usability guidelines of Shneiderman, Nielsen, or Tognazzini: Some guidelines are relevant in both domains (e.g. consistency), but the safety-critical domain additionally aims for **timeliness**, **simplicity in design** and **cognitive compatibility**.

[1]WIMP stands for „windows, icons, menus, pointer" and represents the typical interaction style used on windows-based desktop computers

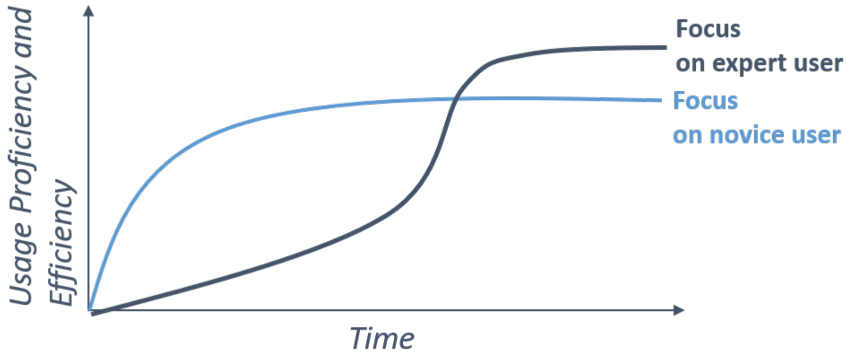

Figure 2.5: Difference between learnability and usage efficiency for systems for novices and systems for expert users (based on [Nielsen, 1994]).

2.3.2 Patterns

Patterns describe the reusable design elements that have been proven to be efficient. This was provided, for instance, by Tidwell [Tidwell, 2010] or Hussey et al. [Hussey, 1999].

Tidwell: Tidwell presents an extensive collection of various design patterns ranging from interaction patterns (e.g. menu navigation) over displaying complex data structures to visual aesthetics. In the underlying dissertation, the displaying of complex data, in particular, is relevant. In this connection, Tidwell presents different patterns. An example is shown in Figure 2.6. This example represents the „data spotlight" pattern in which the user can click on relevant data to get a more salient representation. Tidwells pattern are strongly situated in the WIMP domain (and lately added some pattern for mobile devices). The example shows that the focus strongly lies on designing interaction for end-users in everyday-life applications and not in the safety-critical environment.

Hussey et al.: In the safety-critical domain, Hussey et al. contributed design patterns. These patterns are derived through review of safety-critical interface literature [Rae, 2007]. Compared to Tidwell, Hussey's patterns remain quite generic as no visual solution is presented. Hussey rather describes the concepts to be considered for different cases—e.g. *„if the system has entered a hazardous state, the user should be notified of the state that the system is currently in and the level of urgency with which the user must act."* [Hussey, 1999].

2.3.3 Standards

While the guidelines and patterns described previously offer loose guidance and advice on how to design HMIs, the standards can be seen as established norms.

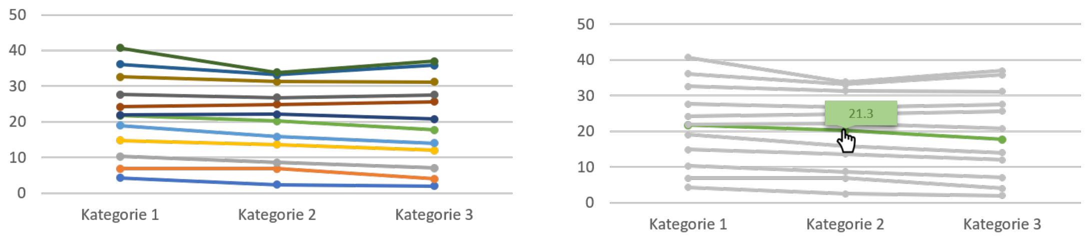

Figure 2.6: Data Spotlight Pattern (based on [Tidwell, 2010]).

ISO-9241: The ISO-9241 [ISO, 2006] is the most known source for standards linked to human machine interface design. It presents ergonomic requirements for office work with visual display terminals. The parts of the standard cover, among others, menu design, form-filling, keyboards and displays. Examples of rules are that dialogues should mind *suitability for the task*, *suitability for learning*, *suitability for individualization*, *conformity with user expectations*, *self-descriptiveness*, *controllability* and *error tolerance*. Like the guidelines of Shneiderman, Nielsen, and Tognazzini, the ISO-9241 focuses on usability, which is not the intended field of Konect.

ISA-5.5-1985: The ISA standard provides a list of industry-accepted graphic symbols for process control applications—e.g. that *red is always used as color code for an alarm* or the icon representations for electrical equipment [ISA, 1985] [Fiset, 2009].

MIL-STD-1472F: MIL-STD-1472 represents the USA military standard for user-computer interfaces. This standard offers general principles (similar to ISO-9241), but also very specific guidelines for the appearance of displays and controls [Rae, 2007]—e.g. that in case of visual alert management using flash coding *no more than 3–5 flashes should be used per second.*

NASA-STD-3000: Compared to the MIL-STD-1472, the NASA-STD-3000 provides the equivalent NASA guidance. This guide also gives a general overview of the norms to be applied—e.g. that a *simple design is preferable.*

The aforementioned standards are quite similar to the guidelines and patterns. They do not offer a systematic engineering method to apply the knowledge stepwise for generating visual forms. Regarding the visual forms, they are often too concrete (e.g. ISA-5.5-1985) to establish a new innovative and fast way for an optimal solution for fast and correct perception or too general (e.g. ISO-9241 or NASA-STD-3000) for the problem addressed in the underlying dissertation.

2.3.4 Procedures

Procedures for the HMI design in the safety-critical domain are two-fold: Some are constructive procedures for designing HMIs, while the others are verification procedures. For the latter, THERP [Kirwan, 1996a] is an example. THERP is a technique for predicting human error-rates. This is mainly done on the basis of the tasks themselves rather than on the HMI. As the verification of HMIs in the safety-critical domain is a broad field which lies not in the focus of the underlying dissertation (as it rather focuses on an engineering method for constructing an efficient HMI Design), no details of the HMI verification are given here. The details can be found for instance in [Kirwan, 1994a] [Bell & Holroyd, 2009].

With regard to the design construction procedures only the ones are considered that are common in the safety-critical domain. In the end-user domain, there exists the human-centred design process [ISO, 2006] which explores iteratively design options by evaluating different designs with users. The professional users in safety-critical domain are rare, expensive, and in most cases not available for empirical evaluations—this makes the human-centred design process less applicable in the safety-critical domain.

The design construction procedures are common in the safety-critical domain considering two different perspectives: a human-centred perspective and a system-oriented perspective. In the first case, the information that is important for the human operator is raised by investigating routine operations via interviews, the literature review, or observations. This can be structured by conducting a task analysis (see subsection 2.3.4 for details). The second aspect (system-oriented perspective) provides not only support for routine monitoring tasks, but also for supporting the problem-solving activity of the human operator in unforeseen situations. For collecting the necessary information, a work domain analysis is carried out (see subsection 2.3.4 for details).

Task Analysis

As stated before, the task analysis focuses on routine operations a human operator executes. This involves „identifying tasks, collecting task data, analysing the data so that tasks are understood, and then producing a documented representation of the analysed tasks" [Nemeth, 2004]. The documented representation of the analysed tasks can be done in the form of a hierarchy (HTA) [Nemeth, 2004] [Stanton et al., 2006]. In this regard, tasks on higher abstraction levels are iteratively divided into lower level subtasks. On the lowest abstraction level these tasks represent concrete actions. In this way, an abstraction hierarchy of tasks is constructed. The task models contain all data or information which is necessary to execute the tasks successfully—e. g. parameters to monitor the process state. These information elements deliver essential requirements for the design of the human machine interaction and the human machine interface—for instance, graphical displays, which present the necessary information in an adequate presentation form at any point during task execution.

The task model can be documented in the form of a task tree (cf. e.g. Figure 2.7). The nodes in the task tree represent tasks. Arcs between the nodes indicate a task—sub-task hierarchical relationship, meaning that in order to perform the top-level task, the sub-tasks on the next level have to be performed.

In this manner, a deep understanding of the work performed and information needed by the human operator can be systematically build up.
Diaper suggests that „task analysis is potentially the most powerful technique available to human-computer-interaction (HCI) practitioners, and it has potential application at each stage in the system design and development process"[Diaper & Stanton, 2003] [Stanton et al., 2006]. Ware states that this kind of knowledge is needed to derive successful designs: „[...] in order to do successful design we must understand the cognitive tasks and visual queries a graph is intended to support."[Ware, 2010]

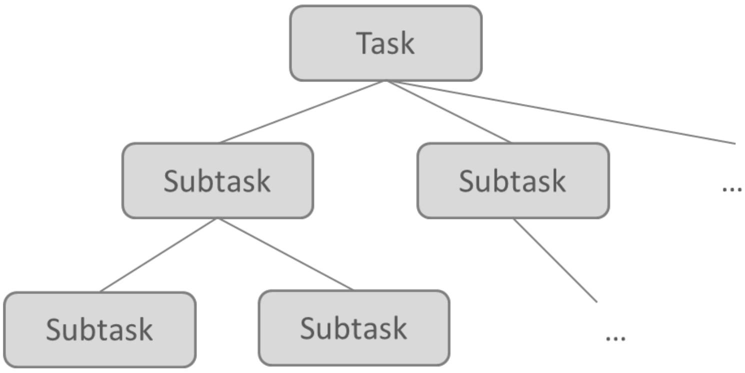

Figure 2.7: Example for HTA structure.

Ecological Interface Design (EID)

While task and procedure models determine the behaviour in well-defined situations, work domain models are constructed to support monitoring and controlling in unforeseen situations—e.g. unforeseen disturbances. In such a case, operators need to have a clear understanding of the underlying system to detect and diagnose the failure or even failures to initiate the right countermeasures. This is the basic concept of ecological interface design (EID)—a theoretical framework developed by Kim Vicente and Jens Rasmussen for designing interfaces for complex human-machine systems [Vicente & Rasmussen, 1992] [Burns & Hajdukiewicz, 2013]. To establish the information to be shown on the HMI, EID applies a so-called abstraction hierarchy (AH). This hierarchy is shown in Figure 2.8 and explained in detail in the following text using a simplified structure of an aircraft as a continuous example to illustrate the concept.

Functional Purpose

On this layer the purpose for which the system is developed is described. The purpose of an aircraft is to transport passengers from A to B. Further criteria

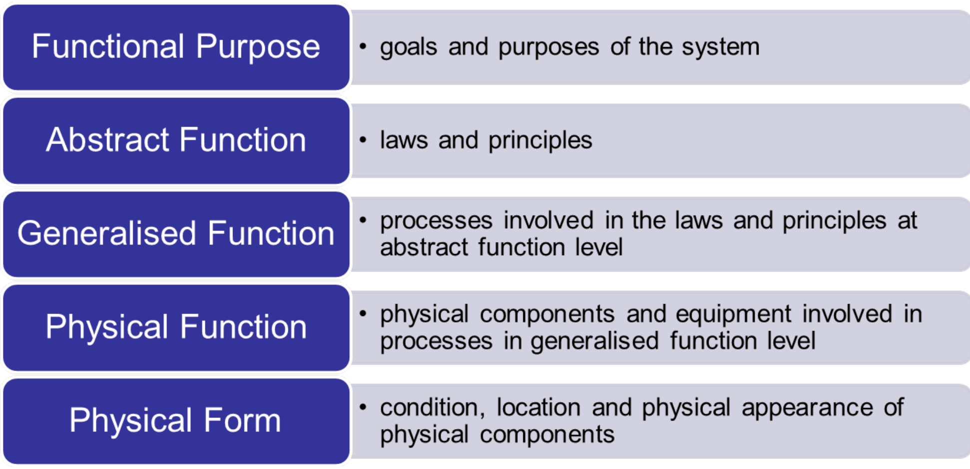

Figure 2.8: Abstraction Hierarchy (AH) of EID framework.

need to be defined to estimate if the system is working correctly: The passengers should be transported safely and on due time.

Abstract Function

On this layer the underlying laws and principles that exist in the system are described. In most cases, these are physical laws to calculate mass, energy, or information. Further laws to describe the abstract function are organizational and legal principles. For the aircraft, the physical laws of mass movement, energy generation, and conservation can be applied. For instance, energy never gets lost, but is only transformed from one form into another (e.g. potential energy can be transformed into kinetic energy and vice versa).

Generalized Function

On this layer the basic functions, which realize the laws and principles on the abstract function layer, are described. In case of the aircraft, these are the basic functions that are used, for instance, to reduce kinetic energy and altitude during landing to ensure a smooth and safe touch down on the runway. In contrast to the abstract function, where only the laws and principles are listed, the generalized function layer describes which functions are applied in what sequence. Thus, in addition to the relationships based on physical laws, the flow of masses, energy, and/or information is considered. The aircraft has potential energy, which has to be reduced during landing. The plane is equipped with specific mechanisms to reduce altitude, speed, and to maintain lift. These mechanisms have to be coordinated adequately at different points in time to ensure that potential energy is reduced, while at the same time the lift is maintained. On the generalized function layer the time sequence is described by in-and output relationships: Potential energy is reduced during descend. This, in turn, increases the speed, which needs to be compensated using mechanisms to reduce the flow of fuel and by mechanisms to change the air flow. A decrease of speed needs to be compensated by mechanisms for maintenance of lift etc. In an industrial production process, the generalized function layer describes the flow and transformation of raw material via heating, cooling, shaping, grinding, pressing, or rolling.

Physical Function

On this layer the system components with their physical characteristics are described. While the generalized function level just depicts the mechanisms to reduce height, a description of how the mechanism is concretely realized is provided on this level. For instance, the decrease of altitude is achieved by movement of the elevator surface. The physical function of the elevator is the vertical rotation of the surface.

Physical Form

On this layer the physical system components are described with regard to their physical appearance: shape, dimension, color, position, and material. For example, the elevator is positioned at the aircraft tail unit. Any information should only be included in the abstraction hierarchy if it has a potential relevance for the modelling objective: support for detection and analysis of unforeseen events.

Unlike classical part-whole hierarchies, the levels in the functional abstraction hierarchy are connected via means-end links: The functional purpose is realized by making use of the physical laws (abstract function); therefore, these laws are realized by applying certain generalized functions in specific sequences; the generalized functions are realized by physical system components, which are described with regard to their physical functions and their physical forms creating the physical function. This structure shall support operators in problem-solving. If the system is working correctly, the principles and general conditions on each level, as well as their relationships, are fulfilled; in case of failure, some of them are violated. The abstraction hierarchy allows to systematically "zoom" into the system via the means-end links. Often a failure becomes apparent at the system surface by the fact that a particular purpose of the system is not fully obtained any more. Starting from there it is possible to detect the physical laws that are violated due to the fact that particular generalized functions are not fulfilled, which can be further tracked down to the loss physical functions and thus to malfunctions of one or more system components. The "zooming" from abstract levels to more concrete levels allows to focus on those physical components, which are involved in producing the violated functions. In this way, the abstraction hierarchy allows goal-oriented and efficient problem-solving, and thus, countermeasures can be initiated faster.

2.4 Summary – Actual Problems

In the previous sections, the state of the art has been examined by looking at two different perspectives: the state of the art of HMIs actual in use and the state of the art of their design procedure. With regard to this state of the art, various problems were identified:

P1. No systematic procedure All approaches presented in the previous section do not come up with a systematic procedure enhanced with a sound theoretical basis about efficiently perceivable **visual forms** as it is aimed in the underlying dissertation. EID and TA can determine information and structure of the HMI, but they do not systemize the finding of optimal graphical design solutions. This leads to HMI designs that are suboptimal regarding the visualization, which impedes fast and correct recognition of critical system states.

P2. Visualizations are not rationally justified The case studies revealed that visual forms are often chosen intuitively without any objective reason. Thus, the efficiency of chosen visualizations is strongly based on the designer's intuition. As this can be erroneous, this might not lead to an efficient HMI for the monitoring task [Hegarty, 2011]. The latter aspect was also observable in the case studies. The dissatisfaction of users with the current HMIs has also led them to increasingly demand objective reasons for selected visualizations.

P3. HMIs are not well tailored to the operator's tasks The case studies as well as the literature revealed that HMIs are currently not well tailored to the tasks of the operators. This is based on the structure—e.g. the operators have to switch between views to collect information needed in one task and on the visual form, for instance, by using textual information for encoding variable parameters impedes fast and correct recognition of anomalies: „Text fields are an inefficient way for humans to interpret information. Humans can interpret more information more quickly if it's presented *graphically.*" [Gruhn, 2011].

P4. Missing Overview The state of the art revealed that on most HMI designs an overview is missing. During the case studies, the interview participants expressed that they would appreciate such an overview to estimate the current systems state with one glance.

P5. Misplaced salience The HMIs that were analysed to ascertain the state of the art suffered from misplaced salience: Nearly all HMIs used visual forms that do not encode information, but are used for supposedly decorative purposes. As these visual forms misguide the operator's attention, they also impede the fast and correct recognition of anomalies.

P6. Difficulties applying guidelines, patterns, standards, procedures The actual state of the art for designing such HMIs showed that there exist different guidelines, patterns, standards, and procedures (see section 2.3). The case studies revealed that the application of such guidelines, patterns, standards, and procedures is a major problem as they often span a high number of pages and there is no exact guideline. This problem is exacerbated by the difficulty of conducting empirical tests in the safety-critical domain: The intended users of these HMIs are experts in their domain. These experts are rare and expensive. Furthermore, testing is difficult because the tests must be conducted under laboratory conditions, as testing under more realistic conditions might pose serious threats to the safety of the whole system. Nevertheless, the quality of the HMI must be guaranteed, especially regarding to the intended use (ensuring the safety of the whole system).

3 Requirements

The previous sections examined the state of the art existing in the domain the dissertation is situated in. With this examination, it was possible to further specify problems and gaps to be solved (see section 2.4). This problem specification is used to infer the objectives and requirements the Konect method should fulfil:
P1 and *P6* revealed that currently no procedures for deriving **visual forms** exist and standards, patterns, and guidelines are rarely applied. This leads to various problems with the resulting HMI designs, as chosen visualizations are not rationally justified (*P2*) and produce misplaced salience (*P5).* Moreover, such visualizations are not well tailored to the operator's task (*P3*), and in most cases, do not provide an overview of the parameters that allow a quick assessment of the system status at a glance (*P4*).
For addressing these problems, the quality of the resulting HMI has to be ensured directly at the design stage. This can be achieved by following **engineering** method. This leads to the first requirement that can be viewed as the overall objective:

O – The dissertation should provide a constructive method that allows systematic derivation of information visualizations optimized for fast and accurate perception.

As this constructive method follows an engineering approach, as presented by Feldhusen et al. [Feldhusen & Grote, 2013], Ehrlenspiel et al. [Ehrlenspiel & Meerkamm, 2013] or Eder et al. [Eder & Hosnedl, 2007], it will follow the requirements for such constructive methodologies, as specified by Feldhusen et al. [Feldhusen & Grote, 2013] and described in Section 1.2. This takes into account also the fact that the method is not restricted to be used by designers, but should be also applicable by engineers. Furthermore, the method will address the problems specified in Section 2.4. This leads to the following requirements for the resulting method called Konect:

> **R1 – Konect should work in a problem-oriented manner and thus be industry-independent for every design activity.**
>
> *The case studies presented in the previous section were conducted in three different domains and branches of industry. Even if the domains were different, the*

problems in the areas are similar. Thus, the method to be developed should work in a problem-oriented and industry-independent manner. Furthermore, this requirement is based on the characteristics that need to be fulfilled by a constructive method. This implies that the method is not limited to one domain (e.g. maritime). Instead Konect should be applicable in various domains, such as automotive, maritime, control rooms, and rather works in a problem-oriented manner. Problem-oriented means that the monitoring task is supported with regard to problems to be solved (fast and accurate detection of system criticality) independent of the domain.

R2 – Konect should promote invention and knowledge, and thus, should facilitate the finding of optimal solutions.

In relation to the actual state of the art, current HMIs are often text-laden and do not use visualizations for representing information graphically (P2). Furthermore, actual designs are not well tailored to the operator's tasks (P3) and suffer from misplaced salience (P5). In this regard, the question arises how designers can be encouraged to prefer suitable graphical visualizations during the design process to visualize information instead of showing raw text or numbers. Therefore, the ***creativity*** *of a designer has to be fostered and at the same time* ***guided into a way for using more efficient visualization attributes*** *to result in an* ***optimal solution****. These aspects result in a more detailed specification of this requirement in the following sub-requirements:*

R2.1 – Konect should allow creation of innovative new graphic forms.

The construction method should facilitate the finding of an ***optimal*** *solution. The optimal solution might not always be realizable via simple visual forms. Also, the high-usage of text should be avoided and thus the creation of new innovative graphic forms should be allowed to result in an optimal HMI solution for the monitoring task at hand. The term* ***optimal*** *is further specified in R2.3 and R2.4.*

R2.2 – Konect should foster creativity of the constructor/designer.

This requirement is necessary for promoting invention and knowledge and for finding an optimal solution as the ***optimal*** *solution can be a quite new innovative form.*

R2.3 – Konect should optimize the time needed to perceive a critical system state.

This requirement specifies the first optimization objective of the Konect method: A critical system state should be perceived by the human operator as fast as possible so that he/she can execute adequate countermeasures in time. This will further ensure the suitability of the chosen visualizations with the task of the operator and addresses P3.

R2.4 – Konect should optimize the accuracy of perceiving criticality of a system state in terms of reducing the amount of overlooked critical information relevant for estimating the system's criticality level.

This requirement specifies the second optimization objective in a way that the amount of assessment failures for critical system states should be reduced.

R2.5 – Konect should tailor the HMI to the operators tasks.

As described in the state of the art, current HMIs are often not optimized to adequately support the human operator in conducting his/her tasks efficiently (P3). HF methods, such as the EID or task analysis, already head towards assessing the tasks of the human operator to allow a better tailoring of the HMI to the human operator's work. As these methods consider only information elements and structure of these elements and neglect systemizing the choice of exact visual forms, Konect should consider the tailoring of the visual form to the operator's tasks. Therefore, Konect has to mind the expressiveness of visual forms. Expressiveness means that a graphical form exactly encodes the information needed by the human operator and does not allow less or more (e.g. missing information or misinterpretations).

R3 – Konect should be compatible with terms, methods, findings of other disciplines.

As the state of the art revealed that there exist different approaches for designing HMIs in the safety-critical domain (see section 2.3), the new method should consider previous works and be compatible with terms, methods, and findings. Furthermore, R3 is based on the requirements for a constructive method specified *by Feldhusen et al. [Feldhusen & Grote, 2013]. This can be specified in more detail:*

R3.1 – Konect should represent an extension of existing HF methods or allow compatibility with them.

The HF methods, such as the EID or task analysis (see Section 2.3.4), represent the state of the art for ***engineering*** *an HMI in the safety-critical domain. The state-of-the-art section revealed that there exists a gap regarding the exact visual form (P1). This should be closed by the Konect method. So, the Konect method should directly build upon the state of the art so that the current engineering way for defining such HMIs can still be applied, but in an enhanced manner for specifying the exact visual form.*

R3.2 – Konect should consider previous knowledge coming from the data visualization domain and the way of working in this domain (e.g. abstraction level).

The Konect method considers, on the one hand, the actual state of the art for engineering HMIs (see R3.1). On the other hand, the Konect method should bridge the gap between these HF methods and the visualization of information. Therefore, the Konect method has to apply knowledge coming from the data visualization domain. To include knowledge coming from this domain and to be able to later adapt or extend the method based on new findings in this research area, Konect should not only consider the actual knowledge coming from this domain, but also the way of working in this domain (e.g. abstraction level).

R3.3 – Konect should be compatible with guidelines and standards existent in the HMI design for safety-critical systems.

Besides HF methods (R3.1) and the data visualization domain (R3.2), Konect should be compatible with guidelines and standards existing in the domain (HMI design for safety-critical systems). This is especially important regarding the standards as NASA-STD-3000 or ISO-9241: The Konect method should enhance the HMI design activity with knowledge and a systematic procedure for finding an optimal visual solution. At the same time, it has to be ensured that requirements coming from the standards can be fulfilled and that promoted knowledge in Konect does not conflict with the instructions in the standards.

R4 – Konect should not create solutions by chance.

This requirement addresses P2 and is absolutely necessary as Konect follows an ***engineering*** *approach and thus HMI solutions should not be created by chance, but should be rationally justified. This leads to further sub-requirements:*

R4.1 – Konect should work with rational constraints.

To have a rational justification for choosing a certain visualization, Konect should work with rational constraints.

R4.2 – Konect's rational constraints should offer compatibility with perceptual and cognitive skills.

The constraints mentioned in R4.1 should be based on the perceptual and cognitive skills of the human operator: As the state of the art of current HMIs revealed, the choice for visualizations for the information shown on the HMI is not optimal with regard to human perceptual skills. The focus is rather on old systems and process hardware than the operator's mind [Opto22, 2014]. To provide visualizations that are optimized for the human operator's perceptual skills a design method has to mind these cognitive abilities. For this, the underlying dissertation has to examine actual cognitive models for human perception and ways as to how these models can inform the design.

R4.3 – Konect should provide a theoretical framework for rationally supporting decision-making for visual forms during design phase.

The aforementioned rational constraints have to be made applicable in an engineering procedure. Therefore, the knowledge has to be captured in an appropriate form. This can be done in form of a theoretical framework.

R4.4 – Konect's theoretical framework should offer help for synthesizing visual elements appropriately.

This requirement is derived on the basis of concepts of engineering methodologies and construction theory. Hansen presented the requirements for a systematic construction system [Feldhusen & Grote, 2013], stating that the possible construction elements should be combined appropriately as all different solu-

tions arise from such combinations. This step is often called synthesizing in the engineering theory.

R5 – Konect should allow easy transferability of design solutions to related tasks.

This requirement arises from characteristics that have to be accomplished by the construction methodologies in the engineering domain (see section 1.2). This can be concreted as follows:

R5.1 – Konect's theoretical framework should be based on perceptual and cognitive skills of humans in general and thus be domain-independent.

The HMI solutions created with Konect should be easily transferable to related tasks. For this, the theoretical framework should be based on perceptual skills of humans in general (instead of being specifically compliant with cognitive skills and prior knowledge of a certain group of expert operators [e.g. the control room operator for a specific power plant or truck driver]). Thus, the HMI solutions are domain-independent regarding the rational constraints posed by the theoretical framework and are consequently transferable to related tasks in other domains.

R5.2 – Konect's procedure should work on a partially abstract level that creates generally valid reusable solution documents.

This requirement is again based on the aspects important for constructive methodologies (see section 1.2) and is absolutely necessary for the transferability of HMI solutions to related tasks.

R6 – Konect should be teachable and learnable.

Feldhusen et al. stated that each constructive method should be teachable and learnable [Feldhusen & Grote, 2013]. As Konect represents such a method, it should follow this requirement. This will help to overcome P6 that current stan-

dards, guidelines, patterns, and procedures are actually not applied as the learning curve is too high and no systematic step by step approach can be followed.

R7 – Konect offers a numeric indicator system[1] for roughly comparing alternative solutions.

As the Konect method is oriented towards the construction system according to Hansen [Feldhusen & Grote, 2013], the Konect method might offer a numeric indicator system. With such an indicator system, it is possible to determine deficiencies of different HMI solutions systematically and determine the solution with the least amount/ lowest sum of deficiencies. Furthermore, this numeric indicator system offers a demonstration of rational reason for choosing a visual form and thereby addresses P2.

R7.1 – Konects numeric indicator system should reveal deficiencies of a design solution.

This requirement was directly derived on the basis of the construction system according to Hansen, as described before.

R8 – Konect should lead to a solution document that is usable as input for a software engineering process.

Similar to requirements specified before, this requirement is also directly derived from the characteristics of a construction method. A solution document, usable as direct input for a software engineering process, allows a sound implementation of the HMI design solution that can ensure the functional validation of the design and traceability in a V&V activity.

[1] german original: Kennzahlensystem

4 Related Work

Figure 4.1 gives an overview of the related works in comparison with the requirements of the Konect method developed in the dissertation. The details are described in the upcoming text. The requirements form the first row of the table shown in Figure 4.1 and are used as categories for comparison with related work.

User interface engineering that involves the systematic derivation starting from user scenarios, via task analysis, to the modelling of abstract, modality independent to concrete and final, executable user interfaces presentations has a long-lasting background in the user interface engineering domain [Meixner et al., 2011]: **Model-based user interface design (MBUID)** succeeded in generating (multimodal) form-based interfaces for that widgets are pre-set (e.g. via a toolkit). These methods mind a systematic procedure at the expense of creativity and a total design space. They can only be applied for a small range of user interfaces as toolkit widgets are limited. This aspect leads to the fact that the requirement R2.1 (new graphic forms), as shown in Figure 4.1, cannot be fulfilled and that MBUID does not foster creativity (R2.2). In contrast to these works, Konect aims at having a systematic approach that still leaves open the design space to very different and creative visual solutions and still minds the efficiency of visual forms. The similarity is that both approaches strive for systematization to offer a sound engineering base for HMI design. Both offer traceable design decisions—e.g. via mappings between models [Stanciulescu et al., 2005]. This is the reason why MBUID fulfils R4 (rational constraints) and provides task fitness (R2.5) as well as a solution document (R8). An example of such an MBUID method is **Gummy** [Meskens et al., 2008]. Gummy offers a systematic procedure for designing user interfaces for different computing platforms.

MBUID is mainly situated in the end-user domain, as most often desktop or web-based user interfaces are in the main scope. Furthermore, the main optimization focus of MBUID lies in optimizing the usability of these systems. Thus, compared to the Konect method, MBUID is situated in another context and does not directly aim for optimization of fast and accurate perception (R2.3, R2.4) and does not consider fostering the creativity of the designer.

In addition, MBUID does not offer any numeric indicator system as intended by the Konect method (R7).

Nevertheless, MBUID is industry-independent (even though mainly focusing on WIMP

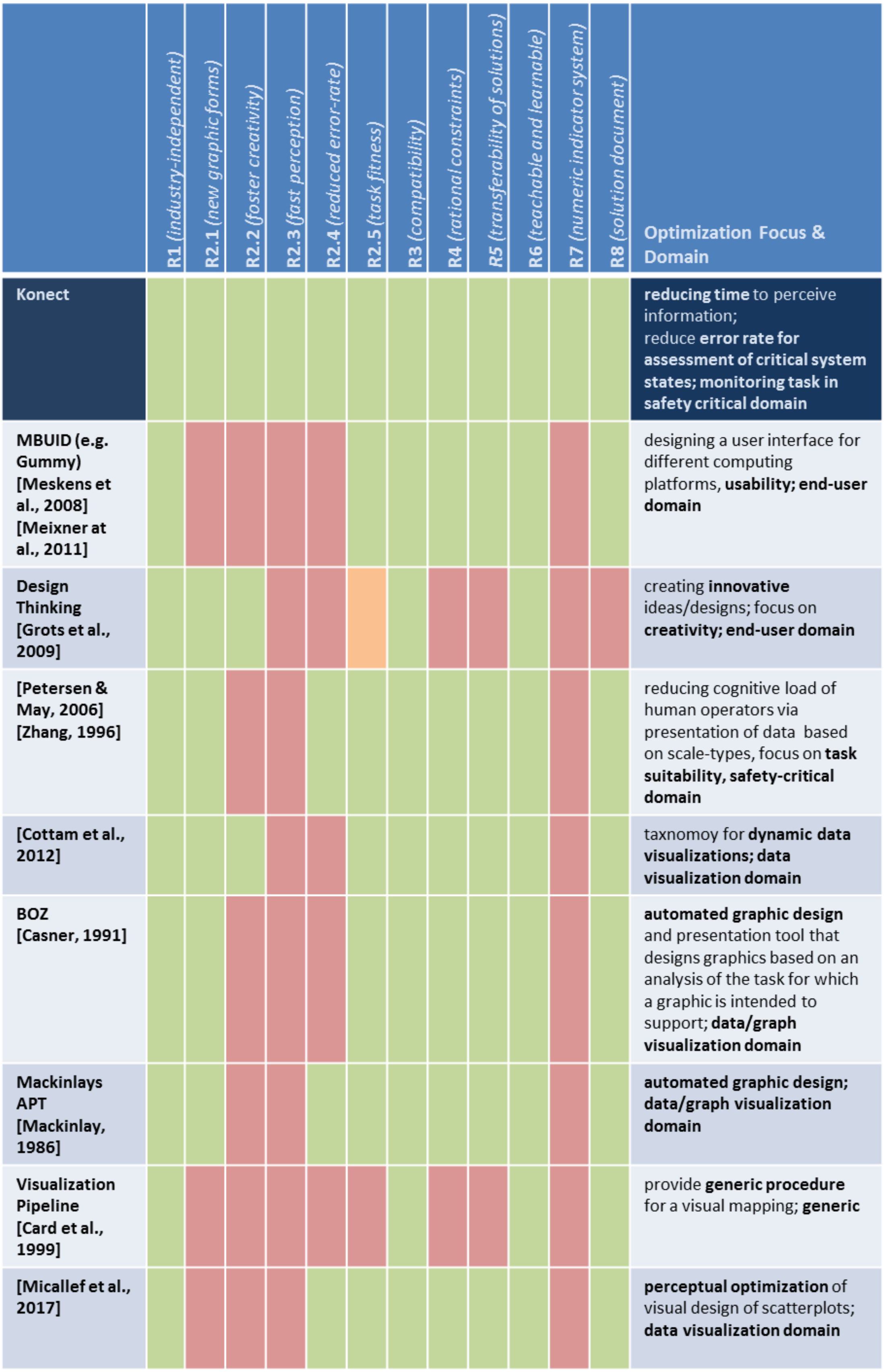

Figure 4.1: Overview of related procedural approaches for deriving visualizations.

applications) and is teachable and learnable as concrete instructions that can be followed (e.g. [Meskens et al., 2008] exist.

Design Thinking is widely applied in the user-centred design process. Design thinking is based on the assumption that problems can be better solved if people from different disciplines work together in a creativity-promoting environment, jointly develop a question, consider the needs and motivations of people, and then, develop concepts that are tested multiple times. Compared to MBUID, design thinking focuses on fostering creativity and aims for coming up with innovative solutions (R2.1, R2.2). This is done at the expense of a systematic procedure that allows the traceability of design decisions. Such traceability might only be achieved in case that the design activity is carefully documented. But this is not the main objective of design thinking. This leads to a missing solution document (R8) and the aspect that design solutions are not transferable to other problems (R5). Furthermore, design thinking does not include rational constraints (R4). All knowledge applied in the design phase depends on the knowledge of the experts involved in the design thinking activity. This is also the reason why the task fitness is colored in orange in Figure 4.1: This strongly depends on the experts' knowledge included in the design thinking workshop.
As the design thinking approach leads to the creation of different design solutions without having rational constraints, the designs have to be evaluated extensively in empirical studies in case the resulting design should be used for safety-critical purposes. As safety-critical domains often have expert users, such tests are expensive and there exists only limited access to the users. This is the reason why design thinking is well-accepted in the end-user domain (in which a lot of potential users are available and a high amount of post-hoc tests can be conducted), while design thinking is less common in the safety-critical domain, even though it is industry-independent (R1)

In the safety-critical domain, related work was conducted by **Petersen & May** [Petersen & May, 2006]. Similar to Konect, Petersen, and May are situated in the context of visual displays for the supervisory control task. In this regard, Petersen et al. discuss the use of the so-called *scale types* (e.g. nominal, ordinal, interval, ratio). Scale types are based on well-established works of Stevens et al. [Stevens et al., 1946] and are important in relation to information presentation: „When one wants to present data, it is important to consider the scale type of data because it provides important cues about which formats are suitable for the presentation of data" [Petersen & May, 2006]. Having the scale type of information, Petersen et al. tailor the information presentation to the information needs of a human operator in particular task situations and thus reduce their cognitive load. The authors refer to the findings of Woods et al. [Woods, 1984] that information presentation „has shown to be crucial with respect to how well operators can perform their tasks" [Petersen & May, 2006]. To define the scale type, the authors present rules for the mapping data shown to the operator to a certain type of scale. To convert the information into a visual form, Petersen et al. make use of a theoretical framework, developed by Zhang et al. [Zhang, 1996], thereby making use of rational constraints (R4).

Zhang et al. presented a theoretical framework for describing properties and structures of relational information displays (RIDs). The framework does not apply an efficiency ranking for visualizations, but is more oriented towards expressiveness. Thus, the framework can only be applied for deriving suitable visualizations and does not aim to deduce the most efficient visualization with regard to time and correctness level of percept: „... the information that can be perceived from an RID should exactly match the information required for the task. Thus, although there are no best displays that are efficient for all types of tasks, there is a correct or incorrect mapping between the representation of a display and the structure of a task" [Zhang, 1996]. This leads to the aspect that this prior work is applicable to ensuring task fitness (R2.5) and considers a reduced error rate for perceiving information (R2.4), but it does not optimize the design for fast perception (R2.3).

Konect's aim is to go one step further and offer a possibility of systematically optimizing the HMI for fast perception of critical system states and to reduce failures based on overlooking relevant information. This implies that not only expressiveness, but also effectiveness is considered. Both approaches consider human perception in general and thus are industry-independent (R1).

Owing to the mapping, the approach of Petersen et al. results in a solution document (R8) after conducting the design procedure. Furthermore, the concrete description leads to the fulfilment of R6 that the approach is easily teachable and learnable.

Aside from works in the user interface design domain, there exist related works in the data visualization domain, as this domain is mainly concerned with visual appearance of information. Especially in the graph visualization domain, considerable progress was made during the last decades, starting with works of Bertin [Bertin, 2011] in 1967. Bertin was an experienced cartographer. Based on his background and practice, he constituted the *semiology of graphics*, in which he presented the first theoretical foundation of information visualization. The work of Bertin is strongly cited in the scientific domain and can be seen as the fundamental cornerstone for a science of visualization. Most of the works in the data visualization domain are based on this first cornerstone, such as works of **Cottam et al.** [Cottam et al., 2012]: Cottam et al. presented a taxonomy and conceptual framework for understanding how data changes influence the interpretability of visual representations. The difference between Cottam et al. and the work done in the dissertation lies in the regarded subject: Cottam et al. focus on the dynamics of data and its interpretability and is less concerned with fast and correct perception in supervisory control tasks. Thus, R2.3 and R2.4 are not fulfilled. Furthermore, the approach presented by Cottam et al. does not provide a numeric indicator system and thus does not fulfil R7.

The approach provides a mapping of visualizations to different categories and thus provides rational constraints (R4) as well as a solution document (R8). As Cottam et al. provides a detailed overview of all categories, the approach is teachable and learnable (R6). The mapping approach of the presented taxonomy can be applied for creating new graphics (R2.1) and fostering creativity (R2.2). In this regard, it has to be kept in mind that the taxonomy aims for describing or even criticize existing dynamic data visualizations. Thus, it is not optimized to be used as a constructive design method, even though it can be applied to ensure that visualizations are well tailored to tasks (R2.5).
In contrast to this, Konect follows a more constructive approach to fulfil R1-R8.

Further works coming from the data visualization domain are works of Casner [Casner, 1991] and Mackinlay [Mackinlay, 1986]: **Mackinlay et al.** proposed a ranking of various graphical attributes to present data of different types (ordinal, nominal and quantitative) that is strongly based on and extends works of Cleveland and McGill [Cleveland & McGill, 1984]. These rankings have been integrated in various automated design approaches such as **BOZ** [Casner, 1991], which is an automated design and presentation tool to help expedite the human performance of information processing tasks. The rankings do not consider the time to perceive information but only perception accuracy. Thus, the works of Casner et al. and Mackinlay et al. do not fulfil R2.3 (fast perception), but support a reduced error rate due to an increased perception accuracy (R2.4). Nevertheless, the rankings ensure task fitness (R2.5) and provide rational constraints to decide for visualizations (R4). As the ranking is on a high abstraction level, the design solutions are transferable (R5) and the mapping process ensures that a solution document can be created as output of the design process (R8).
Owing to the idea of automating the design process, Mackinlay's approach as well as BOZ does not foster creativity (R2.2), even though they can lead to automatic creation of new graphic forms (R2.1) by automatically combining different visualizations. Konect is not aiming at automating the generation of designs, but focuses on guided creativity, while at the same time ensuring that design decisions are traceable and rationally justified. Similar to BOZ, the resulting designs aim to support the human's information perception performance. In this connection, the dissertation is based on cognitive models that inform display design: „Empirical methods used in cognitive science and related fields (e. g. human factors) are central to testing and revising design principles based on objective data. Moreover, knowledge of human information processing and empirical measures of performance with visual displays can inform the development of cognitive models that make a priori predictions about display effectiveness."[Hegarty, 2011]. These are objective measures, which are especially important since expert intuition can be erroneous.

Card et al. presented the so-called **visualization pipeline** for converting raw in-

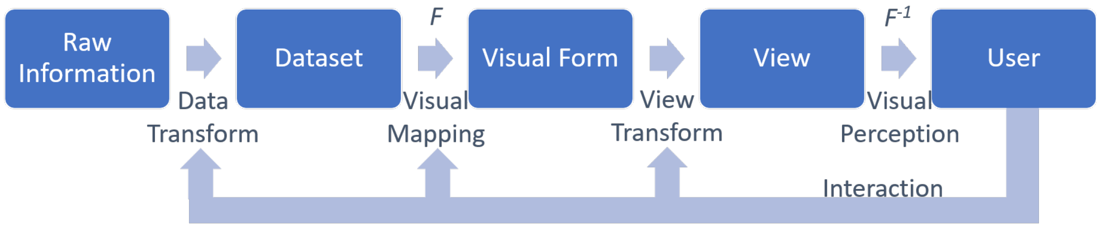

Figure 4.2: Visualization Pipeline (based on [North, 2006] and on adaption by [Card et al., 1999]).

formation into visual representations [Card et al., 1999]. The visualization pipeline is shown in Figure 4.2. The pipeline starts with raw information that needs to be transformed into the dataset. A very important aspect of the visualization pipeline lies in the visual mapping to derive a visual form for the data to be shown. Based on Card et al., this mapping should be computationally done by some function F by taking the dataset as input and generating the visual form as output [North, 2006]. This function F implies four important characteristics:

computable F can be computed by some algorithm.

invertible F must be invertible by some function to ensure that the visualization is not ambiguous or not understandable by the user looking at the visualization.

communicable The visual mapping F must be known by the user so that he/she can understand the visualization and interpret the shown information in the right way. Based on North [North, 2006], this is a learnability issue.

cognizable The function F should be easily perceivable by the user and should minimize his/her cognitive load for decoding and thereby interpreting the visualization.

Card et al. aim at systemizing the design activity having the focus solely on a sequence of steps and characteristics of a mapping function. The exact specification for the mapping is not determined in detail. Thus, the requirements R2.2, R2.3, R2.4, R2.5, R4, R5, and R7 cannot be fulfilled. Nevertheless, the sequence of steps is industry-independent (R1), teachable and learnable (R6), ensures that a solution document is provided as input (R8), and happens to be compatible with other approaches to fill the steps with content on how to specifically create a design. For this, there exist some guidelines in the literature: Ware et al. [Ware, 2004] [Ware, 2010], Meirelles et al. [Meirelles, 2013] and Tufte [Tufte, 1997] [Tufte, 1990] present some fundamentals about information visualization based on experience. For anyone attempting to capture this knowledge, this is a major challenge as a direct connection between this knowledge of information visualization and a systemizing procedure (e.g. the visualization pipeline) does not exist.

Micallef et al. [Micallef et al., 2017] work on the perceptual optimization of visual design of scatterplots. The authors use models about human perception to determine parameters, such as marker size and opacity, aspect ratio, or color, to optimize the visual design of a scatterplot automatically. This paper contributes to research exploring the use of perceptual models and quality metrics to set such parameters automatically for enhanced visual quality of a scatterplot. For this, the authors developed a function that can be used to search for the optimal visual design for a user's dataset and task objectives (e.g. „reliable linear correlation estimation is more important than class separation"). Thus, the work of Micallef et al. provide rational constraints (R4), even though it is actually limited to scatterplots. As the optimization is calculated automatically, the approach does not aim to foster creativity (R2.2). As the focus lies on scatterplots, the approach is not applicable to new graphic forms (R2.1). The models of human perception used by the authors focus on the accuracy of perception (R2.4) and not on fast perception (R2.5).
Like this work, Konect also aims for setting rational constraints to the design based on the compatibility of visual forms with human perceptual and cognitive skills. But Konect is situated in another context and does not work with single graph visualizations. Furthermore, Konect does not aim to generate such HMIs automatically, but proposes a constructive method applicable by HMI designers and engineers.

Summarizing, it can be said that none of the existing works fulfil all requirements intended by Konect. Even though all works reviewed in this chapter can be applied independent of the industry domain (R1), are teachable and learnable (R6), and offer full compatibility with existing standards (R3), each work has a slightly different optimization focus: The works mainly ensure task fitness (R2.5). Some works further aim at increasing the perception accuracy, thereby reducing the error rate for perceiving information (R2.4), while none optimize the time to perceive critical system states (R2.3). Despite the design thinking approach and the visualization pipeline, all works include rational constraints (R4) to substantiate the choice for visualizations. This leads to a good transferability of design solutions as the design decisions are transparent (R5). This is similar for a solution document as transparent design decisions allow traceability of visualization choices (R8). Especially noticeable is the fact that no constructive design method exists which includes a numeric indicator (R7).

5 Conceptualization of a Method for Deriving Rationally Justified Information Visualizations - The Konect Method

In this chapter, the method conceived in the dissertation is depicted in detail. An overview of the contribution is shown in Figure 5.1. This is composed of three different aspects: The first aspect, which builds the core of the approach, is the theoretical framework. This theoretical framework constitutes the scientific base of the method and is presented in Section 5.1. On this scientific basis, a systematic step-by-step procedure is specified that makes use of the knowledge established in the theoretical framework and allows easy applicability of the method (see Section 5.2). To further support the designer in applying the method, a tool support is implemented and shortly illustrated in Section 5.3. To proof the validity of all parts of the method, several evaluations and studies were conducted and are presented in Chapter 6.

Figure 5.1: Konect: Overview.

5.1 The Konect Theoretical Framework

The Konect method should offer rational justifications for visual forms and ensure that critical system states are fast and correctly recognizable by a human operator. To ensure this aspect, accepted knowledge has to be incorporated. Therefore, this chapter identifies *key concepts* of the Konect method, analyses well-established **theories**, and establish orderly **connections between different concepts and theories** that are needed to incorporate existing knowledge in the design procedure. In this regard, „a theory is a well-established principle that has been developed to explain some aspects of the natural world. A theory arises from repeated observation and testing and incorporates facts, laws, predictions, and tested hypotheses that are widely accepted." [Cherry, 2018]. *Theoretical Framework* is an established term [USC, 2018]: A theoretical framework consists of concepts and offers a structure to show the key concepts to be considered and the connections established between different well-accepted theories. The theoretical framework is strongly based on the current literature and provides the scientific basis for the method presented in the dissertation. This theoretical framework ensures that the chosen visualizations are rationally justified and the designer works towards an optimal design solution regarding the time needed to perceive the criticality level of a system and with respect to the reduction of assessment failures for such states. The theoretical framework is shown in Figure 5.2. In the following sub-section, a short overview of all key concepts in this framework is provided. Details for all parts are then described in the subsequent sections.

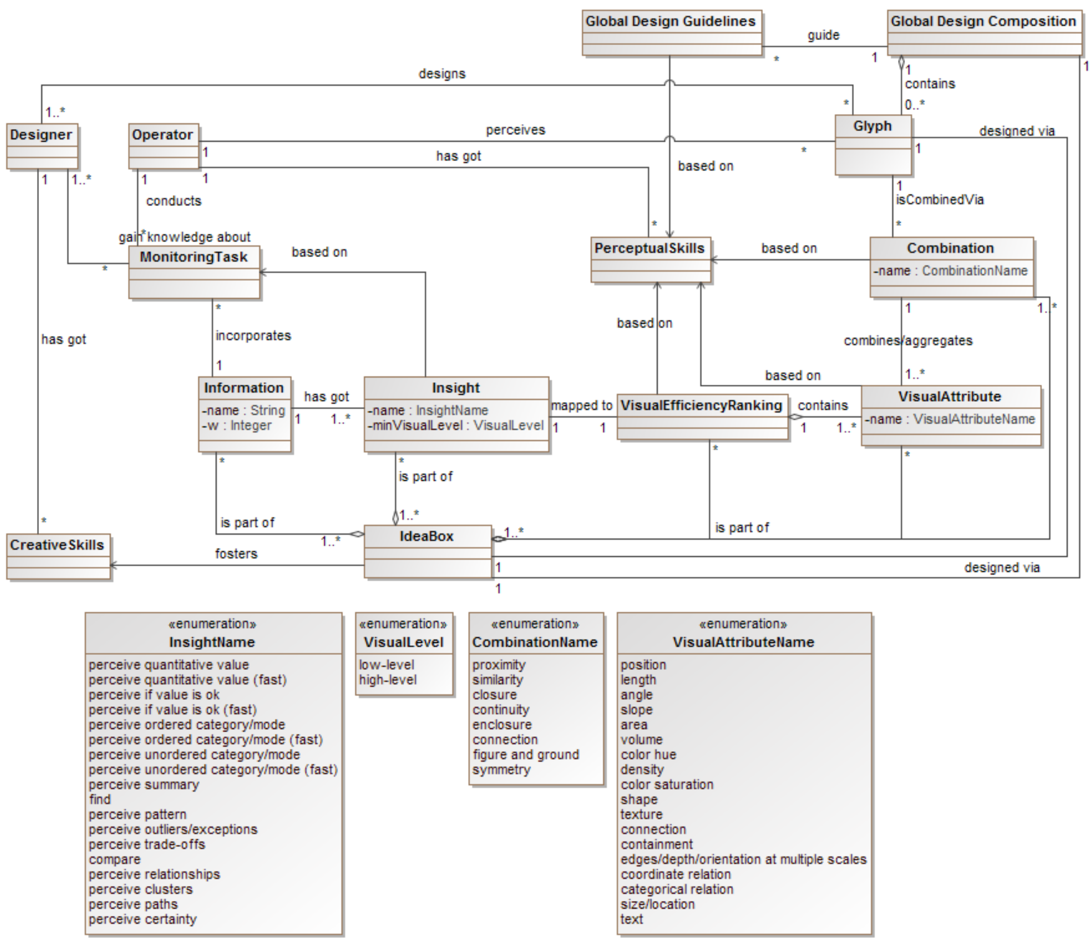

Figure 5.2: The theoretical framework of Konect.

Overview

In the left corner of the theoretical framework, the two main actors are depicted: On the one hand, there exists the *designer* of the HMI who applies the Konect method; on the other hand, the human operator is of importance as he/she is the user of the

resulting HMI. The theoretical framework investigates different cognitive skills of these two actors. With regard to the designer, the *creative skills* are of interest as these skills should be fostered within the application of the method (cf. Requirement R2). With regard to the operator—e.g. the user of the HMI—the *perceptual skills* are important as they should be optimally supported by the HMI (cf. Requirement R4.2).
The state of the art and related works have shown that the task of the human operator is important for the design of the HMI. Therefore, the designer has to gain knowledge of the *monitoring task* with HF methods (Section 2.3.4). This task incorporates *information* elements that need to be visualized. Such an information element can be specified via a name and has an importance (w) for the monitoring task. Each information is coupled to at least one *insight*—the knowledge the human operator wants to acquire when looking at the information (e.g. a quantitative value or whether the value is ok or not). This insight is strongly based on the task the human operator conducts. The information with the defined insight has to be visualized via a *visual attribute*. To ensure that this visualization can be perceived most efficiently by the human operator, a *visual efficiency ranking* for each insight is provided. This is based on the knowledge of the *perceptual skills* of the operator. Besides these perceptual skills, the Konect method has another core concept: the use of so-called glyphs. Glyphs are integrated visual forms that combine different visual attributes to allow the perception of information at one glance and support better remembrance of the seen elements [Ware, 2004]. To construct such a glyph, the visual attributes have to be synthesized via *combination* possibilities (e.g. symmetry, connectedness). This combination is strongly based on the Gestalt laws. To create the overall design, called *global design*, various glyphs have to be combined in a *Global Design Composition*. This is guided by the *global design guidelines* which are based on the knowledge of human perceptual skills.
As the designer has to construct glyphs creatively, but always in a rationally justified way, the information needed at the design stage has to be prepared and provided in a suitable format that fosters his/her creative skills. This is achieved via the *idea box*.
Details of parts of the theoretical framework are described in the upcoming sections.

5.1.1 Information

The HMI should optimally support the supervisory control task of the human operator (cf. Requirement R2.5). To achieve such optimal support, the information to be displayed plays an important role. In this regard, the term *information* specifies data that contains a valuable meaning for the task at hand (e.g. speed, temperature of a certain equipment). All information needed by the human operator should be visualized—neither more information nor less information. More information could have the effect of distracting the human operator and producing clutter on the HMI. On the other hand, less information can lead to overlooked problem situations or anomalies. So, no countermeasures will be initiated, and this might pose a threat to the safety of the whole system.

The state of the art already offers possibilities to assess the information needed by the human operator to successfully conduct his/her task. This can be done via HF methods (section 2.3.4). Furthermore, previous works exist for investigating the inconsistencies between information supply and demand [Denker et al., 2014].

Previous works proved that HMIs are more efficient in case a good fitness between the information needed during the task execution and the information visualized is obtained [Gillan & Callahan, 2000] [Hegarty, 2011]. In this regard, Peebles et al. even recognized that a less familiar graph can be more effective than a familiar one in case it is better tuned to the task requirements [Hegarty, 2011] [Peebles & Cheng, 2003].

Thus, it plays an important role to assess and specify information required for the operator's task at hand. This includes the information itself (specified via a name—e.g. engine temperature) as well as the importance of the information.

5.1.2 Insight

„If the goal of visualization research is to transform data into a perceptually efficient format, and if we are to make statements with some generality, we must be able to say something about the types of data that can exist for us to visualize" [Ware, 2004].

Besides having the right amount of information and the right information elements, the reason **why** the human operator needs the information is quite important to allow a better tuning of the interface to task requirements. Within the Konect approach, this is called the *insight*. The term insight is based on works of North and Card et al.: „Yet, a more important benefit is the human ability to visually reason about the data and extract higher level knowledge, or insight, beyond simple data transfer [Card et al., 1999]. This enables users to infer mental models of the real phenomena represented by the data. "[North, 2006]. *Insight* is „an instance of apprehending the true nature of a thing, especially through intuitive understanding"[1]. In connection with the Konect method, insight defines what the human operator should intuitively apprehend when looking at the visual form—e.g. *quantitative value* of an information, *certainty* of an information, or to which *category or mode* the information belongs.
The insight further ensures the fitness of the HMI to the operator's task and allows an estimation for the expressiveness of graphic forms (Requirement R2.5).

As mentioned before, one aspect of the theoretical framework is to establish connections between key concepts. What the operator wants to apprehend and gain as higher

[1] https://www.dictionary.com/

level knowledge when looking at the visual form naturally depends strongly on his/her task. In the dissertation, the focus is on the supervisory control task, more specifically on monitoring. According to North [North, 2006], the number of possible insights in the monitoring task is limited. These are listed in the following text. The insights were derived according to the literature ([North, 2006]) and the case studies presented in Section 2.2.1.

Perceive quantitative value: With this insight, it is specified that the human operator is interested in the quantitative value of an information element. This is a numeric value—e.g. a number or an amount on which arithmetic operations can be performed. An example can be the quantitative value of the temperature of a certain technical equipment (e.g. in °C).

Perceive quantitative value (fast): The quantitative value should be perceived as fast as possible. The value is of higher importance and should visually stand out from the surroundings.

Perceive if value is ok: The human operator should be able to assess the state of the underlying parameter or information element(value is ok or not ok). In this case the value should be perceived as a nominal value. Nominal means that the value can be categorized without having a natural order (ok, not ok)—e. g. regarding a temperature indicator, the human operator wants to assess whether the temperature is within the normal range for the regarded technical equipment or if it exceeds permissible limits.

Perceive if value is ok (fast): The state should be perceivable as fast as possible and should visually stand out from its surroundings.

Perceive ordered category/mode: This insight specifies that the human operator is interested in the values' category or mode. This implies that the information is classified as ordinal value. Ordinal means that the value can be categorized and the categories have a natural order—e.g. the value has low urgency, middle urgency, high urgency.

Perceive ordered category/mode (fast): This insight indicates that the ordered category or mode information is of high importance and should be perceived rapidly.

Perceive unordered category/mode: Compared to the previously described insight, this insight deals with *unordered* categories or modes. In contrast to the previously defined insight (*perceive ordered category)*, the information is not classified as ordinal, but as nominal information (without natural order). This can be, for instance, the mode *on* or *off* of a certain technical equipment.

Perceive unordered category/mode (fast): Like the previously mentioned insights with addition *fast*, this information category should be used to define the information as being of high importance that must be perceived rapidly.

Perceive summary (min, max, avg, %): A quantitative summary of a certain value should be perceived by the human operator—e.g. a kind of aggregation is calculated via mathematical formulas. This can be an average, the value as percentage, the minimum or maximum.

Find: The finding of a value should be supported via the visualization. This means that the parameter must visually stand out from the surroundings.

Perceive pattern: A pattern should be perceived. In this case, a pattern describes a discernible regularity that should be observable by a human operator as the parameters forming this pattern might get repeated in a predictable manner. This can, for instance, help to visually indicate a known solution to a class of problems occurring during the supervisory control task in the system under observation.

Perceive outliers/exceptions: An outlier or exception should be identified by the human operator. This means that a parameter is not within its defined range or behaves unusually, and thus, represents an outlier or exception.

Perceive relationships: The information should be perceived as a relationship (often between two different information elements). This might be a correlation between two parameters—the impact one parameter can have onto another or dependencies between parameters. In case more than two different information elements are involved, there can also be multi-way interactions.

Perceive trade-offs: A trade-off should be perceived by the human operator. Compared to the insight (perceive relationship), this insight regards exchange of relationships as a balance between information elements or a combined minimum and maximum.

Compare: The human operator should be able to use this information to compare two or more different information elements like the height of two parameters.

Perceive clusters: A cluster should be perceivable. This means that similar elements or groups are easy perceivable by the human operator.

Perceive paths: The human operator should perceive the information as path. This is strongly related to spatial and physical proximity of different information elements e.g. the distance between a ship and a quay wall.

Perceive certainty: This insight is not defined by North et al. [North, 2006]. But the case studies presented previously have shown that this insight is often needed by human operators when dealing with sensor values. In this case, the certainty of the correctness of the values is often needed as insight by the human operator.

As the insight is strongly coupled to the task at hand, the specification should be done carefully by the designer of the HMI. The better the chosen insight fits the human operator's tasks and his/her desired knowledge that should be retrieved when looking at the HMI, the better the chosen visualization can support the operator in achieving his/her tasks. The choice for an insight has influence onto the efficiency of a visual attribute (e.g. color, shape, position, etc.). For instance, if a human operator wants to know the quantitative value of a parameter, a bar chart is a good indicator; in case he/she only wants to know if the parameter is in a critical state, a color indication is perceivable and sufficient in a much faster way for the task at hand. Thus, the insights described before are of crucial importance for defining which visual attributes are efficient for visualizing information in a way that the tasks of the human operator are well supported. Which visual attributes are most efficient regarding the predefined insights is described in the upcoming section dealing with the perceptual skills of the human operator.

5.1.3 Perceptual Skills of the Human Operator

Deciding for a visualization during the design of the HMI depends on the one hand on the task of the human operator (see description about information and insight). On the other hand, the visualization has to meet the optimization objectives defined in the dissertation (cf. Requirements R2.3 and R2.4): Thus, it has to be considered what is most efficient in matters of the time and correctness by the human operator to perceive the desired insight. This involves the perception of visual attributes by the human perceptual system. The efficiency of visual attributes—concerning time and correctness to perceive them—differs strongly. The reason for this aspect lies in the human perceptual skills and in the way the human eye and brain process these attributes. The following sections examine actual cognitive models for human perception and ways how these models can inform the design.

The scientific research on the way the human visual system works has a long history starting in the year 1021/1024 with works of ibn al-Haytham Alhazen, who is regarded as the „father of visual cognition and optics". Alhazen already detected the way the visual system works regarding light entering the human eye and being transformed into signals which are transferred to the human brain [Darrigol, 2012]. In the years 1856 to 1967, Helmholtz published his „Handbuch der physiologischen Optik" in six parts. This book describes the basics of the human visual system as we understand it today. These early works on the human visual system provided the basis for further research conducted in this field.
Later works can be roughly subdivided into works about „low level vision" and works focusing on „high level vision". While *low level vision* focuses on the perception of single visual attributes as color and length, *high level vision* deals with the so-called perceptual organisation of single visual attributes: „When we view the world we do not see a collection of edges and blobs – unless we adopt a very analytical perceptual attitude – but we see instead an organised world of surfaces and objects. How is such perceptual organisation achieved?" [Bruce et al., 2003].
Works having a focus on *low level vision* are concentrating on the perception of graphical elements [Cleveland & McGill, 1984] [Mackinlay, 1986] and how efficient elements are processed. The latter aspect especially addresses how fast visual elements can be perceived. In this regard, the concept of „pre-attentive processing" was identified. Visual attributes that can be perceived within the millisecond range are considered as being *preattentive* [Ware, 2004]. The first time the concept of pre-attentive perception has been raised in the literature was within the filter model of attention published by Donald Broadbent in 1958 [Broadbent, 1958]. Later, further works have been published studying this effect ([Treisman, 1985] [Wolfe, 1994] [Healey et al., 1996]).
High-level vision works are, for instance, the Gestalt laws [Wertheimer, 1923], Garners Good Patterns [W.R. & Clement, 1963], Marr's work on the computational investigation into the human representation and processing of visual information [Marr, 1982], Biederman's recognition by components theory [Biederman, 1987], Kosslyn's architecture for *high level vision* [Kosslyn et al., 1990], Rensink's architecture for the visual system [Rensink, 2000] [Rensink, 2002], and the structural information theory provided by Leeuwenberg et al. [Leeuwenberg & Van der Helm, 2012].
The findings and knowledge established in this profound research is applied within the Konect method to inform the interface design in a suitable manner. This is described in detail in the following sections.

5.1.4 Visual Attributes

As defined in the requirements section, the Konect method should be compatible with terms, methods ,and findings of other disciplines (Requirement R3). Regarding the visualization, it becomes especially important that Konect considers prior knowledge coming from the visualization domain and the way of working in this domain (cf. Requirement R3.2). The way of working in this domain should specifically consider the abstraction level of working in this domain. Otherwise, findings and especially new knowledge established in these domains will not be includable in potential future extensions of Konect.
The works of Bertin [Bertin, 2011] and Carpendale [Carpendale, 2003] represent one of the most fundamental cornerstones in the visualization research. Later scientific works adopt this abstraction level (e.g. [Mackinlay, 1986], [Rautenbach et al., 2015], [Halik, 2012], [Weber, 2017], [MacEachren et al., 2012], [Kornhauser et al., 2009]). This is the reason why the Konect method will apply the way of working and the abstraction level.

The visual attributes used on this level are shown in Figure 5.3 and are *position*, *length*, *angle*, *slope*, *area*, *volume*, *color hue*, *density*, *color saturation*, *shape*, *texture*, *connection* and *containment*. Related to prior work stated in the previous paragraph, *text* (including numbers and characters) is not a visual attribute in this sense and rather occupies a special role: Text is very inefficient for encoding information (regarding fast perception and state estimation with one glance) and should be avoided as the only attribute for encoding information [Gruhn, 2011]. However, it is common practice to use text as a label. This is called *double-coding* and does not affect the efficiency of any selected visualization and the overall global design [Ware, 2004].

Position refers to a spatial location of a visual element. This can change via the x- and y-coordinates of the element. In case the visualization is three-dimensional, the position can be defined by the x-, y- , and z-coordinates.

Length describes the height or width of a visual element. Important is that only one dimension (height ***or*** width) is regarded.

Angle refers to a visual gap that is formed by two connected lines. In accordance with planar geometry, the angle can lie between 0 degrees and 360 degrees.

Slope describes the orientation (in vertical and horizontal direction) of a visual element—e. g. in case of a line, this is the gradient or steepness of the line.

Area has a width and length and thus depicts the size a visual element captures.

Volume is much related to area. Compared to area, volume describes the space in

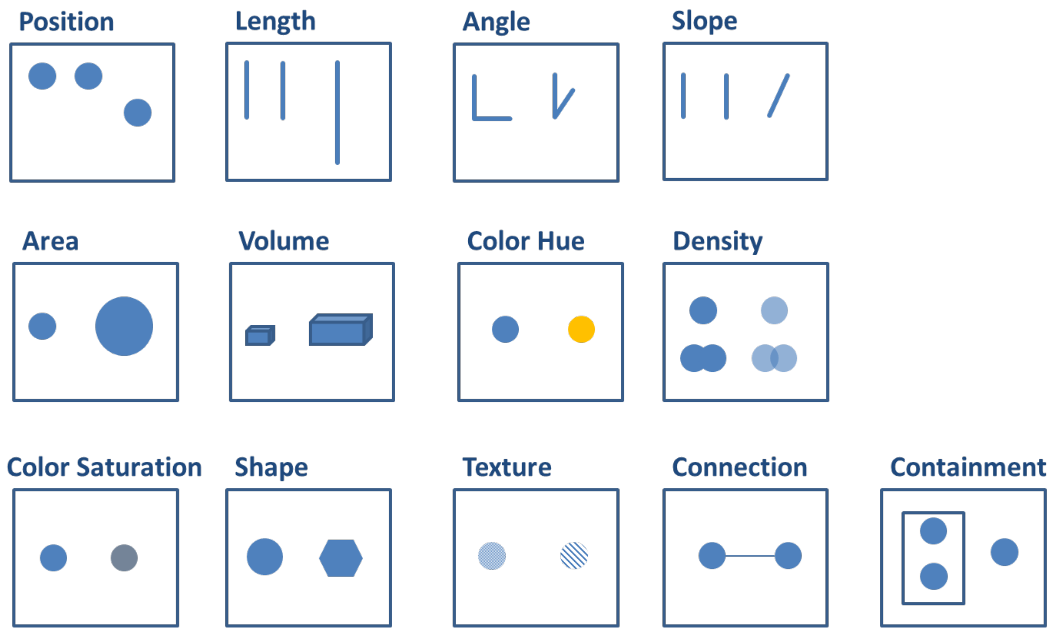

Figure 5.3: Visual Attributes (*Low Level Vision*).

3D a visual element captures. Hence, it has width, length, and height, while the area is only specified via width and length.

color hue represents the color of a visual element e.g. red, blue. In this regard the word „hue" is important. It characterizes that the differences between two different colors are not achieved via adjustment of saturation or density (see next two points), but really refer to different color tones like green, red, blue, yellow.

Density represents the opacity of the filling of a visual element. This can lead to transparency effects as shown in Figure 5.3.

color Saturation describes the intensity of a color. This is determined by the light intensity in the color. To reduce color saturation, the color can be mixed with white, black or grey.

Shape describes the contour of a visual element. There exist almost infinite possibilities for assigning different shapes.

Texture is sometimes called „grain" (see [Carpendale, 2003]) and refers to the filling of a visual element with a pattern—e.g. horizontal stripes.

Connection portrays a visual link between two visual elements. This can be, for instance, a connecting line between two circles or other visual elements (see Figure 5.3).

Containment means that visual elements are included in another visual element. This means that the outer visual element surrounds the inner visual elements.

The described visual attributes mostly address *low level vision*. To allow conducting visual tasks that can only be conducted in *high level vision* (e.g. in case the human operator has to see relationships between two elements), these attributes have been extended in the underlying dissertation by visual attributes based on works of Kosslyn [Kosslyn et al., 1990, Kosslyn, 2006] and Rensink et al. [Rensink, 2000, Rensink, 2002]. These are shown in Figure 5.4 and described in the following text. So, these attributes include one or more visual elements and rather describe the visual relationships between them.

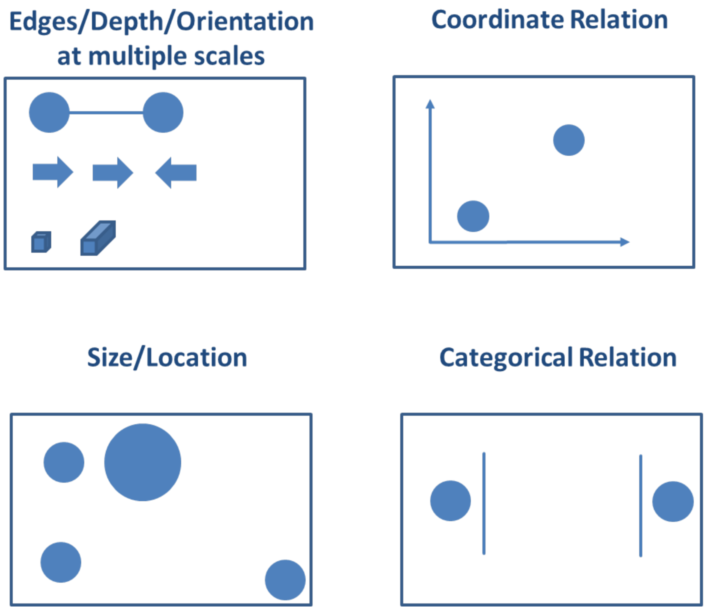

Figure 5.4: Visual Attributes (*High Level Vision*).

Edges/Depth/Orientation at multiple scales refer to three kinds of relationships between visual elements at multiple scales: An *edge* is closely related to the connection described before. It can be realized via a line between two elements. At *multiple scales* means that this can be either done in a 2D arrangement in the form of a 2D connection line or also at more scales (x, y, z) in 3D space. The *depth* refers to the arrangement of elements in 3D space. So, the virtual distance to the viewer specifies the depth of a visual element. The *orientation* addresses the direction and spatial alignment of a visual element in space.

Size/Location strongly refers to the visual attribute of the area and position described before. The distinction is now that the focus lies on the differences of the size or the location of two elements, as this describes the relationships between them (e.g. *a is larger than b*).

Categorical Relation defines a spatial relation between visual elements via categories (e.g a is *below* b or a is *left of* b).

Coordinate Relation also defines a spatial relation between visual elements but via coordinates. This can be either done in 2D space (x, y) or in 3D space (x, y, z).

5.1.5 Visual Efficiency Ranking

After the definition of the visual attributes, the visual mapping between the previously described insights and an efficiency ranking of these visual attributes have to be conducted on a scientific basis. This mapping is essential for providing rational constraints to find an optimal HMI solution. This is indispensable for fulfilling Requirement R4. The visual mapping is the „most critical aspect in designing a visual representation." [Mazza, 2009]. For conducting the visual mapping, a visual efficiency ranking is established based on the findings about human perceptual skills (cf. Requirement R4.2) and is tailored towards the optimization objectives of the underlying dissertation (R2.3 [time] and R2.4 [correctness of assessment]). The visual efficiency ranking is, therefore, strongly coupled to the insight— the knowledge the human operator wants to extract when looking at the visualization to further fulfil Requirement R2.5 (fitness to task). In Figure 5.5, the visual efficiency ranking for each insight is given. The explanation of how these efficiency rankings have been specified in the underlying dissertation is described in the following text.
As mentioned before, *text* occupies a special role. It should be avoided as it is a quite inefficient form (regarding fast perception and state estimation with one glance) for encoding information. Nevertheless, text might be an appropriate choice—e.g. for information elements that have a quite low importance for the task at hand and should not be visualized too prominently to make more important information stand out visually. As this aspect should be reflected in the efficiency rankings, *text* is mentioned as the penultimate element in all rankings. Similarly inefficient is choosing a visual attribute which would be *not expressive* for the insight (e.g. choosing *texture* for displaying a quantitative value). Less efficient is not displaying the information at all (*missing*).
As stated before, the visual efficiency rankings have been determined on the basis of findings about human perceptual skills. The first work on the efficiency of visual attributes was published by Cleveland and McGill in 1984 [Cleveland & McGill, 1984]. The authors stated that „the subject of graphical methods for data analysis and for data presentation needs a scientific foundation". In this work, the authors experimented with different visual attributes: They identified a set of elementary perceptual tasks that are carried out when people extract quantitative information from graphs. Based on this, the visual attributes suitable for conducting this task are specified and tested

Insight	Visual Efficiency Ranking	Scientific Justification
perceive **quantitative value** perceive **summary**	position(0), length(1), angle(2), slope(3), area(4), volume(5), density(6), color saturation (7), color hue(8), text/not expressive (9), missing(10)	[Cleveland & McGill, 1984], [Mackinlay, 1986]
perceive **quantitative value (fast)**	length (0), slope (1), volume (2), color hue (3), text/not expressive (4), missing (5)	[Cleveland & McGill, 1984], [Mackinlay, 1986], [Healy et al., 1996], [Treisman, 1985], [Broadbent, 1958], [Ware, 2004], [Ware, 2010]
perceive **if value is ok** perceive **unordered category/mode**	position(0), color hue (1), texture (2), connection (3), containment (4), density (5), color saturation (6), shape (7), length (8), angle (9), slope (10), area (11), text /not expressive (12), missing (13)	[Cleveland & McGill, 1984], [Mackinlay, 1986]
perceive **if value is ok (fast)** perceive **unordered category/mode (fast)** **find** perceive **outliers/exceptions**	color hue (0), shape (1), length (2), slope (3), volume (4), text/not expressive (5), missing (6)	[Cleveland & McGill, 1984], [Mackinlay, 1986], [Healy et al., 1996], [Treisman, 1985], [Broadbent, 1958], [Ware, 2004], [Ware, 2010]
perceive **ordered category/mode** perceive **certainty**	position (0), density (1), color saturation (2), color hue (3), texture (4), connection (5), containment (6), length (7), angle (8), slope (9), area (10), volume (11), text/not expressive (12), missing (13)	[Cleveland & McGill, 1984], [Mackinlay, 1986]
perceive **ordered category/mode (fast)**	color hue (0), length (1), slope (2), text/not expressive (3), missing (4)	[Cleveland & McGill, 1984], [Mackinlay, 1986], [Healy et al., 1996], [Treisman, 1985], [Broadbent, 1958], [Ware, 2004], [Ware, 2010]
perceive **pattern** perceive **relationships** perceive **trade-offs** **compare** perceive **clusters** perceive **paths**	edges/depth/orientation at multiple scales (0), size/location (1), categorical relation (2), coordinate relation (3), text/not expressive (4), missing (5)	[Rensink , 2000], [Rensink, 2002], [Marr], [Kosslyn]

Figure 5.5: Visual Efficiency Rankings coupled to insights.

regarding their accuracy. Based on their experiments, Cleveland and McGill were able to specify a ranking of visual attributes (see Figure 5.6) which is well accepted and broadly used in design tasks today.

The ranking of Cleveland and McGill strongly focuses on encoding quantitative data with visual attributes. This was extended in 1986 by Mackinlay et al. [Mackinlay, 1986]. Mackinlay et al. not only presented rankings for quantitative data, but also for nominal and ordinal data (see Figure 5.7). This strongly emphasizes that an efficiency ranking is only applicable when coupled with the type of data visualized. Within the underlying dissertation, this fact is recognized by coupling different visual efficiency rankings with various insights (see Figure 5.5).

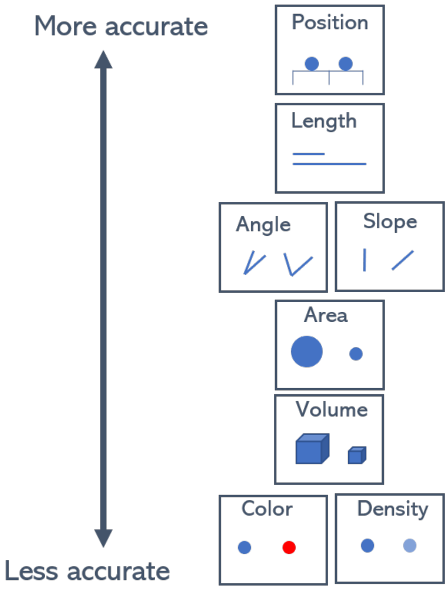

Figure 5.6: Empirically verified accuracy ranking of visual attributes for quantitative data type (based on [Mackinlay, 1986]).

The findings of Cleveland and McGill, as well as the extension done by Mackinlay et al., are applied in the method, as they offer the accuracy ranking and expressiveness for the following insights.

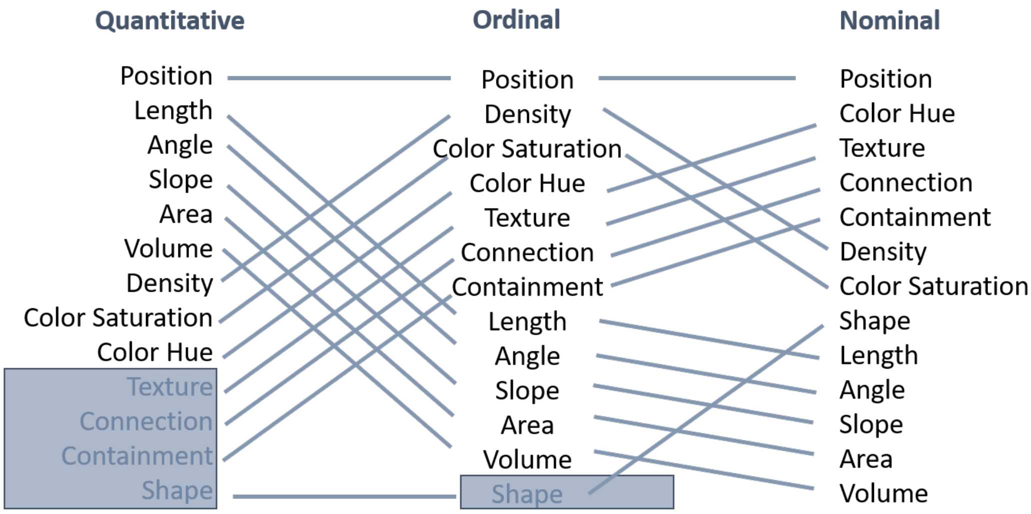

Figure 5.7: Extended ranking by Mackinlay et al. (based on [Mackinlay, 1986]).

Ranking for *perceive quantitative value*: For encoding information to be perceived as a quantitative value accurately, the ranking of Mackinlay (that already recognized the works of Cleveland and McGill) can be applied.

Ranking for *perceive if value is ok*: The information whether a value is ok or not can be classified as a nominal data type, as two categories (ok, not ok) are described that do not have an ordering. So, the nominal ranking of Mackinlay et al. is applicable here.

Ranking for *perceive unordered category/mode*: Analogous to the insight *perceive if value is ok*, the data can be classified as nominal data. Hence, the nominal ranking of Mackinlay et al. is again applied in this context.

Ranking for *perceive ordered category/mode*: The ordered category or mode can be classified as ordinal as these are categories with an important ordering (e.g. the temperature of a certain technical equipment is low/high). This is the reason why the ordinal ranking of Mackinlay et al. [Mackinlay, 1986] is applicable.

Ranking for *perceive certainty*: Similar to category or mode, the certainty can also be classified into ordinal scale—e.g. the value transmitted by the sensor has low certainty, mean certainty, or high certainty. Talking to industry partners revealed that this is the desired level for certainty values, otherwise one might argue that this can also be defined as quantitative value.

Ranking for *perceive summary (min, max, avg, %)*: A summary can be seen as a quantitative value (e.g. min, max, avg). Thus, the ranking for quantitative values can be applied.

The rankings of Cleveland et al. and Mackinlay mainly focus on the effectiveness of visualizations in terms of accuracy. This primarily addresses the first optimization objective of the underlying dissertation (reducing the number of assessment failures; R2.4). The second objective (optimizing the time for perceiving critical states; R2.3) is not yet addressed. Hence, the time needed to perceive a visual attribute needs to be considered: For this, the scientific findings of pre-attentive perception is recognized and applied within the Konect method. Pre-attentive visual attributes are perceivable within the millisecond range by human beings. These are, for instance, color or length. Both are visual attributes that produce a kind of "pop-out" effect, as exemplarily shown in 5.8.

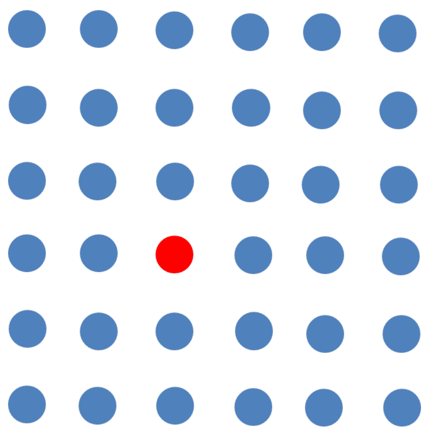

Figure 5.8: Preattentive perception of color hue creating a pop-out effect.

Based on the findings about pre-attentiveness, the visual efficiency rankings for the insights *perceive quantitative value (fast)*, *perceive if value is ok (fast)*, *perceive category/mode (fast)*, *find*, *detect anomaly*, in which the time factor plays an important role, are adapted in the following way: Only visual attributes that can be perceived pre-attentively by the human visual system are left in the ranking. This is exemplarily shown in Figure 5.9 for the insight *perceive if value is ok (fast)*.

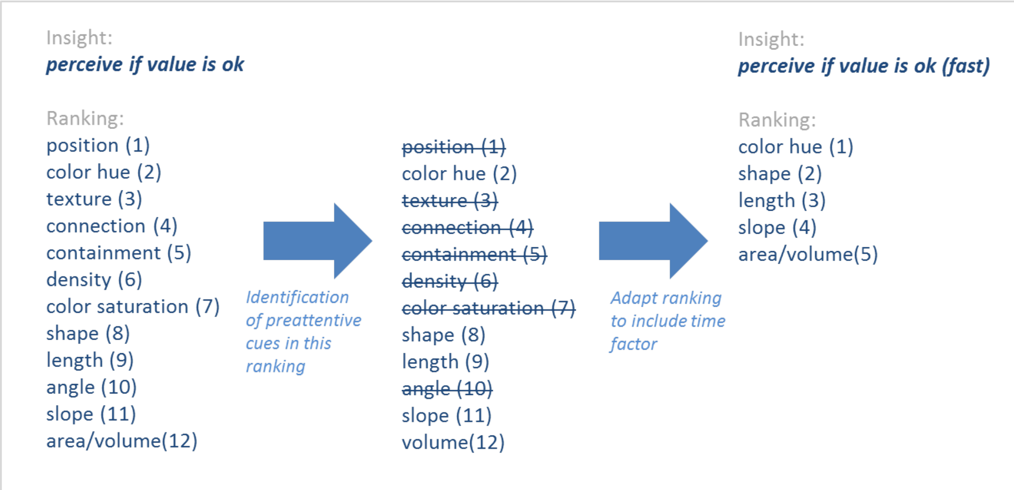

Figure 5.9: Adaptation of ranking for including time factor.

Insights in which more than one visual element is involved (*perceive relationships*, *perceive pattern*, *perceive trade-offs*, *compare*, *perceive clusters*, *perceive paths*) are not expressible with *low level vision* visual attributes as they include some kind of organization of visual elements and interaction between them. As stated at the beginning of the chapter, this kind of visual perception is covered as part of *high-level vision*.
In contrast to *low level vision*, efficiency rankings in *high level vision* are not explicitly examined in the current literature. Nevertheless, research investigating the functioning of the high-level visual system exists [Kosslyn et al., 1990] [Rensink, 2000] [Rensink, 2002] [Marr, 1982]. Based on these profound findings, the efficiency rankings are deduced in the underlying dissertation. This is illustrated in the upcoming text.

Works examining the operating principle of the high-level visual system are provided by Kosslyn et al. [Kosslyn et al., 1990], Marr [Marr, 1982] and Rensink et al. [Rensink, 2000] [Rensink, 2002]:
David Marr addresses the visual processing of 3D models. He revealed four stages that the human visual system undergoes to identify 3D images. The four stages are illustrated in Figure 5.10. The first stage is the input image.

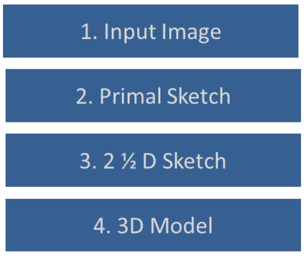

Figure 5.10: Four Stages of Vision based on the theory of David Marr [Marr, 1982].

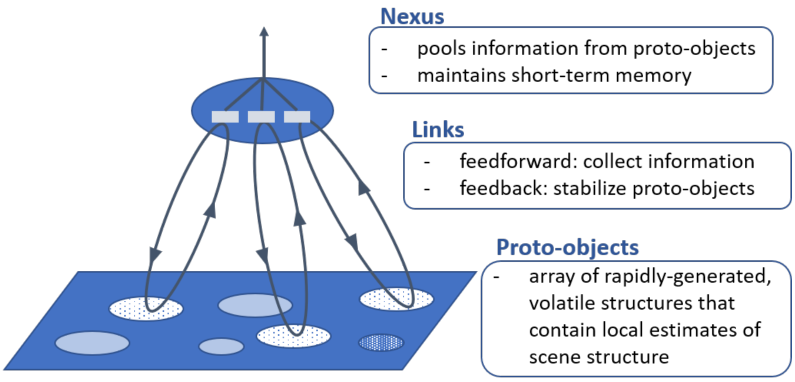

Figure 5.11: Coherence Theory (based on [Rensink, 2002]).

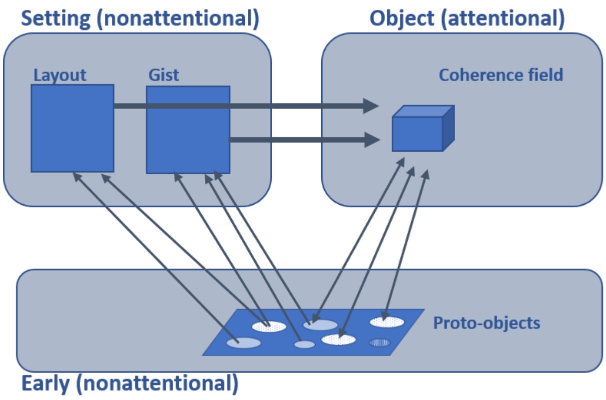

Figure 5.12: Triadic architecture (based on [Rensink, 2002]).

Rensink's work focus on how the brain combines and converts singles visual elements into a scene to form the „whole picture". Rensink established the so-called *triadic architecture* and the *coherence theory* which is a subpart of the triadic architecture. The triadic architecture is shown in Figure 5.12 and the coherence theory is shown in Figure 5.11.

The coherence theory addresses the integration process of single visual elements. Single visual elements are called „Proto-Objects". These are the low-level visual attributes mentioned in the dissertation. As stated before, these objects are perceived rapidly: „low level „proto-objects" are continually formed rapidly and in parallel across the visual field" [Rensink, 2000]. To recognize combined information (e.g. a relationship between two visual elements), the visual system works on a higher level compared to the rapid processing of early vision components. This aspect is represented in the triadic architecture in which „visual processing is split into three largely independent systems". [Rensink, 2002]. These three systems are *Setting*, *Layout*, and *Early* Vision.

Early vision involves the perception of visual attributes, as described before.

Setting already builds up a scene, but on a non-attentional basis. It means that humans do not have to turn their attention consciously to the combination of visual

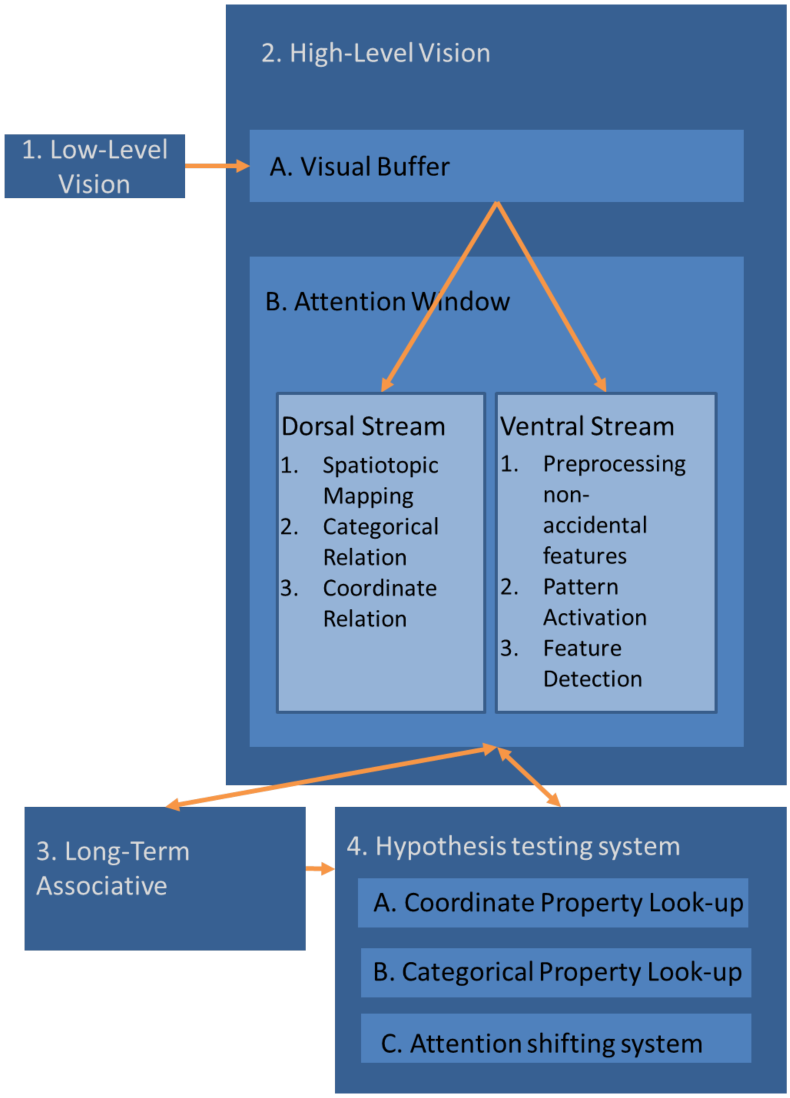

Figure 5.13: Kosslyns cognitive architecture for *high level vision*.

objects. Instead they can perceive a *layout* or *gist*. A layout guides attention based on the arrangement of objects. A gist is the meaning of a scene—e.g. when a picture of a forest appears in front of the human eye, the human will be able to recognize the scene („forest") in a split second.

The perception of **Objects** needs attention. To understand human object recognition, the coherence theory can be applied: First, single visual elements (proto-objects) are discerned. The *nexus* holds information about the proto-objects (e.g. what is needed to establish relationships between elements or detect pattern and clusters). Thus, the nexus „pools information from proto-objects" that can be maintained in short-term memory. For this, *links* between proto-objects are build.

Rensinks coherence theory and triadic architecture explain the difference between *low level vision* and *high level vision* quite well. To further understand the mechanisms behind high-level visual processes, a look at Kosslyn's cognitive architecture is done.

Kosslyn is a psychologist and neuroscientist who provided profound research in the area of cognitive psychology and cognitive neuroscience, especially with regard to human perception and vision. He contributed a cognitive neuroscience analysis about the components and processes involved in *high level vision* [Kosslyn et al., 1990]. An overview of his findings is given in Figure 5.13: Elements perceived within low level processes (e.g. lines, shapes, colors) deliver the input to the visual buffer, which is the first part of the high-level vision component. In the visual buffer, Kosslyn revealed that already **edges, depth, and orientation at multiple scales** are perceived. After this first component, the information is split up into two different streams—the dorsal stream and the ventral stream. The dorsal stream processes spatial information, while the ventral stream operates on the related object.
In the *dorsal stream*, a spatiotopic mapping is conducted first. This includes the recognition of **size and location of objects**. After this, **categorical relations** are distinguished by the human visual system. A categorical relation is, for instance, *„above"* or *„next to"*. Subsequently, the **coordinate relations** between the objects are detected. Coordinate relations refer to the global or local coordinates of an object.

Compared to the dorsal stream, the ventral stream is responsible for object recognition. At first, non-accidental geometric features of an object are pre-processed. *Non-accidental* means that the shape looks the same regardless of the perspective from which the human eye glances at this object (e.g. a ball as a shape looks the same from each possible visual angle). After this pre-processing, a pattern activation takes place: Within this step, an interaction with the long-term associative memory and the hypothesis testing system takes place. The pattern is matched against modality-specific representations of previously seen objects (e.g. if a totally round object is recognized, it can be matched to „ball" as object due to the fact that in human memory round objects are often considered as being a ball.). After pattern activation, a feature detection is applied to further identify the object. A feature in this case is primarily the color and texture of the object. In this case, interaction with the long-term associative memory and the hypothesis testing system is established. An example is that a ball having white and black patches is rather identified as a soccer ball, while an orange colored ball is likely to be classified as a basketball.

The understanding of the functioning of the high level visual system is used in the underlying dissertation to deduce the efficiency ranking for insights involving more than one single element (*perceive relationships*, *perceive pattern*, *perceive trade-offs*, *compare*, *perceive clusters*, *perceive paths*): Based on the findings of Kosslyn et al. (as shown in Figure 5.13), the first stage after low level perception is the recognition of **edges, depth and orientation at multiple scales (1)**. Hence, the efficiency ranking starts with this element (see Figure 5.5 to see whole ranking). After this **size and location (2)** of objects is detected followed by **categorical relation (3)**. The last relationship

to be identified will be the **coordinate relation (4)**.
The findings about object related perception are not usable as part of showing relationships, comparisons, or clusters between elements. Thus, they are not directly appearing in the efficiency ranking shown in Figure 5.5. Nevertheless, they provide important information about how to design objects that are easily recognizable. This aspect is considered within the overall and global composition of the HMI (see Section 5.1.9).

5.1.6 Glyphs

„There are two fundamental ways in which visualizations support thinking: first, by supporting *visual queries* on information graphics, and second, by extending memory." [Ware, 2004].

Glyphs especially address the second part: the extension of the visual working memory capacity. A glyph integrates different visual attributes in one combined form. This especially addresses Requirement R4.4 (the synthesizing of visual elements). An example of a glyph is given in Figure 5.14. This is a so-called *radarchart* representing the state of technical equipment (e.g. for a CWSA – a condensate water separator assembly as used within the ECLSS of the ISS). This glyph combines different visual attributes: The value for each parameter of the technical equipment is visualized via *position*. Each position is combined in one symmetric form—the circle. Additionally, a *color* is added to visualize whether the overall state is ok or not ok. In case everything is ok and no anomaly occurs, the circle is white and round (see Figure 5.14 on the left). If an anomaly occurs because one parameter is too low or too high, the circle changes its form due to the changed position of the parameter value and changes its color to red in case this deviation is critical (see Figure 5.14 middle and right).

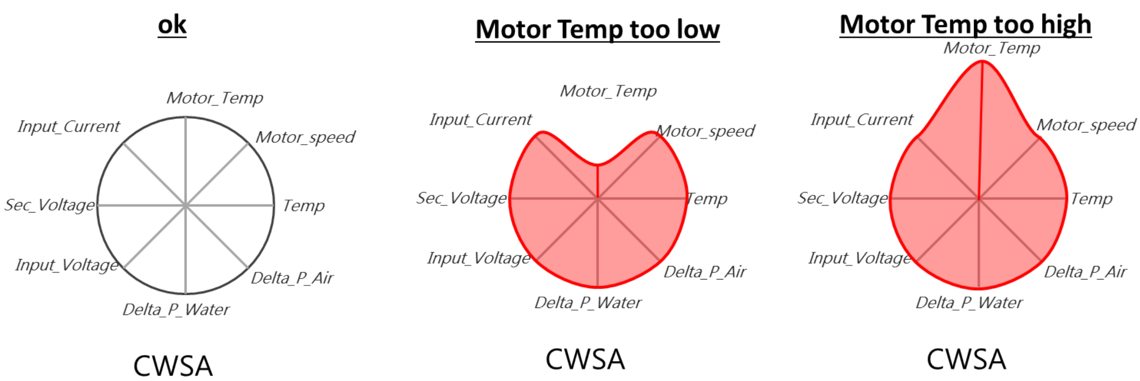

Figure 5.14: Example for a glyph - a radarchart.

The use of glyphs has an obvious advantage: a human operator monitoring an integrated visual form can perceive more than one value at once and estimate the state fast. Moreover, he/she can easily remember the seen visualization. Even when turning the head away, he/she can retrieve the picture easily from memory. If each value would have been visualized separately, the operator would have to remember eight different visual attributes which are cognitively demanding for human beings: „George A. Miller published in 1956 the seminal article "The Magical Number Seven, Plus or Minus Two", where he examines our limited capacity for receiving, processing, and remembering information. [...] When more than seven levels are needed, we should strive to group information into familiar units to expand our limited working memory capacity. For example, the design and use of glyphs depicting integrated variables can extend our visual working memory capacity." [Meirelles, 2013].

Thus, the usage of glyphs allows to perceive more information at once and more information can be held in working memory.

5.1.7 Combination

In order to design a glyph and produce groupings of visual attributes, the so-called Gestalt laws provide a fundamental basis. The Gestalt laws have been developed by German psychologists at the beginning of the 20th century [Wertheimer, 1923]. The Gestalt laws are still valued today, as they provide a „clear description of many perceptual phenomena" [Ware, 2004] and their positive effect for organizing structures have been proven in science [Novick & Catley, 2007].

„Gestalt's principle is that the whole [...] is not the simple sum of its parts but has greater meaning than its individual components. Gestalt principles aim to define rules according to which human perception tends to organize visual elements into „unified whole, also referred to as groups" [Mazza, 2009]. Examples of the application of rules are shown in Figure 5.15. The rules are described in the following list.

Proximity Proximity refers to a spatial closeness of two visual elements. The closer two visual elements are to each other, the more the viewer will assign these elements to a conjunct group. This facilitates „the detection and search for associated data" [Meirelles, 2013]. For instance, in Figure 5.15, the viewer perceives three rows of circles, as the circles are spatially closer together on a horizontal line compared to the vertical distance of the circles.

Similarity Similarity describes the resemblance of the appearance of two visual elements. Owing to similarity, the viewer will group these elements into a perceptual unit. This is, for instance, essential for categorical association: „For example, the use of color coding for categories can enhance search and comparison between them" [Meirelles, 2013]. In Figure 5.15, the viewer perceives again rows of circles as the circles appearance is the same in one horizontal row compared to the appearance of circles seen in columns.

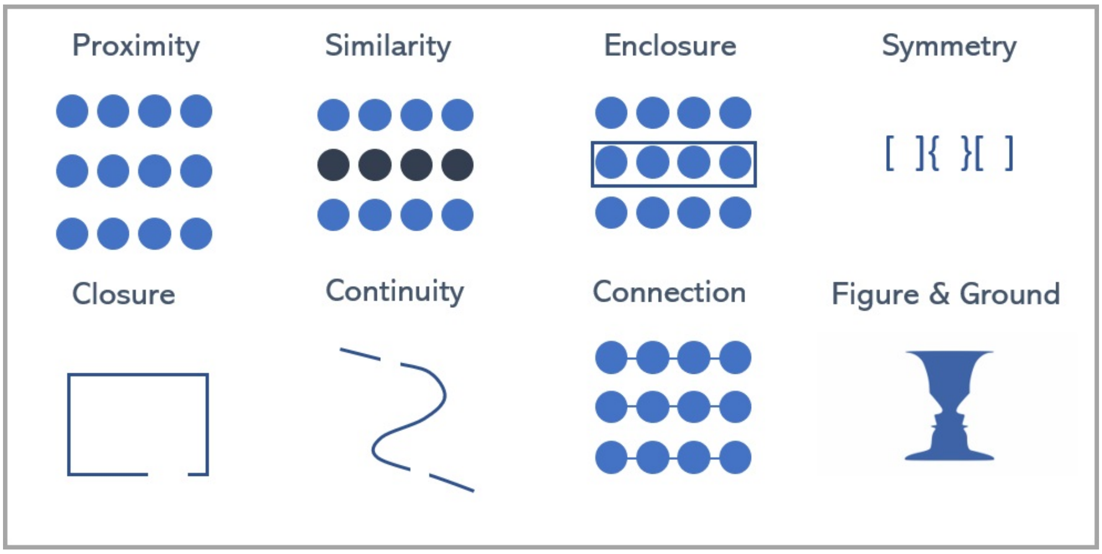

Figure 5.15: Gestalt laws.

Closure „The closure principle of perception describes our tendency to see bounded visual elements as wholes and to unite contours" [Meirelles, 2013]. In Figure 5.15, this is visualized exemplarily: the viewer will likely perceive a circle and a square instead of the single lines actually shown.

Continuity The law of continuity is closely coupled to the law of closure and describes the human tendency to close contours that represent a continuous form. Compared to the law of closure, the viewer will mentally continue a line (see Figure 5.15) and likely perceive this as a single visual element.

Enclosure Enclosure is strongly coupled to the visual attribute of containment. In Figure 5.15, the enclosure is shown via one background color (first row) or via a surrounding line (fourth row). This leads to the aspect that the viewer assumes that these elements belong to one group and form a unit.

Connection The connection law states that the viewer will likely group visual elements together that are connected. In Figure 5.15, the viewer perceives rows of circles instead of columns as the circles are connected horizontally. The law of connection is said to be quite a strong visual hint for viewers for grouping visual elements: „The lines that connect various components [...] are a notation that is easy to read because the visual cortex of the brain contains mechanisms specifically designed to seek continuous contours. Other graphical notations for showing connectivity are far less effective" [Ware, 2004].

Figure and Ground „The segregation between figures and ground principles describes the tendency to organize visual elements into units and construct relationships. In this process, some elements are selected as figures and the remaining as ground" [Meirelles, 2013]. In Figure 5.15, the viewer can either see a vase (deciding to perceive the black colored area as figure) or two faces looking at each other (deciding to perceive the white area as figure and the black part as ground).

Symmetry Symmetry is also used to visually join elements: Elements that build a symmetric form are grouped together. Furthermore, humans strive symmetry and prefer symmetric forms and perceptual constancy [Dickinson & Pizlo, 2013].

Combination exists in two different ways. On the one hand, the integration of different visual attributes in a combined visual form (glyph) has to be realized according to appropriate rules, as described before. On the other hand, the overall design of the display integrating several glyphs has to be taken into account. The latter is captured in the upcoming section.

5.1.8 Global Design Composition

The design of glyphs represents the design of visualizations on a local part of the display. When turning the attention towards the overall structure of the HMI, the global design has to be considered. The term global design refers to a multi-element display that contains more than just one glyph. For this, two different aspects should be considered:

1. The structure of information elements: Which glyphs have to be displayed on which level of the displays? Which elements should be grouped together?
2. The global visual appearance: Do glyphs visually interfere with each other and thus impede fast and correct detection of critical system states?

The first aspect focuses on the *structure*. As mentioned previously, the systematic derivation of the information structure is systematically derived by incorporating actual existing HF methods (EID, TA) in the design procedure. The concepts of EID and TA will be considered for the following aspects:

- Which information is shown?
- On which abstraction level is the information shown?
- Which information elements are shown together e.g. as they are needed in the same task or in case the combination of different information values can reveal a system state?
- Which information will be aggregated?

In case of EID, the structuring is strongly based on the abstraction hierarchy (see section 2.3.4). Details on how to apply this abstraction hierarchy to build the overall global design—e.g. for a whole control room or the whole working environment—can be found in [Burns & Hajdukiewicz, 2013] or [Ostendorp, 2014].

In case of the TA, the structuring is strongly based on the hierarchical task structure (see Section 2.3.4)—e.g. information that belongs to one task should be spatially grouped together to avoid that a human operator has to search for information while conducting one task. Details can be found in [Diaper & Stanton, 2003].
The choice for an appropriate method has to be taken based on the overall aim of the HMI: Task analysis is a good choice if the HMI should support routine tasks, while ecological interface design is a good choice to support fast detection of unforeseen problems and supports the human operator in finding appropriate problem solutions as a deeper understanding of the working principles of the underlying system. There exist also approaches that combine both approaches by Jamieson et al. [Jamieson et al., 2007].

The second aspect focuses on the visual interference and relationships of elements. As presented in the state of the art, current HF methods focus on the structure rather than on the visual form. Thus, the Konect method offers fundamental guidelines to ensure that various glyphs on the display do not interfere each other and that fast perception can be obtained even with several different glyphs . These are described in the upcoming section.

5.1.9 Guidelines for global visual appearance

The guidelines for global design refer to the *visual* component for the global design composition and ensure that various glyphs on the display do not visually interfere each other.

These guidelines are:

1. Consistency Use the same visual attribute for the same kind of insight for similar important information elements.

2.1 Simplicity in Shapes Choose simple shapes and visual forms, choose non-accidental visual forms with regard to orientation.

2.2 Simplicity in colors Reduce colors for elements that do not carry any information, besides structuring the interface.

The guidelines are based on knowledge of human perception and are explained in the following text.

Consistency

Consistency plays an important role in interface design and is a widely accepted principle. It is considered in the ISO 9241 [ISO, 2006] as well as the first rule in Shneiderman's 8 Golden Rules for interface design [Shneiderman et al., 2016]. Both works represent well-accepted standards in ergonomics for interface design and with regard to the requirements specified in Section 3, Konect should be compatible to the guidelines and the standards existent (cf. Requirement R3.3).

Consistency is also the core component of the *principle of visual momentum*, as described by Woods et al. [Woods, 1984]. In this principle, the authors state that multiple displays should be encoded consistently to help users make referential connections between different displays and avoid disorientation. Similar is claimed by Wickens and Holland in their *proximity compatibility principle* [Wickens et al., 2015]. The principle states that „more integrated tasks are facilitated by displays that are high in display proximity; more focused tasks are facilitated by displays that are low in display proximity" [Hegarty, 2011]. In this regard, the term *proximity* describes „how close together two display components are" [Wickens et al., 2015]. This distance can be either defined in spatial terms (which is considered via the task analysis by the Konect method as information that belongs to one task or system should be grouped together) or in terms of object-based properties (e.g. two variables are both visualized with a length). The latter exactly refers to the consistency term, as applied by Konect. According to Wickens et al. [Wickens et al., 2015], the use of this principle has as advantage that emergent features can be created. Emergent features refer to the pop-out effect of pre-attentive visual attributes [Treisman, 1985]. To allow the human operator to perceive such a pop-out effect, a high consistency among visualizations for information elements with similar insight and importance is absolutely necessary. Otherwise, the visual clutter produced on the display is too high—this causes an interference that impedes this pop-out effect.
As a side effect, this guideline addresses the principle of *Informative changes* stated by Kosslyn which indicates that large changes across properties of a display that do not carry information should be avoided [Hegarty, 2011] [Kosslyn, 2006].

Simplicity

Simplicity is often a key aspect in presenting information in a way that is easily understandable. This can help the human operator to interpret the information shown on the HMI without being distracted: „[...] clarity and excellence in thinking is very much like clarity and excellence in the display of data." [Tufte, 1997]. As the state-of-the-art chapter has shown (cf. section 2), the new technological possibilities induced some designers to overuse colors and produce *fancy* and complex 3D shapes as part of the HMI. The literature has shown that 3D shapes are quite complex to be perceived by the human eye and thus are not an efficient choice for an HMI design for monitoring tasks [Ware, 2004] [Hoffman, 2000]. These factors contribute to confusion and clutter rather than offering help in understanding the displayed context. According to Tufte, confusion and clutter should be reduced as they represent „failures of design, not at-

tributes of information.” [Tufte, 1990].
The guideline *Simplicity* of the Konect method should guide the designer in choosing simple shapes and a reduced color scheme to avoid confusion and clutter. So, simplicity addresses two different dimensions: The simplicity of the shapes chosen to visualize information (2.1) and simplicity with regard to visual features as colors (2.2).

As described in Section 5.1.5, simplicity of shapes has a high correlation to the findings about *high level vision* provided by Kosslyn et al. [Kosslyn, 2006] (see also Figure 5.13): Non-accidental features are pre-processed in the ventral stream during object recognition. As a short reminder, non-accidental means that a shape looks the same regardless of the visual angle the human eye looks at this form. This is closely related to the so-called „geons” in the recognition by components (RBC) theory of Biederman [Biederman, 1987]. Biederman claimed that objects are recognized by segmenting them into simple components—the „geons”. Geons are, for instance, a block or a cylinder. An important characteristic of geons is that they are non-accidentally perceivable regardless of their orientation. Biederman revealed that „if an arrangement of two or three geons can be recovered from the input, objects can be quickly recognized even when they are occluded, novel, rotated in depth or extensively degraded.” [Biederman, 1987]. Thus, the simpler a form, the easier it to be recognized. Similar findings have been achieved by Garner et al. [W.R. & Clement, 1963] and Leeuwenberg et al. [Leeuwenberg & Van der Helm, 2012].
Garner et al. [W.R. & Clement, 1963] conducted studies on the so-called *figural goodness*: In these studies, the authors asked participants to rate the goodness of a figure. The key observation is that „better figures produce fewer transformational variants than do worse figures” [Pashler & Yantis, 2004]. Transformational variants of figures were constructed by rotating and reflecting the form and counting the number of different appearances in these so-called equivalence sets. An example is given in Figure 5.16. One can see that the equivalence set of a circle has a count of 1 as a circle looks the same independent from its orientation. The count and complexity increases for a rectangle and even more for a half circular line. The highest complexity has the icon for the excavator with the count of eight different representations for the transformations.

Similarly, it has been found out by Leeuwenberg et al. and has been specified in the so-called *structural information theory (SIT)* [Leeuwenberg & Van der Helm, 2012]. SIT is again based on the simplicity principle: „The simplicity principle implies that the visual system tends to select the stimulus organization that can be described using a minimum of structural information parameters. This structural information load, or complexity, of descriptions can be quantified in a fairly objective way so that SIT enables falsifiable predictions about perceptually preferred stimulus organizations” [Leeuwenberg & Van der Helm, 2012]. For calculating the structural information load, SIT offers a description for coding visual shapes into symbol strings. These symbol strings can then be simplified by applying three kinds of regularity that represent simplicity in shapes:

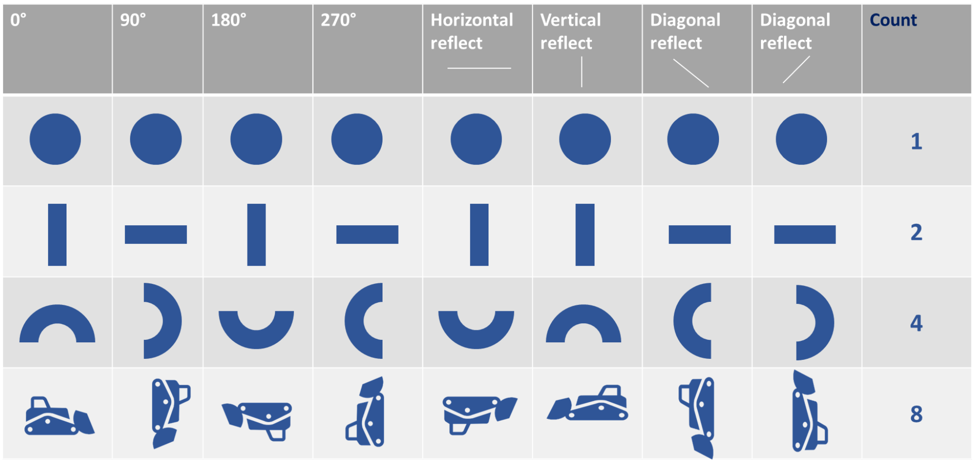

Figure 5.16: Examples for application of Garners Equivalence Sets.

iteration, symmetry, and alternation. For each of these kinds of regularity, a so-called „chunk" is used to simplify and adapt the symbol string. The structural information load is then calculated by counting the number of symbols (representing edges and angles) and the number of chunks (unless the content of a chunk is just one symbol or it is a symmetry chunk). SIT offers a quite complex process for calculating the simplicity or complexity of visual shapes. As key observation, the research of Leeuwenberg et al. emphasizes the findings of Garner et al. in a more detailed form: „After all, Garner's concept is almost equivalent to simplicity" [Leeuwenberg & Van der Helm, 2012]. Thus, it can be said that the research on the perception of visual forms agrees on the fact that simple forms are easier to perceive and should be preferred. This means that „the information that is the basis of recognition should be relatively invariant with respect to orientation and modest degradation" [Biederman, 1987]. The common understanding of this aspect of perception led to the deduction of Law 2.1 in the Konect method for the design of the overall appearance: *Choose simple shapes and visual forms, choose non-accidental visual forms with regard to orientation.*

The second part of the simplicity law involved the use of color (*2.2 Simplicity in colors: Reduce colors for elements that do not carry any information besides structuring the interface.*). This can be explained having a look at the preconditions for pre-attentive perception: This is, for instance, explained as part of the feature integration theory developed by Treisman et al. [Treisman, 1985] or the guided search model 2.0 by Wolfe [Wolfe, 1994] which looks at visual search behaviour of humans: „An important component of routine visual behaviour is the ability to find one item in a visual world filled with other, distracting items" [Wolfe, 1994]. The authors found out that feature search becomes less efficient as the target-distractor difference declines and as distractor inhomogeneity increases. Furthermore, „search is „parallel" for feature searches with large target-distractor differences" [Wolfe, 1994]. This is considered in Law 1 (*1. Consistency: Use the same visual attribute for the same kind of insight for similar important* *information elements.*) as the distractor inhomogeneity decreases and also in Law 2.2 as the reduction for colors for all elements that do not carry any information, besides structuring the interface, aims for a higher target-distractor difference.

Thus, all in all, it can be said that „simplicity is not a matter of increasing white space on the screen, but of what is shown and how it is presented." [Opto22, 2014]. This should be well guided within a method aiming for supporting efficient monitoring of safety-critical systems and is thus an important aspect in the Konect method developed in the dissertation. How the guidelines can be applied in a systematic way is explained in Section 5.2 in detail.

5.1.10 Creative Skills of the Designer

Aside from the perceptual skills of the human operator using the HMI, the creative skills of the designer creating the HMI design are considered within the method. This is specified in the requirements section (Section 3) in the requirement R2 and more specifically R2.2. For this reason, research on human creative skills is applied.
In this context, it should be borne in mind that Konect's focus is on optimizing fast and correct perception. Other optimization aspects that might exist—e.g. user satisfaction, intuitive understanding, or that the design is graphical appealing—are not considered in the fostering of creativity, as this would be a different optimization objective that can even result in contrary visual forms.

Profound research on creativity has been conducted by Young et al. [Young, 2003] and Wallas et al. [Wallas, 1926] and is still valued today. This research resulted in the so-called *Idea Box* of the Konect method, which is explained in the following section.

5.1.11 Idea Box

Decades ago, Young defined two key principles for creativity: „The first [principle is] that an idea is nothing more nor less than a new combination of old elements. [. . .] The second important principle involved is that the capacity to bring old elements into new combinations depends largely on the ability to see relationships. Here, [...] is where minds differ to the greatest degree when it comes to the production of ideas. [. . .] Consequently, the habit of mind which leads to a search for relationships between facts becomes of highest importance in the production of ideas" [Popova, 2015a]. Later, this principle was approved by other researchers: Bill Bernbach said that „[it] is a tribute to [Young] that such scientific giants as Bertrand Russell and Albert Einstein have written similarly on this subject. They agree that knowledge is basic to good creative thinking, but that is not enough and this knowledge must be digested and eventually emerge in the form of fresh, new combinations and relationships" [Popova, 2015a]. Steve Jobs agreed in claiming that „creativity is just connecting things".

To support this creative thinking, Konect offers a systematic form for the gathering of raw material, which is guided by knowledge as well as the support for finding new combinations of visual attributes. This is the idea box. The idea box is used for fostering creativity in the form so that it represents a matrix of aspects that can be combined. This idea box or matrix can help to find new combinations or discover unforeseen relationships: „The matrix, or idea box, provides a structure to combine or recombine ideas to develop new alternatives. The 4 x 4 box depicted yield 1,024 combinations—a far greater number than you are likely to generate without the aid of these combinations. The purpose of the idea box is simply to get you start thinking about multiple options" [Denhardt et al., 2015]. The idea box is sometimes called „Zwicky box" as Fritz Zwicky conducted extensive research on this format for fostering creativity [Zwicky & Wilson, 1967]. In this regard, some authors also talk about a morphological box, as the idea box is a structure to investigate the total set of relationships contained in multi-dimensional, usually non-quantifiable, problem complexes [Zwicky & Wilson, 1967] [Ritchey, 1998]. In this regard, it represents a well-accepted concept in the engineering domain.

To apply knowledge about human perceptual skills within the creative process, the idea box of the Konect method has predefined columns, which are shown in Figure 5.17.

Importance ranking ↓

Information	Insight	Visual Level	Efficiency Ranking	Combination

Figure 5.17: Predefined columns of the Konect Idea Box.

The columns represent aspects of the theoretical framework (*information*, *insight*, *efficiency ranking*, *combination*) which have been described in detail in the previous sections. An additional aspect of the idea box is the importance ranking: The entries in the idea box should be ranked from the most important information to be visualized to the least important one. This ensures that most important information elements are visualized efficiently: Sometimes it might be difficult to combine all visual attributes in one integrated form. In this case, the importance ranking offers help. Even if the most effective visual attribute for each information element cannot be integrated in one glyph, the designer is encouraged to choose the most effective visual attribute for the most important information and use less efficient attributes for less important information elements.

On the one hand, the idea box opens up a design space with possibilities of how to visualize the information needed by the human operator to execute his/her tasks efficiently. On the other hand, a direct proposal is made on how to visualize a certain value in order to be most efficient with regard to the state of the art of actual research on human perceptual skills via the effectiveness ranking (e.g. if length is the most efficient visual attribute, the designer will likely try to use a length to visualize this information). This implies a constraint. One can think that these constraints impede creative thinking, yet the opposite is the case: Haught-Tromp found out that constraints facilitate creativity rather than impede it [Haught-Tromp, 2017].

Thus, the idea box offers a profound way of collecting information needed by the designer to create the design with scientific guidance. The whole systematic procedure of the Konect method is presented in the upcoming section.

5.2 The Konect Procedure

In the prior section, the theoretical framework and its constitution in previous scientific works have been described. To allow a designer to apply this knowledge to derive efficient visualizations for the HMI, a step-by-step procedure has been conceived as part of the dissertation. In this step-by-step procedure, the calculation of a numeric indicator system is also involved to reveal deficiencies of different HMI design solutions and heuristically estimate the quality of a solution with regard to the optimization objectives (cf. Requirement R7).

To better clarify the steps to be carried out by a designer, the step-by-step procedure is illustrated using a small engine monitoring example. Engines are typical equipment monitored in control rooms. Following the state of the art and especially existing monitoring systems, an example of HMI is shown in Figure 5.18. The example is created in analogy to Figure 2.3 in the state-of-the-art section. In this example, typical P&ID symbols are used for engine and valves. The text colors indicate the criticality of parameters as well as valve states (green indicates that the valve is open; red shows that the valve is closed).

The Konect procedure offers four basic steps which are shown in Figure 5.19. The first step is the information determination, while in the second step the predefined idea box is configured for each glyph to be designed. The third step is the glyph-sketching phase, in which the designer is working with the idea box to derive the glyphs for the HMI. In the last step, all glyphs have to be composed in a global HMI design sketch. All the steps are described in detail in the upcoming subsections.

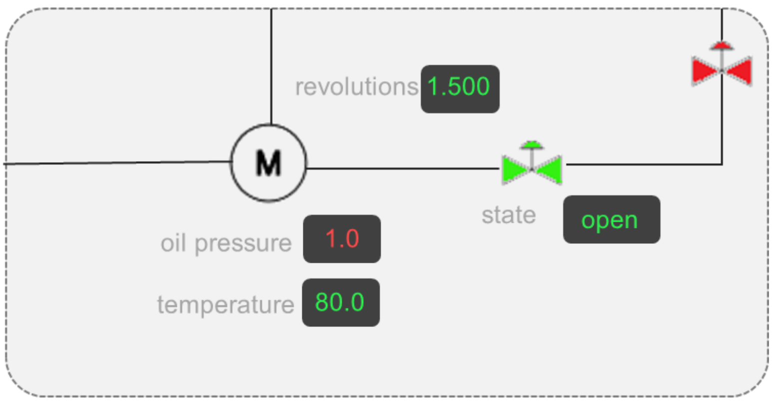

Figure 5.18: Typical visualization for monitoring engine values in control rooms based on state-of-the-art.

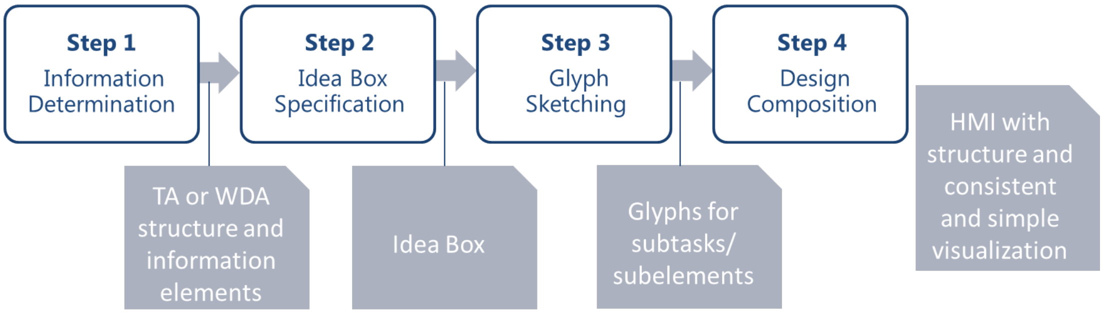

Figure 5.19: The systematic step-by-step procedure of Konect.

5.2.1 Step 1 – Information Determination

The first important step is a systematic derivation of all information elements that need to be shown on the HMI to the operator so that he/she can conduct the tasks at hand. This information can be specified with the help of different analyses—e.g. task analysis or work domain analysis. The kind of analysis depends on the type of the support the HMI should offer. If the HMI should rather support routine tasks, a task analysis is a suitable kind of analysis (see section 2.3.4). If the HMI should be designed to offer help for problem-solving processes in unforeseen problem situations, a work domain analysis structured into the abstraction hierarchy as it is part of ecological interface design in a more suitable kind of analysis (see section 2.3.4).

In this first step, the connection between the current HF methods and the state of the art for designing an HMI for supervisory control in the safety-critical domain is established. Thus, it considers the requirement R3.1, as defined in the requirements specification.

With regard to the theoretical framework, the main concepts considered here are gaining knowledge about the *monitoring task* and *information* to be shown on the HMI in cooperation with the *operator*.

In the engine monitoring example, the information elements can be determined by conducting a work domain analysis which is part of the ecological interface design approach (see Section 2.3.4 for further information about ecological dnterface Design and the work domain analysis). As a result of the work domain analysis, an abstraction hierarchy, as shown in Figure 5.20, can be constructed.

In this case, the *functional purpose*—the overall goal—is that the propulsion system operates in the safe mode. Therefore, different laws have to be observed on the *abstract function* level. This is, for instance, the principle of conservation of energy. On the third level, processes are specified that occur in the propulsion system— these are combustion and fuel supply. The involved entities are engine and valves. The relevant parameters to monitor these physical functions are e.g. *revolutions*, *torque*, *temperature* and *oil pressure* for engine, and the *state (open/closed)* for a valve.

This abstraction hierarchy represents just a short extract. The analysis (TA or WDA, as shown in the example) in this first step serves two purposes: First, to determine the information that needs to be shown on the HMI (e.g. engine torque, engine revolutions, engine temperature, oil pressure), and second, to determine the structure (e.g. engine parameters should be grouped together with valve parameters to allow an overall estimation of correct operation of the propulsion system).

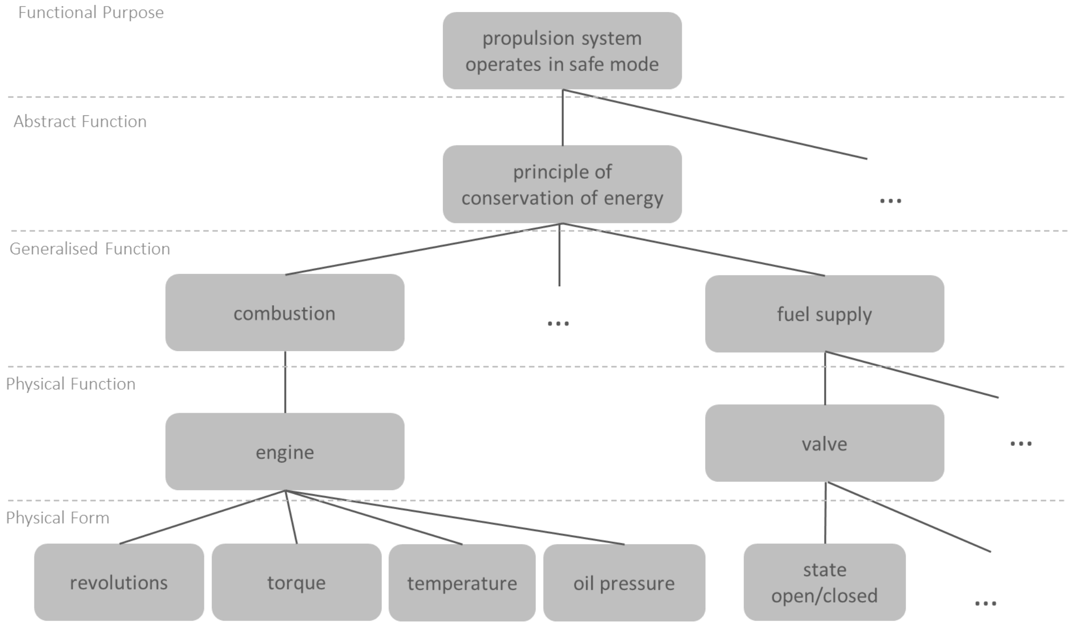

Figure 5.20: Extract of the WDA for a propulsion system.

5.2.2 Step 2 – Idea Box Specification

As stated previously, Konect prepares knowledge in a form that is easily applicable by a designer and allows him/her to optimize the design for fast and correct perception of the human operator. This is realized via the idea box, as described in Section 5.1.11, and shown in the theoretical framework part (Card B). Further concepts coming from the theoretical framework and that form the base of this step are the columns *insight*, *visual efficiency ranking*, *visual attribute*, *combination* and *the perceptual skills* of the *operator* as well as *creative skills* of the *designer*. The second step prepares all knowledge need during the rationally justified HMI design in the form of the idea box. This can be done by conducting further defined sub-steps, as shown in Figure 5.21: First, a decision has to be made on how many glyphs the HMI design should contain (*2.1 Decide for glyphs*). This decision can be made based on the analysis conducted before. In this regard, it has to be considered that information that belongs to one subtask (based on a task analysis) or one element that belongs to a higher abstraction level (based on the work domain analysis as conducted in the ecological interface design) has to be grouped into one glyph. During the evaluation phase of the Konect method and

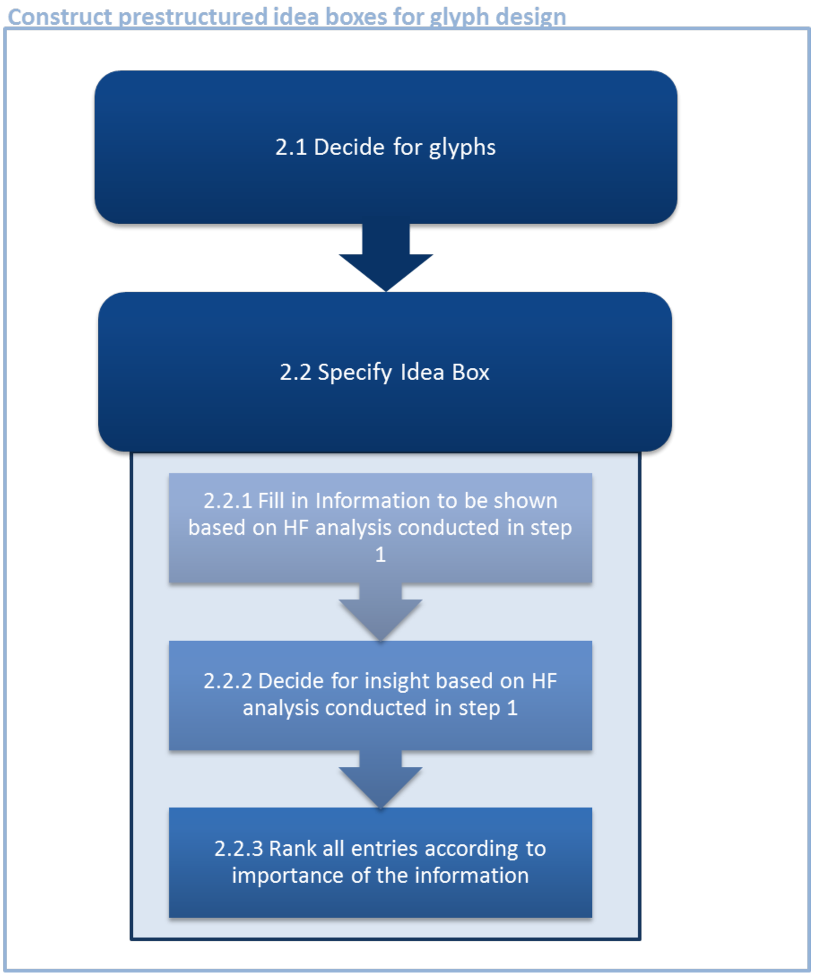

Figure 5.21: Substeps for step 2 - prestructured idea box for glyph design.

the application of the method by different designers with various background knowledge, the experience has been gained that a suitable amount of information elements integrated in one glyph should not exceed 12 information elements.

In case of the engine monitoring example, the information elements can be found on the lowest abstraction level. These are *revolutions*, *torque*, *temperature*, and *oil pressure* that can be grouped together in one glyph informing about the *engine state*. To design the engine glyph, the idea box can be constructed in the upcoming sub-step (*2.2 Specify Idea Box*). This step can be further subdivided into three sub-steps:
As the first sub-step (*2.2.1 Fill in information to be shown based on HF analysis*), the information elements can be entered in the first column of the idea box (see Figure 5.22).
In the second sub-step, an insight needs to be chosen for each information element. This can lead to an increase of entries in the idea box as one information element can have more than one insight. This aspect can be clarified by looking at the engine monitoring example. The idea box containing information elements and insights is shown

Information	Insight	Visual Level	Efficiency Ranking	Combination
revolutions				
torque				
temperature				
oil pressure				

Figure 5.22: Idea Box - Fill in information elements.

Information	Insight	Visual Level	Efficiency Ranking	Combination
revolutions	perceive quantitative value (fast)			
revolutions	perceive if value is ok (fast)			
torque	perceive quantitative value (fast)			
torque	perceive if value is ok (fast)			
temperature	perceive quantitative value (fast)			
temperature	perceive if value is ok (fast)			
oil pressure	perceive quantitative value (fast)			
oil pressure	perceive if value is ok (fast)			

Figure 5.23: Idea Box - Decision for insights.

in Figure 5.23. One can see that each piece of information should be *perceived as a quantitative value (fast)* to estimate the exact number—e.g. the number of revolutions of the engine. On the other hand, the human operator wants to know if the values are within acceptable limits and thus wants to perceive *if the value is ok (fast)*. As a result, the number of entries in the table is doubled.

In the last sub-step (*Rank all entries according to importance of information*), all entries in the idea box are ranked according to their importance—e.g. in case of the engine monitoring task, all parameters are equally important—but to see whether the parameter is ok or not is a bit more important than its quantitative value (see Figure 5.25). To express the fact that certain elements can be equally important, the elements can be assigned importance values. This value is called the weight W in Konect. W can be calculated by building up a tree starting with the most important information and ending with the least important one. This is exemplarily shown in Figure 5.24. Each element gets the number of the stage it is assigned to as weight W.

The content of the columns *visual level* and *efficiency ranking* can be filled in with the help of the mapping table shown in Figure 5.5, and the combination column is filled in with the elements described in Section 5.1.7. These fillings represent knowledge coming from Konect's theoretical framework.

2 revolutions (ok) torque (ok) temperature (ok) oil pressure (ok)

1 revolutions (quantitative) torque (quantitative) temperature (quantitative) oil pressure (quantitative)

Figure 5.24: Calculation of importance (Weight W).

Importance ranking

W	Information	Insight	Visual Level	Efficiency Ranking	Combination
2	revolutions	perceive if value is ok (fast)	low-level	color hue (0), shape (1), length (2), slope (3), volume (4), text/not expressive (5), missing (6)	symmetry figure and ground spatial proximity connectedness continuity closure relative size similarity
2	torque	perceive if value is ok (fast)	low-level	color hue (0), shape (1), length (2), slope (3), volume (4), text/not expressive (5), missing (6)	
2	temperature	perceive if value is ok (fast)	low-level	color hue (0), shape (1), length (2), slope (3), volume (4), text/not expressive (5), missing (6)	
2	oil pressure	perceive if value is ok (fast)	low-level	color hue (0), shape (1), length (2), slope (3), volume (4), text/not expressive (5), missing (6)	
1	revolutions	perceive quantitative value (fast)	low-level	length (0), slope (1), volume (2), color hue (3), text/not expressive (4), missing (5)	
1	torque	perceive quantitative value (fast)	low-level	length (0), slope (1), volume (2), color hue (3), text/not expressive (4), missing (5)	
1	temperature	perceive quantitative value (fast)	low-level	length (0), slope (1), volume (2), color hue (3), text/not expressive (4), missing (5)	
1	oil pressure	perceive quantitative value (fast)	low-level	length (0), slope (1), volume (2), color hue (3), text/not expressive (4), missing (5)	

Figure 5.25: Idea Box - importance ranking and efficiency ranking.

All specifications done in this second step of the Konect procedure should also be intensively discussed with the operator of the interface, quite similar to the analysis conducted in Step 1. Thus, the designer should not decide on his/her own which information is most important or what the insight the operator wants to acquire when looking at a certain information. The better this specification fits the task of the human operator, the better the HMI can be tailored to support this task.

5.2.3 Step 3 - Glyph Sketching

The third step is the Glyph sketching. In this step, the choice for visual attributes and its synthetization takes place. This step uses knowledge prepared in the second step to design the *glyph*. Step 3 can be further subdivided into the following sub-steps:

1. Choice of visual attribute: As first sub-step, the most efficient visual attribute for each information in the box should be chosen. This can be done with the help of the efficiency rankings in the box shown in Figure 5.25. For further calculating the efficiency of the choice and better revealing deficiencies, a normalized efficiency value VE can be calculated for each choice as follows:

$$VE(i) = \frac{R(v)}{R(max)} \tag{5.1}$$

In this regard, the visual efficiency VE is calculated for one piece of information i. R stands for ranking and v for visual attribute. An example of information i can be the information element *revolutions* with the insight *perceive if value is ok (fast)*, as shown in the first line of the idea box. The visual attribute v has to be chosen. This can be for instance *color*, *shape*, *length*, *slope*, or *volume* to visualize this information efficiently. It would be least efficient to display the information as *text* or another visualization that is *not expressive* for the chosen insight (e.g. *color saturation*) (and thus do not appear in the efficiency ranking of the insight) or even to decide to not display the information (*missing*). Hence, the whole possible ranking R from which a designer can choose a visual attribute v is: *color hue (0)*, *shape (1)*, *slope (3)*, *volume (4)*, *text/not expressive (5)*, or *missing (6)*. As the maximum range from which a visual attribute can be chosen is 6, this results in $R(max) = 6$. If the designer selects color as a visual attribute, this results in $R(color) = 0$, as represented in the position of the ranking. This leads to the calculation of VE as: $VE(revolutions\_ok) = \frac{R(color)}{R(max)} = \frac{0}{6} = 0$. Thus, the most efficient choice will lead to the lowest value (0) and the least efficient choice to the highest value (1). This normalization results in the fact that the choice for a visual attribute can be easily estimated and deficiencies as well as better choices are made obvious.

1.1 Create instantiation of choice: After deciding for a visual attribute, the exact *instantiation* has to be created. Instantiation means that an exact characteristic of a visual attribute is designed. This is exemplarily shown in Figure 5.26. In this case, there exist various instantiations for the visual attribute *color hue* (e.g. blue, red, or green) for *length* or for *shape*. This step reveals the main reason why Konect is intended as a method that should be conducted by a human and does not aim at computing an HMI automatically by the machine. Compared to a machine, the human's advantage lies in creativity [Kasparov & Greengard, 2017] and empathy for the user. This can be considered in this step, especially with regard to choosing an appropriate instantiation that minds the semantics of the underlying task of the human operator—e.g. if a distance *below* a certain element (e.g. distance between ship and seabed (*under keel clearance*)) should be visualized as a quantitative value that is fast perceivable, the idea box in Step 2 states that a length is the most efficient visualization. When creating an instantiation for this length, a human will rather prefer a vertical line or bar instead of a horizontal line due to its semantics of being *below* as *below* or *above* characterizations are internally associated with positions on a vertical axis. Similar things can be found in cultural experience of the designer: In western countries, the color red is often associated with danger and will be rather used to visualize a critical state, while a green color is preferably used to visualize non-criticality. As the designer creates the HMI, this empathic factor is considered, and besides, fast and accurate perception along with the intuitiveness of the design can be considered as a side effect. In the following text, this is addressed with the term *semantics* of the instantiation. Another aspect that should be considered in this step are the *scales* of information: The chosen scale of the information can be adapted to the importance of a piece of information to the size that can be seen by the human eye and to differences between the values that need to be distinguished by the human eye (on the level needed by the human operator to conduct his/her tasks). Like the semantics, this is achieved by the designer's empathic factor when creating the design.

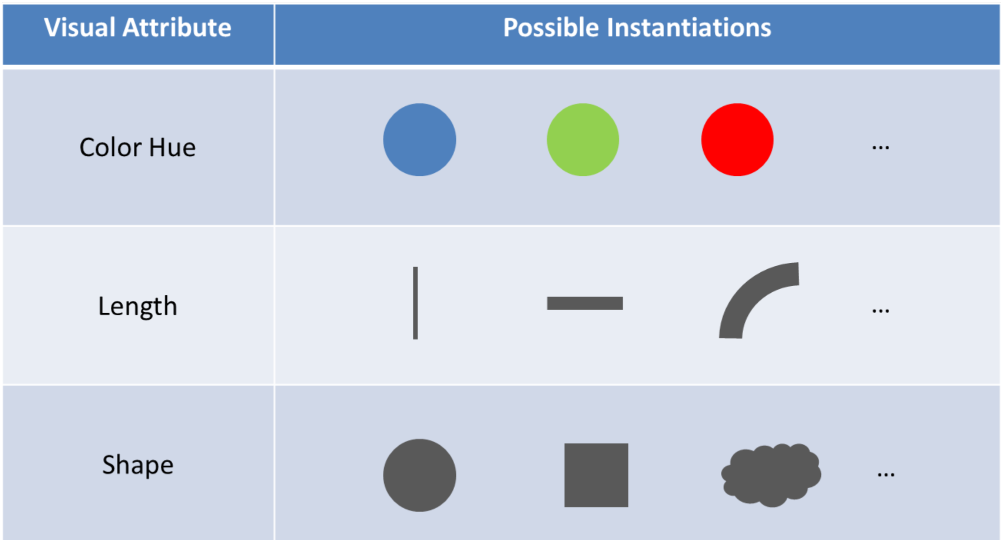

Figure 5.26: Examples for instantiations.

2. Combine chosen visual attributes in one glyph: In a second sub-step, the designer tries to combine the chosen visual attributes in one glyph. In case he/she has problems in this design step, the sub-step 2.1, as described in the following text, offers help.

2.1 In case problems occur combining the visual attributes: In case problems occur, the choice resulted from Step 1 can be adapted in such a way that a less efficient visual attribute for a less important information is chosen. This step emphasizes again the relevance of the importance ranking: In this case, the importance ranking ensures that important information is visualized in the most efficient way. In case compromises have to made (if not every single visual attribute can be combined in one visual form), this decreases the perceptual effectiveness of less important information. This aspect again tailors the HMI to the task of the human operator.
An example of a sketch based on the engine monitoring example is shown in Figure 5.27. The upper example shows the state in case all parameters are ok. The quanti-

tative values for each parameter is shown via the *length* of the quarter pieces of the engine glyph. The combination into one glyph was done on the basis of *symmetry*. Therefore, each length was normalized and aligned in a symmetric circular form. In case, one parameter is out of its acceptable limits, *color* is used to visualized this state (see example at the bottom of Figure 5.27).

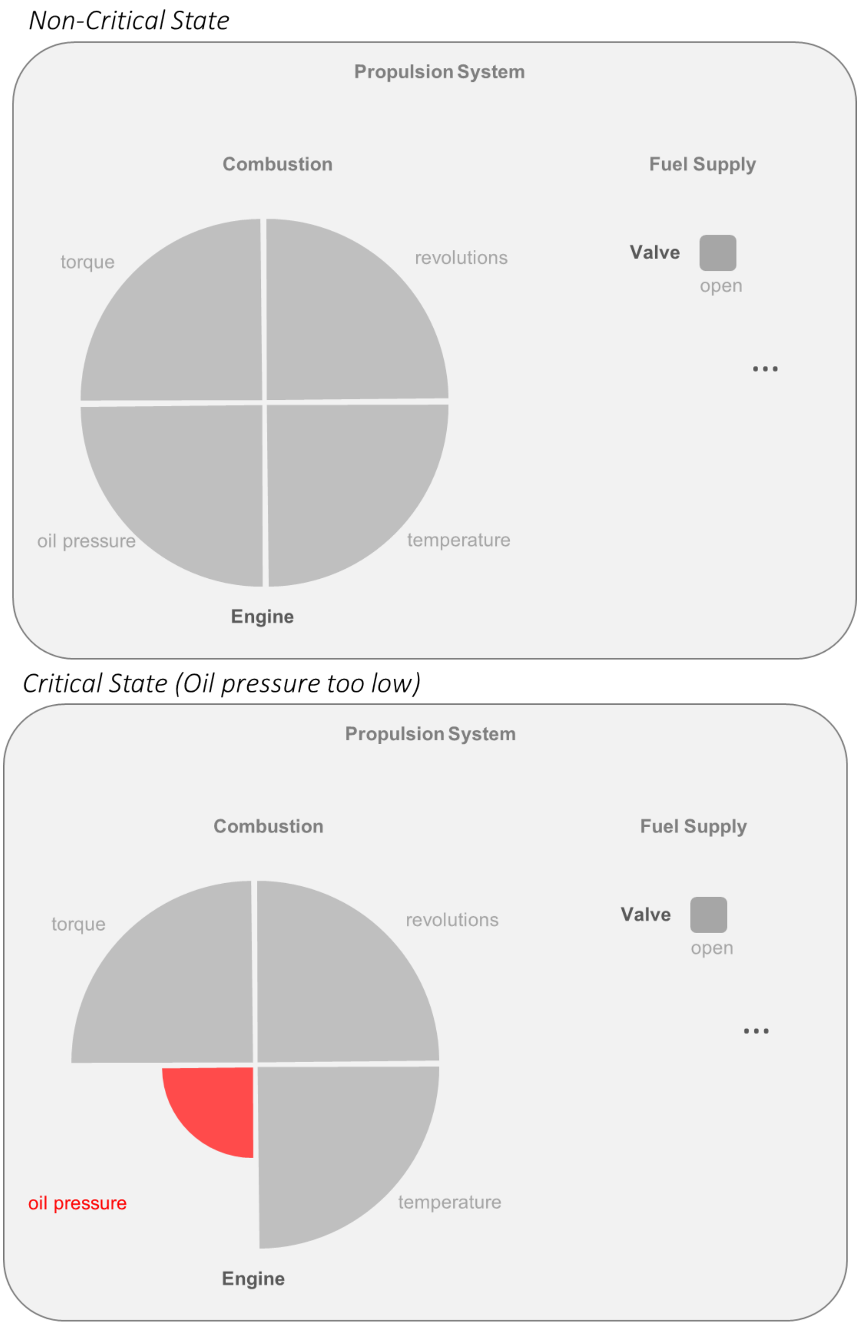

Figure 5.27: Example HMI for engine monitoring example.

5.2.4 Step 4 – Design Composition

While the previous step addresses the creation of glyphs, the following approach is applied afterwards to ensure that the global design will not lead to unintended side-effects (e.g. clutter or visual inferences between different glyphs), which can induce an efficiency decrease, especially for perceiving critical information. As described previously, this includes two aspects: First, *the structure of information elements*, and second, *the global visual appearance*. For the first aspect, all elements are visually grouped according to the prior analysis (TA or EID)—e.g. all parameters indicating the engine state are aggregated and grouped together to form the engine glyph; on the next level, all aggregations, e.g. *engine*, *valve* etc., are grouped together to inform about the combustion. In this regard, it has to be considered that not all aggregation levels have to appear on one single display. There can also be several displays that allow an overview of the whole system state on the highest level and allow „zooming into" different aspects. In this case, the P&ID display can appear again, but it will appear on a deeper level as this represents a rather detailed view of physical arrangement. This is exemplarily shown in Figure 5.28. As this structuring is based on the state of the art, no further details are provided here (details can be found in [Burns & Hajdukiewicz, 2013] or [Ostendorp, 2014]). The second aspect (*global visual appearance*) represents an extension of this state of the art and is thus described in detail in the upcoming text.

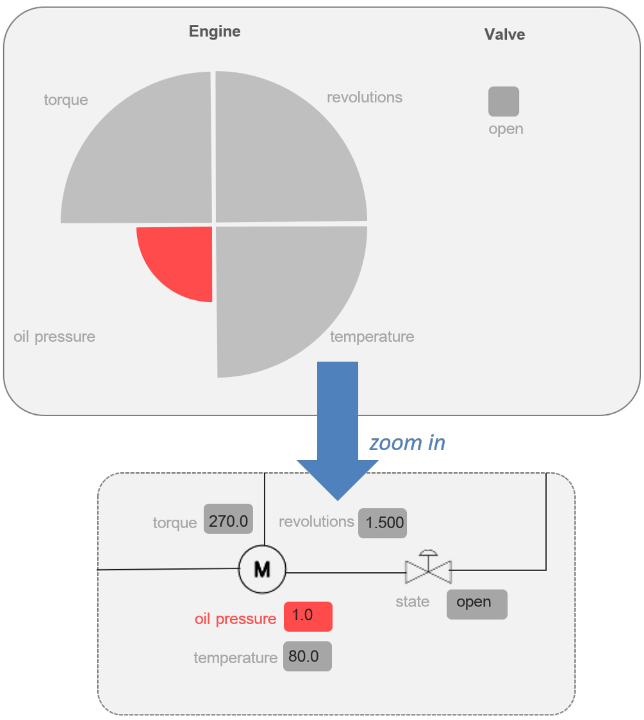

Figure 5.28: Example HMI structure based on EID/TA.

For the global visual appearance, the previously described guidelines (see Section 5.1.9) are applied in a systematic step-by-step approach.

1. Establishing consistency throughout the glyps: For establishing consistency throughout the glyphs, the following sub-steps need to be conducted.

1.1 Grouping according to insights: At first, the idea boxes used in Steps 1 and 2 are reordered according to the insights. This means that all information elements having the same insight are grouped together.

1.2 Mark visual attributes: In the regrouped list, all visual attributes used in Steps 1 and 2 are marked—e.g. if a color has been chosen, color is marked in the efficiency list.

1.3 Adapting visual attributes: In this step, the designer tries to use the same visual attribute for each element in the insight list. To achieve this, the designer has to adapt some visual attributes. For this, it should be considered that he/she should avoid exchanging a high-ranked visual attribute for a piece of important information with a lower-ranked visual attribute. In the other direction, changes can be applied (e.g. using a higher-ranked visual attribute for a less important piece of information to reach a more consistent overall form).

1.4 Adapt instantiation of visual attribute: In this step, the instantiation of visual attributes are brought into a more consistent state. The designer goes through the visual attributes in the insight list and tries to choose similar instantiations (e.g. if green is an indicator for „ok", green should be used throughout the whole sketch for encoding this information).

2 Establishing simplicity for all visual structures and forms in the sketch: To establish simplicity for visual structures used in the sketch, the following steps need to be conducted.

2.1 Rotating forms and counting number of appearances: At first, each structural form or shape should be analysed. This might be forms that belong to the glyphs and structure them, as well as elements that are used to structure the whole sketch. Each form should be rotated in 90-degrees step and reflected on the horizontal, vertical, and diagonal axes (as exemplarily shown in Figure 5.16). Then, the number of different appearances should be counted.

2.2 Adapt forms for higher structural simplicity: Case step 4.1 resulted in a high number of different appearances, structural forms might be adapted to reduce the structural complexity of the overall design. In this step, it should be considered that a trade-off is conducted between fast perception of the form and intuitive understanding of the visualization.

2.3 Reduce colors: For further establishing simplicity, all colors that do not carry information (besides from structuring the interface) should be reduced and a more neutral color coding should be applied (e.g. grey).

An example—how these guidelines change the visual appearance of the HMI—is given in Figure 5.29. On the left side, the original design (as shown at the beginning of the chapter) is presented. The application of the guidelines leads to the HMI shown on the right side: The guidelines application reveals that the red color is once used to visualize the state (ok/not ok) for the parameters. On the other hand, it visualizes the state (open/closed) regarding the valve. This inconsistency is solved (red indicates not ok, dark blue indicates closed). In addition to establishing consistency throughout the glyphs, color coding is once applied to the parameter text (see Figure 5.18) and once to the description text and the background element (see Figure 5.27). Here consistency was achieved by adapting this coloring. Furthermore, Guideline 2.3 leads to a more reduced usage of colors (grey instead of green is applied to indicate a normal state). Thus, the systematic application of the guidelines results in a more consistent visual form and critical states are more salient as no interference with other visual forms (e.g. critical parameter values vs. closed valves) appears.

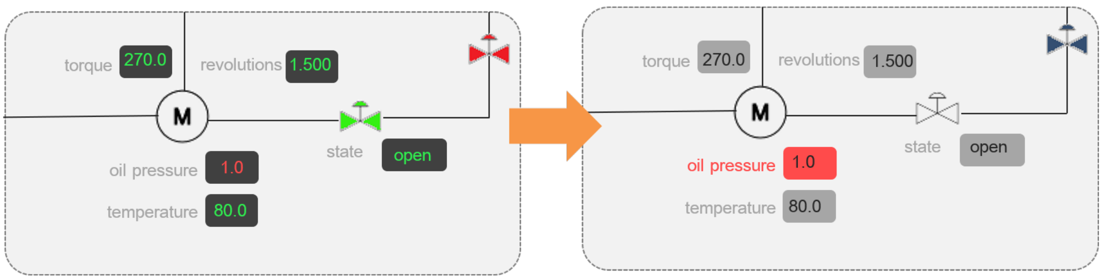

Figure 5.29: Example for global design composition guidelines for visual appearance.

5.2.5 Numeric Indicator for Estimating HMI Efficiency – the Konect Value K

The numeric indicator for estimating the approximated efficiency of a certain design during the design stage mainly addresses the requirement R7, as specified in the requirements section. This numeric indicator system helps to estimate the efficiency of different HMI design solutions regarding the optimization objectives (fast perception of critical system states and reduction of assessment failures). Like the previously described procedure, the numeric indicator is developed on the scientific base provided by the theoretical framework. The numeric indicator system is called the *Konect Value* and is explained with the example of a temperature indicator. The correctness of the Konect Value is evaluated in Section 6.3 and discussed in 7.7. The temperature of a certain technical equipment in a system under supervisory control can be displayed in different ways. Figure 5.30 exemplarily shows three different ways for the HMI design solution.

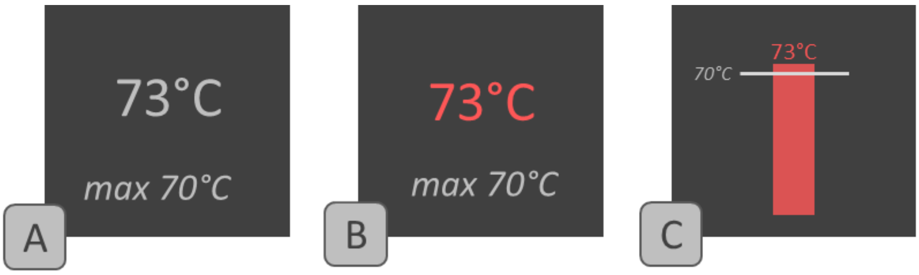

Figure 5.30: Examples for HMI design solutions for a temperature control indicator.

Weight	Information	Insight	Efficiency Ranking	VE
2	actual temperature	perceive quantitative value (fast)	length (0), slope (1), volume (2), color hue (3), text/not expressive (4), missing (5)	0.8
2	actual temperature	perceive if value is ok (fast)	color hue (0), shape (1), length (2), slope (3), volume (4), text/not expressive (5), missing (6)	1.0
1	max. allowed temperature	perceive quantitative value	position (0), length (1), angle (2), slope (3), area (4), volume (5), density (6), color saturation (7), color hue (8), text/not expressive (9), missing (10)	0.9

Inconsistencies: 0, Additional Information: 0, Simplicity in Colors: 0, Simplicity in Shape: 0

Figure 5.31: Example Idea Box for temperature control indicator - HMI Design Solution A.

In the first design on the left (Design A), the actual temperature is displayed as a large number in the middle, the maximum allowed temperature, and thus, the acceptable limit is shown below the number as textual information. The design in the middle (Design B) is quite similar to the design solution A. The difference lies in the coloring of the actual temperature text: If the value exceeds the limit, the text is colored in red. In the third design, a length is used for displaying the actual temperature value, while the limit is shown via a position (white line) and the color of the bar indicates if the actual temperature exceeds the allowed maximum temperature, and thus, represents a critical system state.

It is obvious that Design C allows a much faster and correct estimation of the system state than Design A. With help of the Konect method and the Konect indicator system, this can be revealed on an objective, rationally justified level, thus highlighting the deficiencies of design solutions:
For each of the different design solutions, an idea box can be created (see Figure 5.31 for the idea box of the design solution A). In this case, it has to be considered that the idea box **should now not only comprise one glyph, but the entire HMI design**. In the example, the idea box contains three different information elements: the actual temperature that should be perceived as a quantitative value, the actual temperature (with insight if the temperature is ok or not), and the maximum allowed temperature. The actual temperature is slightly more important than the maximum allowed temperature and thus get a weight of 2, while the maximum allowed temperature gets a weight of 1. The chosen visual attributes are marked with orange in the efficiency ranking list and based on this the visual efficiency VE as explained in Section 5.2.3 is calculated. Furthermore, the violations against the rules specified for the global design solution, as described in Section 5.1.9 and section 5.2.4, should be counted and are written at the bottom of the box shown in Figure 5.31. As this is quite a simple example, no *additional information* is given, no *inconsistency* appears ,and *simplicity in colors and shapes* is fulfilled. Based on this box, the Konect Value can be calculated as follows:

$$K = \frac{\sum(w * VE(i)) + \sum(w * Violations)}{\sum w} \tag{5.2}$$

The weight is multiplied with the visual efficiency to ensure that a less efficient visual attribute for a more important information is more recognized compared to a less efficient visual attribute for a less important information. The weight for the violations is always calculated as 1 with one exception: With regard to *simplicity in color*, there is one specific violation with outstanding impact—color-encoding failures. A color-encoding failure, for instance, occurs if red is always used as the color indicating a critical system state and red is again used on another part of the HMI design to structure the design solution. This becomes more relevant with increasing importance of the information encoded. Thus, the weight of the information itself is taken as the value w for these kinds of violations to consider the importance of the information for the calculation of the Konect Value K.

In case of the example Design A, as shown in Figure 5.30 with the idea box shown in Figure 5.31, this leads to the Konect Value K of:

$$
\begin{aligned}
K &= \frac{\sum(w * VE(i)) + \sum(w * Violations)}{\sum w} \\
&= \frac{((2*0.8)+(2*1.0)+(1*0.9))+(0+0+0+0)}{2+2+1+0} \\
&= \frac{4.5}{5} \\
&= 0.9
\end{aligned} \tag{5.3}
$$

Owing to the sum of the weight values in the denominator, the Konect Value K always lies between 0 and 1. In this regard, the higher the Konect Value K, the less efficient the HMI design solution is estimated to be. In case of the underlying example, Design A gets a Konect Value of 0.9, which is quite high and indicates that the solution is not optimal. The idea box in Figure 5.31 also reveals where the deficiencies lie: the missing indicator for the temperature criticality and the less efficient visual forms. In the idea box, it is directly obvious which choices for visualizations are more appropriate, for instance, to show whether the temperature is ok or not ok, a color can be added to improve the design. This is done in Design B, as shown in Figure 5.30, and leads to the adapted idea box shown in Figure 5.32. Hence, Design B gets a lower Konect Value (and is thus estimated as being more efficient than design A):

$$
\begin{aligned}
K &= \frac{\sum(w * VE(i)) + \sum(w * Violations)}{\sum w} \\
&= \frac{((2*0.8)+(2*0.0)+(1*0.9))+(0+0+0+0)}{2+2+1+0} \\
&= \frac{2.5}{5} \\
&= 0.5
\end{aligned} \tag{5.4}
$$

An even more optimal solution is Design C, which uses the most efficient visual attributes for all information elements and thus gets a Konect Value K of 0:

$$
\begin{aligned}
K &= \frac{\sum w * VE(i) + \sum w * Violations}{\sum w} \\
&= \frac{((2*0.0)+(2*0.0)+(1*0.0))+(0+0+0+0)}{2+2+1+0} \\
&= \frac{0}{5} \\
&= 0
\end{aligned} \tag{5.5}
$$

So, all in all, it can be said that the calculation of the Konect Value K can be used as a metric to estimate the efficiency of different HMI solutions, reveal deficiencies, and at the same time, offer ways for improving the solution and provide the rational

Weight	Information	Insight	Efficiency Ranking	VE
2	actual temperature	perceive quantitative value (fast)	length (0), slope (1), volume (2), color hue (3), text/not expressive (4), missing (5)	0.8
2	actual temperature	perceive if value is ok (fast)	color hue (0), shape (1), length (2), slope (3), volume (4), text/not expressive (5), missing (6)	0.0
1	max. allowed temperature	perceive quantitative value	position (0), length (1), angle (2), slope (3), area (4), volume (5), density (6), color saturation (7), color hue (8), text/not expressive (9), missing (10)	0.9

Inconsistencies: 0, Additional Information: 0, Simplicity in Colors: 0, Simplicity in Shape: 0

Figure 5.32: Example Idea Box for temperature control indicator - HMI Design Solution B.

Weight	Information	Insight	Efficiency Ranking	VE
2	actual temperature	perceive quantitative value (fast)	length (0), slope (1), volume (2), color hue (3), text/not expressive (4), missing (5)	0.0
2	actual temperature	perceive if value is ok (fast)	color hue (0), shape (1), length (2), slope (3), volume (4), text/not expressive (5), missing (6)	0.0
1	max. allowed temperature	perceive quantitative value	position (0), length (1), angle (2), slope (3), area (4), volume (5), density (6), color saturation (7), color hue (8), text/not expressive (9), missing (10)	0.0

Inconsistencies: 0, Additional Information: 0, Simplicity in Colors: 0, Simplicity in Shape: 0

Figure 5.33: Example Idea Box for temperature control indicator - HMI Design Solution C.

justification for choosing a design solution (see section 6.3 for detailed evaluation). The idea boxes shown in Figure 5.31, 5.32 and 5.33 can also be used as a reusable solution document. To ease working with the Konect method and the calculation of the Konect Value, a tool support has been implemented. This is described in the upcoming section.

5.3 The Konect Tool Support

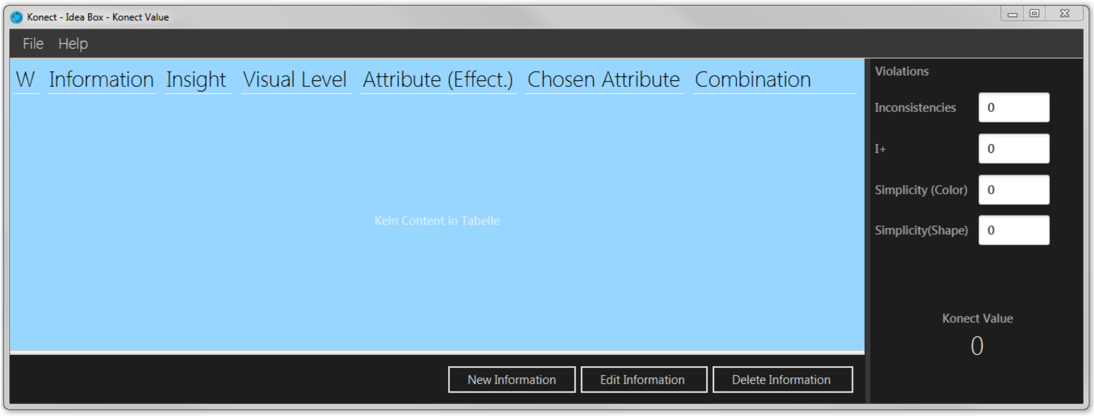

Figure 5.34: The Konect Tool Support - Overview.

To allow easy applicability of the Konect method, a tool support was implemented. The tool support has been implemented as JavaFX application.

An overview of the main display of the Konect tool is shown in Figure 5.34. The main functionality of the Konect tool lies in supporting the filling of the Konect idea box and at the same time calculating the Konect Value. For conducting this task, the designer has the possibility to *specify a new information element*, edit an information element entry, or delete an entry (see buttons at the bottom of Figure 5.34). In case the designer wants to specify a new information element entry or edit an existing one, an edit dialogue opens up.
This dialogue is shown in Figure 5.35. In this dialogue, the designer can insert a name for the information as text. After specifying the information, an insight can be chosen in the form of a predefined choice list. This choice list is shown in Figure 5.36. The weight of the information can be inserted as numerical value. The last value that needs to be specified is the attribute choice. In this case, the choices available for the visual attribute depend on the selected insight. An example of how this list can look like is exemplarily presented in Figure 5.37. In this case, the list is shown for the previously defined insight *„perceive quantitative value"*. If a value is missing or if the weight is not specified as numerical value, the tool states this and will not insert false specified information in itself. So, the tool ensures that the specification of idea box entries is performed correctly and false specifications are avoided. This becomes especially important as the Konect Value is calculated in parallel so that the designer can directly observe implications that design choices have on the Konect Value. So, the consequences of choices on the estimated efficiency of the overall design is directly visible.
The numerical values for the amount of inconsistencies, additional information, and violations in simplicity of colors and shape can be added at each time in the text fields

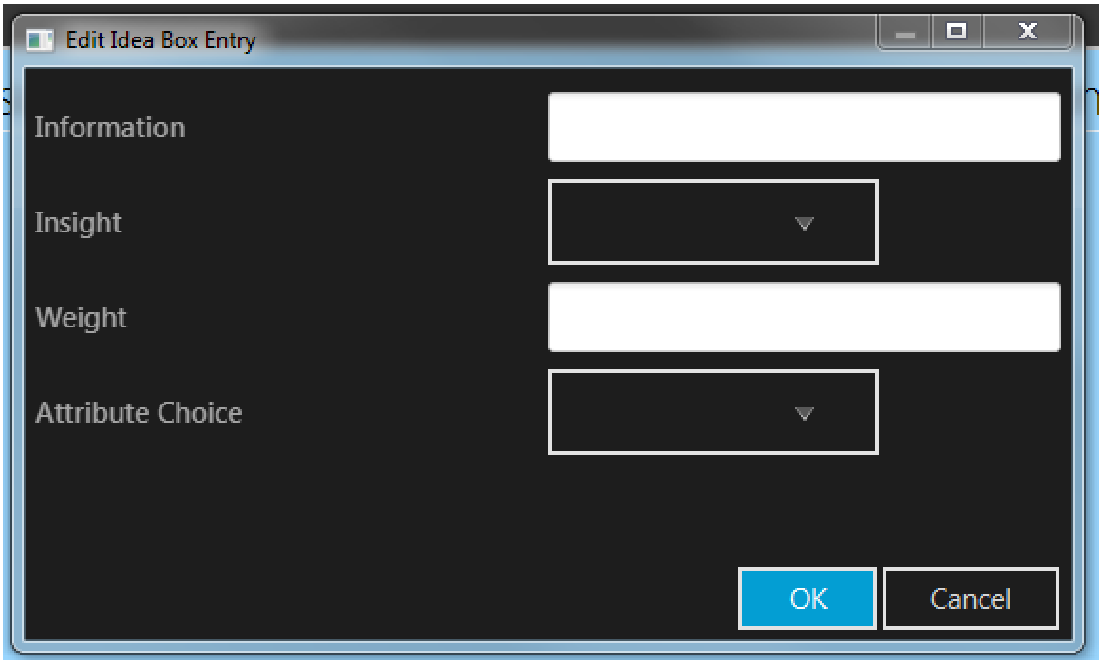

Figure 5.35: The Konect Tool Support - Edit Dialogue.

shown on the right (cf. Figure 5.34). Also in these text fields, the Konect tool does only allow numerical values and ensures that false specifications are not possible.

The calculated Konect Value is shown in Figure 5.38 and 5.39. In this example, the idea box for the temperature control indicator (as presented in the prior section for clarifying the calculation of the Konect Value) for the design solutions A (as shown in Figure 5.31) and C (Figure 5.33) is presented: The idea box and the calculated Konect Value for the design solution A is shown in Figure 5.38, and for the design solution C in Figure 5.39, thereby displaying the Konect tool representation. In these pictures, it can be seen that the Konect tool adapts the color of the Konect Value text label based on the calculated numeric indicator: If the Konect Value is below 0.3, the design solution can be estimated as being efficient regarding the operator's perceptual skills. In this case, the text label is colored in green. In case the value is higher than 0.8, the design solution is quite inefficient and a rework is absolutely necessary for ending up with a good design solution for the task at hand. Thus, the text label is colored in red. In all other cases, the text label appears in white.

In the event that a rework is essential for an efficient design solution, the idea box offers hints for points with the highest potential for improvement in the columns *Attribute* and *Chosen Attribute*: In the column *Chosen Attribute*, the VE value directly reflects the efficiency of the visual attribute choice. A high value indicates the existence of more efficient choices. Better choices can be found in the *Attribute Column*. So, the designer can „play around with the attribute choices" to end up with a more efficient design solution and a lower Konect Value.

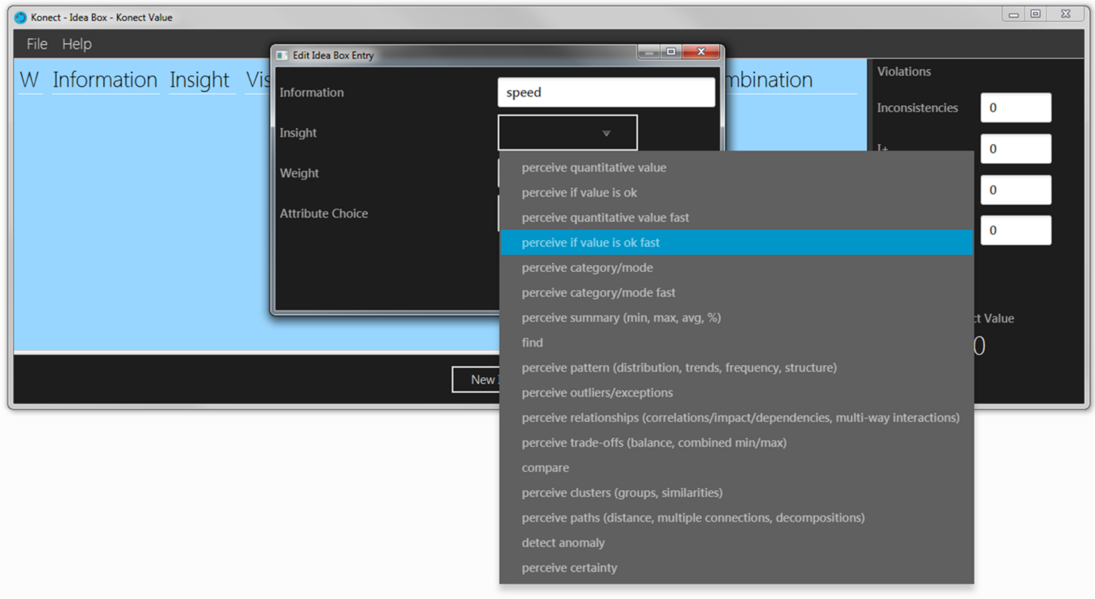

Figure 5.36: The Konect Tool Support - Predefined Insights.

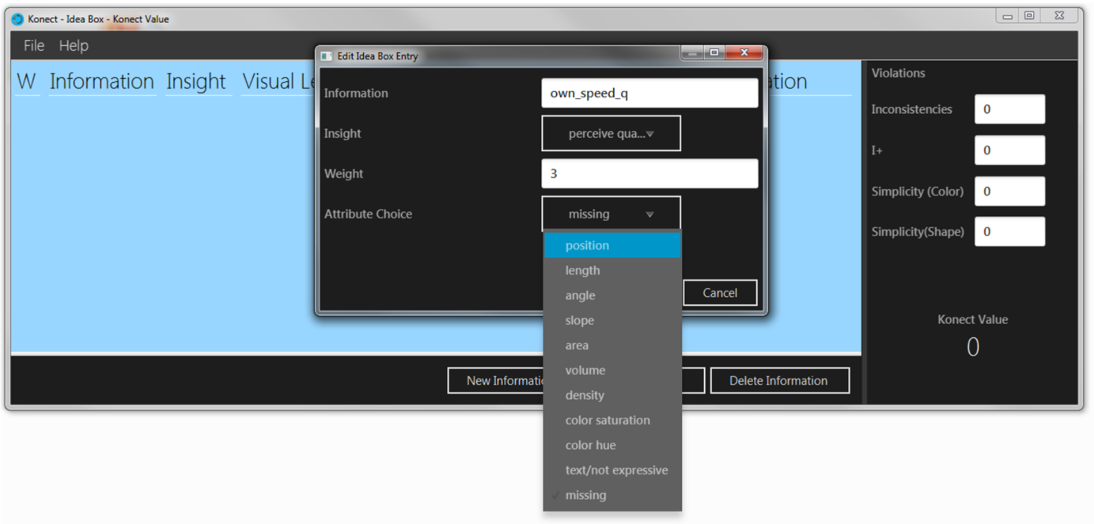

Figure 5.37: The Konect Tool Support - Attribute Choice.

The Konect tool offers further functionalities to ease the work with the idea box. These functionalities can be accessed via the main menu, as shown in Figure 5.40. The designer can create a new idea box, save the idea box, or open a saved one. The data in the idea box can be saved as .xml-File. Thus, the designer can continue working on an idea box at different times and work on several design projects in parallel.

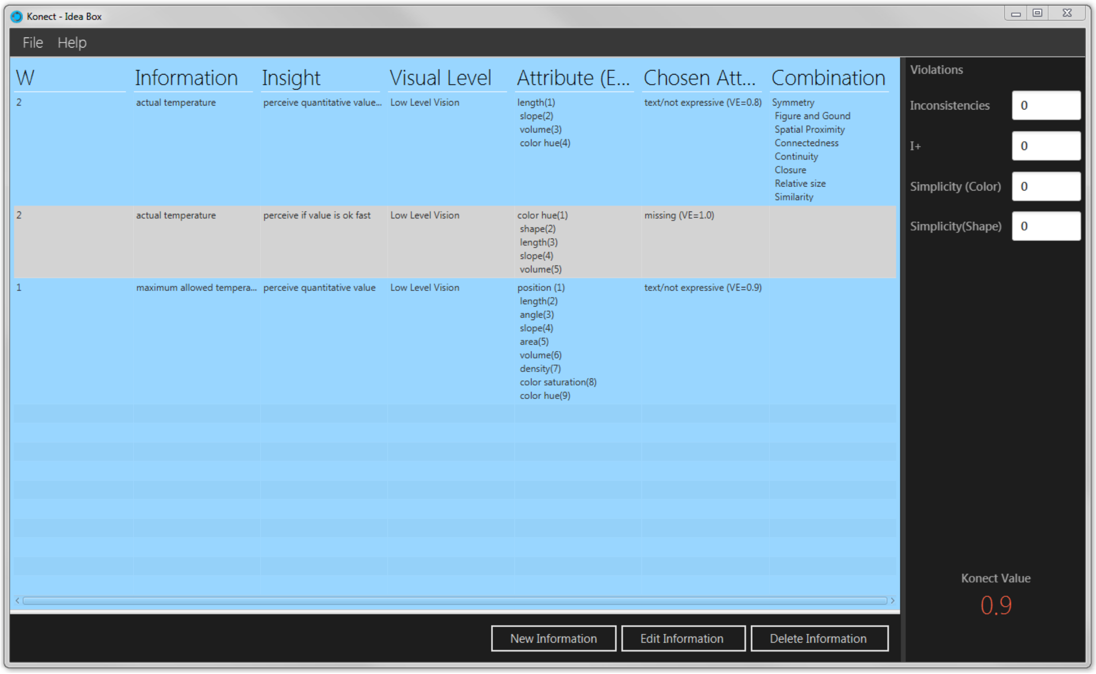

Figure 5.38: The Konect Tool Support - Temperature Control Indicator Solution A.

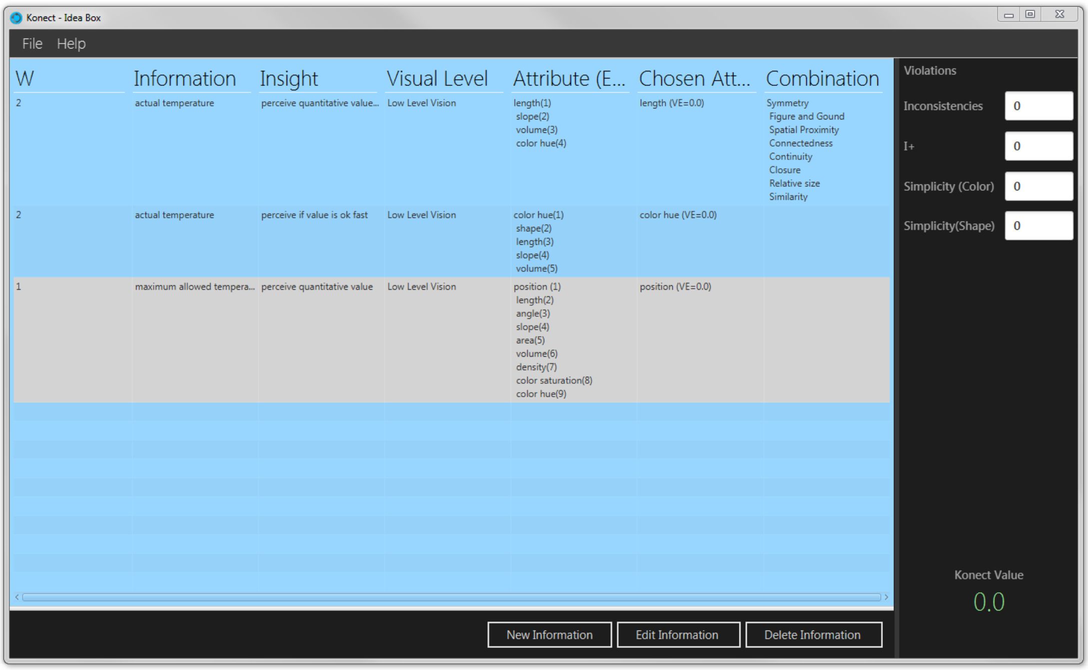

Figure 5.39: The Konect Tool Support - Temperature Control Indicator Solution C.

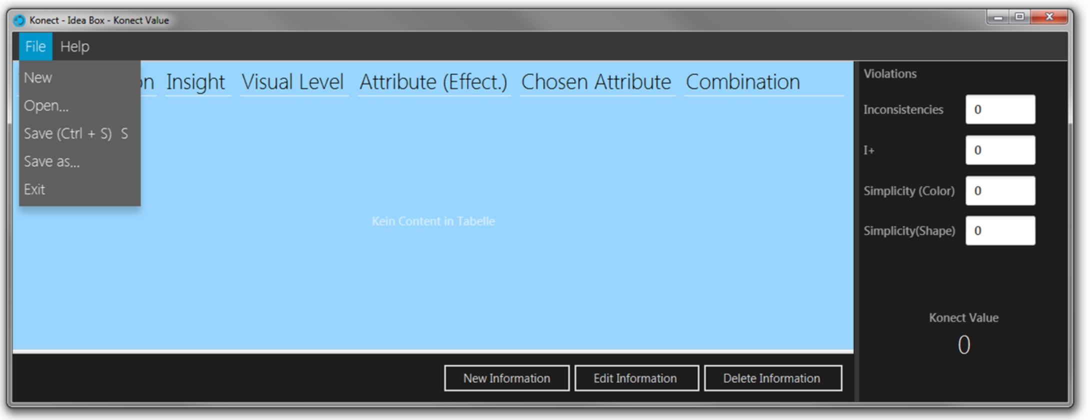

Figure 5.40: The Konect Tool Support - Menu.

6 Evaluation of the Konect Method

In the previous chapter, the conceptualization of the Konect method has been described and reasoned according to prior knowledge coming from the scientific domain. The method was applied and evaluated in different domains—the automotive domain and the maritime domain. The studies conducted and results achieved are described in the upcoming sections.

An overview of the studies is shown in Figure 6.1: In the first part, a workshop was conducted, in which the invited human factors experts applied the method for an automotive use case. The reason for conducting this workshop was twofold: First, the workshop tested the applicability of the method; second, the resulting designs were needed as input for the subsequent laboratory study (Laboratory Study 1). In this study, the designs constructed with the Konect method were compared against those constructed with traditional methods to measure whether the Konect designs perform significantly faster and more correctly than the non-Konect designs. This laboratory study had to be conducted under artificial and controlled laboratory conditions to allow the exact measurement of perception times and correctness. So, the question arises if these results are transferable to more realistic conditions, especially in case more than one task (e.g. a secondary task as steering) is involved aside from the regarded monitoring task. This was the reason for conducting a driving simulator study to test if the effect measured under laboratory conditions remains the same.

This first part keenly focused on the first three steps of the Konect procedure. Step 4 was of minor importance as the whole design involved a limited amount of information elements (11). Hence, a second use case involving another domain (maritime) and a higher complexity of the information visualized was examined. In analogy to the automotive use case, the designs were developed in workshops and then tested under laboratory conditions (Laboratory Study 2).

Finally, the measurement results of Laboratory Study 1 and Laboratory Study 2 were used to validate the Konect Value.

Details for all studies (hypotheses/research questions, method, procedure, and results) are given in the upcoming subsections.

Use Case	Experimental Part	Main Research Question	Measured via
Truck Platooning (5.1.1) 	**Workshop 1 (5.1.2)**	Are HF experts able to apply the method without problems?	empirical observation in workshop, questionnaire
	Laboratory Study 1 (5.1.3)	Are Konect designs faster and more correct perceivable than non-Konect designs?	exact reaction time measurement and correctness of answers under controlled laboratory conditions
	Driving Simulator Study (5.1.4)	Are the results of the laboratory study transferable to less artificial measurement conditions?	reaction in case of ACC failure in driving simulator (point of breaking (TTC), amount of accidents)
Vessel Performance Monitoring (5.2.1) 	**Workshop 2 (5.2.2)**	Are HF experts able to apply the method without problems ?	empirical observation in workshop
	Laboratory Study 2 (5.2.3)	Are Konect designs after step 4 faster and more correct perceivable than Konect designs after step 3?	exact reaction time measurement and correctness of answers under controlled laboratory conditions
Truck Platooning & Vessel Performance Monitoring	**Konect Value Evaluation (5.3)**	Does the Konect Value allow justified conclusions about real reaction times and correctness values and is thus a correct metric?	calculating correlation of Konect Value to measured values of laboratory study 1 and laboratory study 2

Figure 6.1: Evaluations Overview.

6.1 Application of Konect for Truck Platooning

An initial experiment was carried out in the automotive domain for a truck platooning use case. This use case is described in detail in the upcoming section. For this use case, five HF experts applied the Konect method for systematically deriving an HMI optimized for fast and correct perception in a workshop (section 6.1.2). The resulting HMIs have then been tested and compared to designs created with conventional HF methods in a laboratory study (section 6.1.3) as well as in an experiment with the driving simulator (section 6.1.4).

6.1.1 Use Case Description

The use case used for the first evaluation of the Konect method is truck platooning. Truck platooning involves a group of heavy-duty vehicles driving very closely to each other to save fuel and optimize the use of existing infrastructure. The heavy-duty vehicles are interconnected through vehicle-to-vehicle (V2V) communication. The longitudinal control (i.e. speed and inter-vehicle distance) of trucks in a platoon is automated. The short inter-vehicle distance and automated longitudinal control have significant benefits for saving fuel. Nevertheless, the automation has to be monitored by the driver, who, on his part, encounters a new driving situation: They experience semi-automated driving at a very close distance. This close distance leads to a blocked field of view. Prior works have shown that drivers have different, yet recurring, concerns with platooning [Sadeghian Borojeni et al., 2016] [Eilers et al., 2015]. When asked, they mostly state that they fear truck platooning because they are not able to look ahead to anticipate the evolving traffic situation. Drivers also worry that they would not be able to react in time to road events to prevent accidents (e.g. possible failure of the

ACC). As the use case involves monitoring of safety-critical systems by having a focus on fast perception of the situation, it was an especially suitable application domain for the Konect method. Furthermore, the interest in and research on truck platooning is rapidly growing [Dutch & the Environment, 2016].

6.1.2 Workshop 1

As mentioned previously, the first workshop was conducted to test the applicability of the Konect method and to deliver the input designs for the subsequent Laboratory Study 1.

Research Questions

The main questions were:

- Is Konect easy to apply for HF experts (Q1)?
- Does Konect help to produce more HMI design ideas (Q2) and faster (Q3)?
- Does Konect help to develop HMIs that are suitable for the task at hand (Q4)?
- Would the HF experts use Konect in the future (Q5)?

Method

For evaluating the applicability and the concept of Konect, it has been applied in a workshop. The set-up is shown in Figure 6.2.
Five human factors experts (four male, one female) participated in the workshop. Three participants hold doctoral degrees in the field of human factors engineering and thus are deeply experienced in this field. One was a certified UX professional. The experts had different background knowledge regarding the use case: Four did not have prior knowledge of platooning and had never seen a design for the problem at hand. They were chosen to avoid any bias based on pre-existing experience. One was an HMI designer, who has been involved in designing an HMI for the platooning problem within the EU project COMPANION. He/she was chosen to make a statement on how much individual differences in the creativity of the designers might have influenced the results and whether Konect would able to improve design ideas if the person is biased.

Procedure

First, the Konect method was introduced to the participants, followed by a discussion in which questions were answered. In the next step, the platooning scenario was introduced using oral presentations and videos. The task for the participants was to create an HMI design for the given platooning scenario, where drivers should observe the following parameters: distance between the front and back trucks, speed of the

Figure 6.2: Set-up for application of Konect in a workshop with HF experts.

front and back trucks, and their own speed and planned speed. Another requirement was that the drivers should be able to detect if any of the parameters reach values that would possibly impair the safety of the system (e.g. inter-vehicle distance too short, speed too high). Again, the participants could ask questions. After these introductory parts, the participants were given around two hours of time and the paper prototyping material (e.g. pens, paper, crayons, ...) to apply the Konect method to derive an HMI design for the given scenario. During the session, the participants were allowed to ask questions relating to Konect and the scenario.

Results

The paper prototypes have been transferred into digital versions, which are shown in Figure 6.3 on the right (3–7). Designs which were developed without Konect are shown on the left (1, 2). These designs have been developed with conventional methods by HMI designers in the EU project COMPANION [Borojeni et al., 2016]. The HMI designers of COMPANION assisted in the workshop by explaining the use case. As stated before, one of them also applied Konect exemplarily and created Design 7 on the right. Thus, it was possible to compare non-Konect designs with the designs composed with Konect guidance made by the same designer. Each design visualizes the plan speed, the speed of one's own vehicle, the speed of the vehicle in front and the vehicle behind, and the distances with the vehicle in front and behind.
After the design phase of the workshop, each participant went through a questionnaire and gave feedback in a short discussion round. The results of the questionnaire are shown in Figure 6.4.

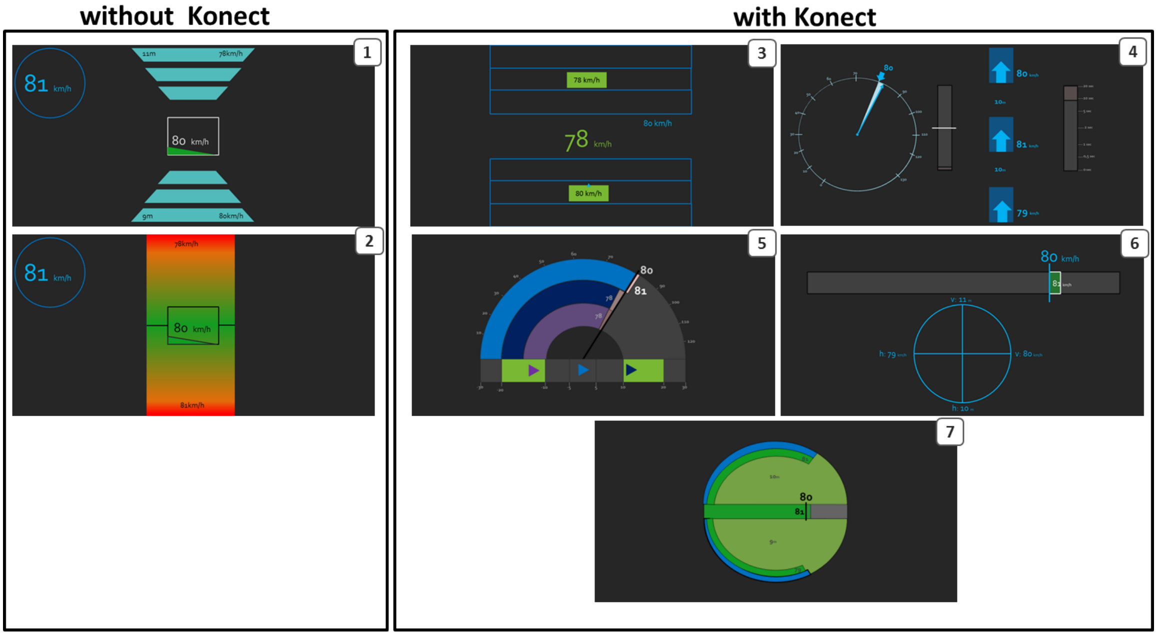

Figure 6.3: Platooning Designs.

The participants all agreed that the method was easy to apply (Q1).

Regarding Q2, three designers agreed that Konect helped to produce **more** ideas. The designer coming from the EU project COMPANION actually had the comparable situation of creating a design without Konect. He totally agreed and stated that Konect really inspired him to create more ideas. One designer mentioned that he cannot make a reliable statement regarding the amount of ideas as he cannot estimate how much ideas he would have produced without guidance of Konect. That was the reason why he stated to be neutral. Another designer did not agree: In the discussion round, he revealed that he experienced Konect as a method to create one improved HMI design. Instead of designing a lot of different HMIs, he focused on one design idea and stated that Konect really supported him in improving that design iteratively. He also admitted that Konect did not help him to produce ideas **faster** (Q3), but was convinced that the resulting HMI was of higher quality and totally agreed to Q4 (that Konect helps to develop HMIs that are suitable for the task at hand). Concerning Q3, all other participants, including the designer from the EU project COMPANION, agreed that Konect helped to produce ideas faster, but two of them were neutral regarding Q4. They mentioned that they wanted to talk to the real users of the system to make a reliable statement for the HMIs' task suitability.

According to Q5, all the participants agreed that they would use Konect in future because it could be applied easily and helps to develop suitable HMI designs quite fast by presenting the possible design space and rational justifications for choosing visual attributes.

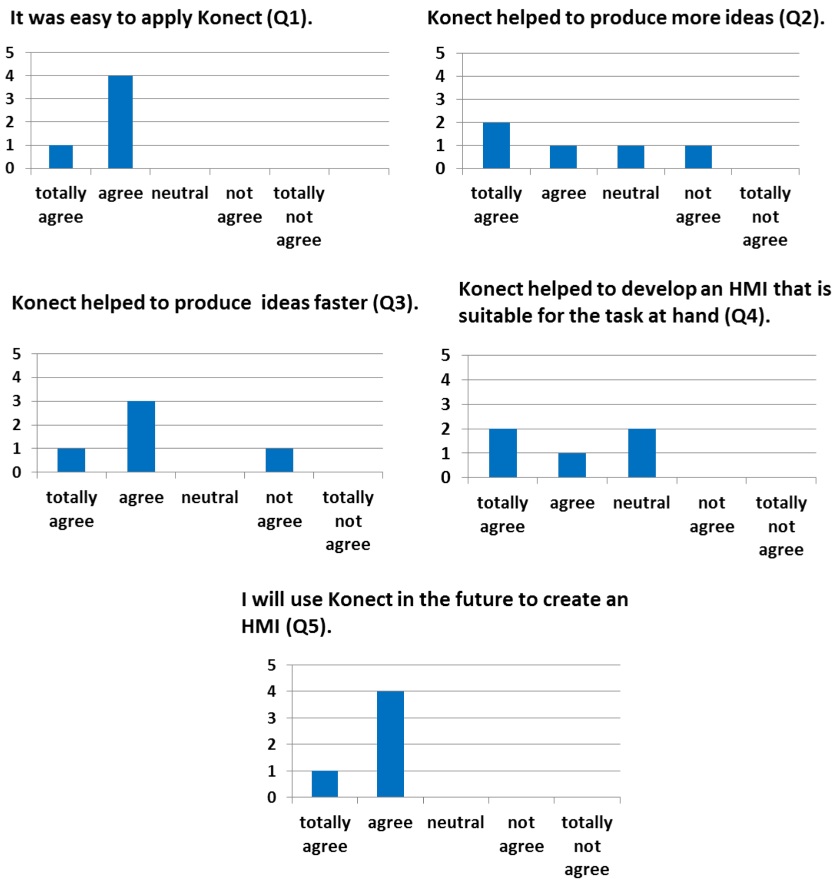

Figure 6.4: Estimation of the applicability of Konect via questionnaire.

6.1.3 Laboratory Study 1

Having the five HMI designs created in the workshop, it must be tested if the Konect HMI designs can be perceived more correctly and at the same time faster than the two non-Konect designs. In the scenario, it is required to assess if a situation becomes critical—it means that either the distance value or the speed value exceeds their operational limits. In a computer-based experiment, the participants were instructed to decide as fast as possible whether a given design reflects a critical situation or not. The time from presentation (activated by pressing the Enter key) until a second pressing of the Enter key as reaction time (RT) had been measured. After each presentation, the participants had to state if the previous situation was critical or not to measure how many errors were made (correctness).

Hypotheses

The following hypotheses with (H0) as the null hypothesis have been formulated:

(H0) There is no difference in RT and correctness of perceiving the situation between non-Konect designs compared to the Konect designs.

Figure 6.5: Set-up for user study under laboratory conditions.

(H1) Konect designs can be perceived faster by the human controller than non-Konect designs.

(H2) Konect designs can be perceived more correctly by the human controller than non-Konect designs.

Method

A total of 33 participants (12 male, 21 female) in the age group of of 19–47 years with a mean age of 24.75 years participated in the experiment, which was conducted using a computer and a test application. For each of the seven designs (five Konect and two non-Konect), four critical and four non-critical situations were created. This sums up to $7 * 4 * 4 = 56$ situations.
A pre-test of the experiment was conducted with three participants. It was found that three blocks are optimal because in the first block the mean reaction times were higher compared to the second and third blocks. It can be explained with a learning effect. In the second and third blocks, the mean reaction times were equal, which led to the assumption that further learning is unlikely to affect the results. In each of the three experimental blocks, the 56 alternatives have been presented randomly, leading to an overall number of trials of 168 per participant. The presentation of the designs had been randomized to avoid any carry-over effects from previous conditions that could affect the overall results of the study. To cancel out any individual differences regarding RT and correctness of perception, a within-subjects design was chosen so that all the participants were assigned to all conditions. On average, it took the participants about 15 minutes to complete the experiment.

Procedure

After being welcomed, each participant answered a pre-test questionnaire capturing statistical information. After that, they were introduced to the platooning scenario and watched a demonstration video. Thereafter, each of the seven (non-Konect and Konect) designs was presented and explained in detail, showing standard values, critical speed, and critical distance values for each design. The participants were asked to explain how each design reflected the given status (e.g. speed too high, distance too low) to support their understanding of the designs. If no questions were open, a reduced version of the test application was presented where each participant performed two reduced blocks of testing to get used to the procedure as well as to minimize the impact of the learning effects on the test results. The actual test was then performed in absence of the experimenter to minimize any distraction and possible pressure. After that, each participant answered a post-questionnaire, stating their favourite design and assigning a value between 1 and 6 (according to the German school grade system) to rate how well they were able to execute their task of detecting anomalous states as fast as possible.

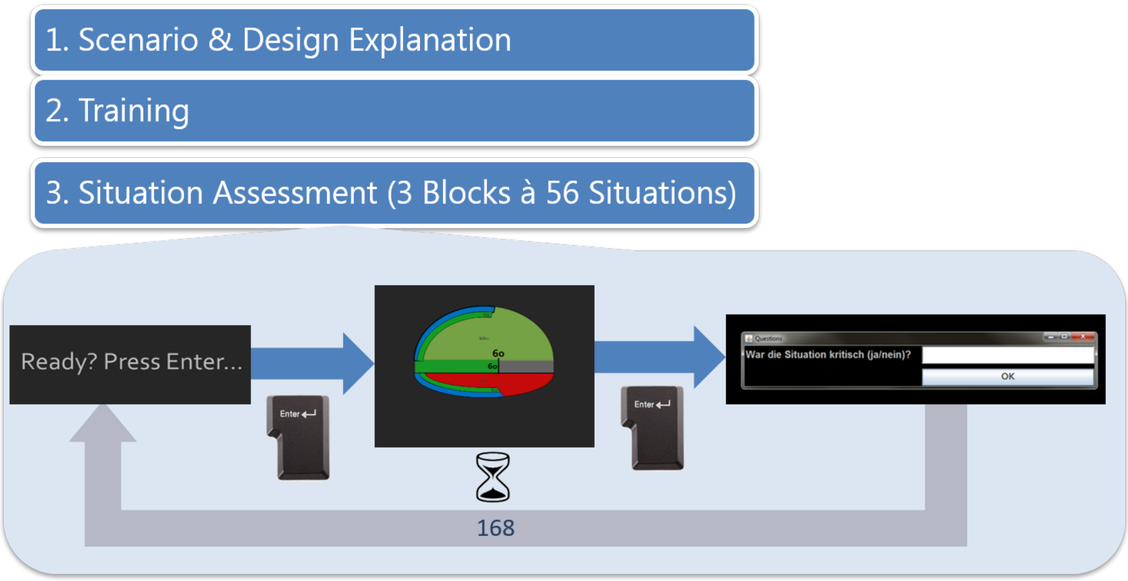

Figure 6.6: Procedure of the user study.

The procedure of each trial is shown in Figure 6.6. The participants pressed the Enter key when they felt ready for the next trial. Then, a random design was shown presenting either a critical situation or a non-critical situation. Here they were instructed to assess as fast as possible whether the presented design shows a critical situation or not. A second pressing of the Enter key ended the presentation of the design, and the participants had to mention in a text box whether the design was critical.

Time [ms]

Descriptive Statistics	Conventional	Konect
Minimum	838,83	816,01
Maximum	5533,92	3863,88
Mean	2122,86	1731,03
SD	951,65	772,31
CI-95	466,30	378,42
Median	1915,58	1553,39

Inferential Statistics		
T-Test	p	2,25E-05
Cohen's d	d	0,45
Effect size	r	0,22

Assessment Failure [%]

Descriptive Statistics	Conventional	Konect
Minimum	2,08	0
Maximum	35,42	13,33
Mean	14,59	5,43
SD	7,93	3,77
CI-95	3,88	1,85
Median	14,58	5,00

Inferential Statistics		
T-Test	p	5,99E-11
Cohen's d	d	1,47
Effect size	r	0,59

Subjective Evaluation

Descriptive Statistics	Conventional	Konect
Minimum	1,5	1,6
Maximum	6	4,6
Mean	3,56	2,51
SD	1,12	0,65
CI-95	0,55	0,32
Median	3,50	2,40

Inferential Statistics		
T-Test	p	5,12E-05
Cohen's d	d	1,15
Effect size	r	0,5

Figure 6.7: Statistics of Time, Assessment Failures and Subjective Evaluation in Truck Platooning Laboratory Study.

Results

The results are shown in Figure 6.7 and Figure 6.8.

Regarding assessment failures, it can be said that the Konect designs led to mean assessment failures of 5.43% ($SD = 7.93$), while the non-Konect designs scored a mean of 14.59% ($SD = 3.77$). With $p < 0.001$ in the T-Test, there was a strong significant effect. As a significance level, the Fisher criterion was chosen with 0.05. Thus, H2 (the Konect designs can be perceived more correctly by the human controller than the non-Konect ones) can be accepted. In this regard, a large effect is observable (Cohen's d of $1.47 > 0.8$, effect size r of $0.59 > 0.5$).

With regard to RT, the participants were faster with the Konect designs (average RT of 2122.86 ms ($SD = 951.65$)) compared to the non-Konect ones (1731.03 ms ($SD = 772.31$)). The T test resulted in $p < 0.001$. Thus, H1 can be accepted and the null hypothesis H0 can be rejected. However, with Cohen's d of 0.45 and an effect size r of 0.22, a small effect was observable here.

In case of the subjective evaluation, the conventional designs led to a mean evaluation grade of 3.56 ($SD = 1.12$), while the Konect designs resulted in a mean grade of 2.51 ($SD = 0.65$). In this case, a significant effect was again observable ($p < 0.001$) with a large effect size (Cohens $d = 1.15, r = 0.5$).

The advantage of the laboratory study was that a lot of data could be captured in a controlled environment. Nevertheless, the laboratory study represents a rather artificial set-up that excludes the main task (driving) as influencing factor. To include this factor, a second study took a more realistic set-up into account. It had been conducted in the driving simulator. The experiment and its results are described in the upcoming subsection.

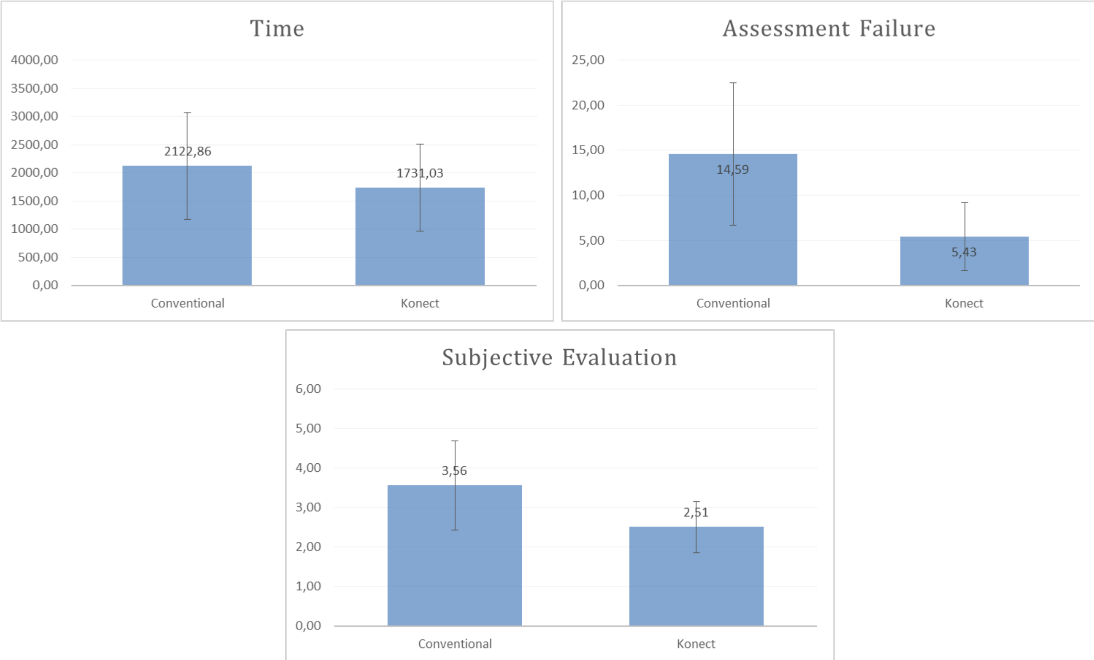

Figure 6.8: Mean Time, Assessment Failures, and Subjective Evaluation in Truck Platooning Laboratory Study.

6.1.4 Driving Simulator Study

The laboratory study presented in the previous section had the advantage that the results were measurable under well-controlled conditions and all HMI designs were tested by each participant. So, individual differences can be compensated. Nevertheless, the laboratory study conditions differ from the real conditions in the truck, neglecting the primary driving task, thereby representing quite artificial test conditions. To further examine if the results are transferable to situations under more realistic conditions, a driving simulator study was performed. In this study, an ACC failure was simulated and the participants' reaction were measured in terms of the distance to the truck in front after breaking and the amount of accidents.

Hypotheses

The following hypotheses were formulated:

(H0) There is no difference in the number of accidents and the remaining distance to the truck in front for the non-Konect design compared to the Konect design.

(H1) The Konect design results in a lower amount of accidents compared to the non-Konect design.

(H2) The Konect design results in a higher remaining distance to the truck in front at the breaking time compared to the non-Konect design.

Figure 6.9: Set-up of the driving simulator study.

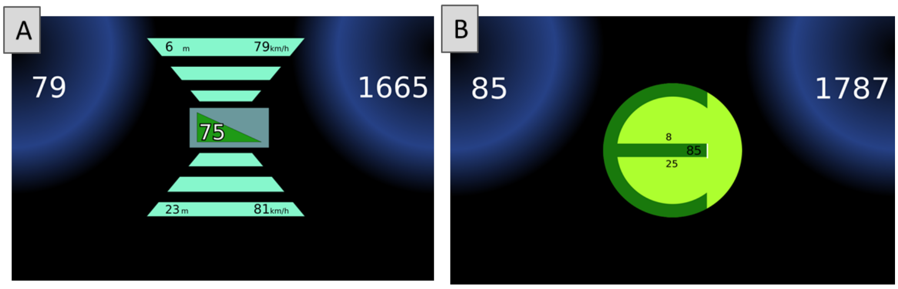

Figure 6.10: Designs in the driving simulator study.

Method

The experiment was conducted with 23 participants (12 female) in a fixed-based driving simulator (cf. Figure 6.9). On average, participants were 24 years old ($SD = 2.34$), held a driving license for 7 years ($SD = 2.2$), and drove 8,200 km per year ($SD = 6250$). All the participants were recruited from the University of Oldenburg and were paid 15 euros each. Professional truck drivers were invited via postings on bulletin boards in local transportation companies to take part in the experiment to maximize the significance of the results regarding the user group. Unfortunately, no truck drivers could be recruited. Reasons for this could be long working hours during the day which result in their lack of interest in participating in laboratory studies in after-work hours or that drivers are often employed non-stationary and thus are "on the road" for weeks or even months. Thus, students who are experienced car drivers were recruited. This was done because the concept of platooning is new both to truck drivers and experienced car drivers, so it can be assumed that the results are only affected to a small extent.

Furthermore, as the Konect method addresses human perception in general and does not focus on a specific user group, experienced car drivers were a favourable choice as participants.

For the driving simulator study, two HMI designs had been implemented: one Konect design and one non-Konect design. The HMI designs came from the same designer, as presented in the previous section (cf. Figure 6.3 were chosen: Design 1 as the non-Konect design and Design 7 as Konect design). This was done to allow better comparability of the design variants and exclude the factor that different designers with different background knowledge made the designs. So, the difference between the two design variants lies in the different development method. The implemented designs are shown in Figure 6.10.

In the simulator study, the real situation should map real conditions at the best possible rate. So, an ACC failure was simulated after a longer driving session. As this ACC failure could only be simulated once to reflect the best realistic conditions, the experiment was conducted as a between-subjects experiment. This means that one group of the participants drove with HMI A, as shown in Figure 6.10, and the other group with HMI B.

Procedure

After welcoming and being provided with general information, the participants were introduced to the platooning scenario with a video presentation and verbal explanations. Each participant was informed that their task was to drive the virtual truck safely with support of the ACC and the HMI to monitor the ACC. The participants were instructed to obey the traffic laws, to look out for any hazardous situations while driving, to use the ACC the whole time, and to observe and use the HMI while driving to their personal extents. They were informed that an overriding of the automation is possible at any time by braking, which would lead to immediate deactivation of the system. The participants got the information that the minimal allowed distance to the front truck was 4 m and that the distance values would generally change during the experiment. However, they were not allowed to fall below the safety threshold. To get used to driving in a simulator, every participant performed a test drive, which lasted about 5 to 10 minutes. None of the participants reported simulator sickness. After this, every participant performed three driving conditions in the following order:

- Baseline driving without HMI assistance (only vehicle speed and engine rounds per minute (RPM) were shown), duration approx. 11 minutes
- Part one: Driving with an HMI (either HMI A or B), duration approx. 11 minutes
- Part two: Driving with an HMI (same HMI as in part one), including an ACC failure at the end of the trial, duration approx. 8 minutes

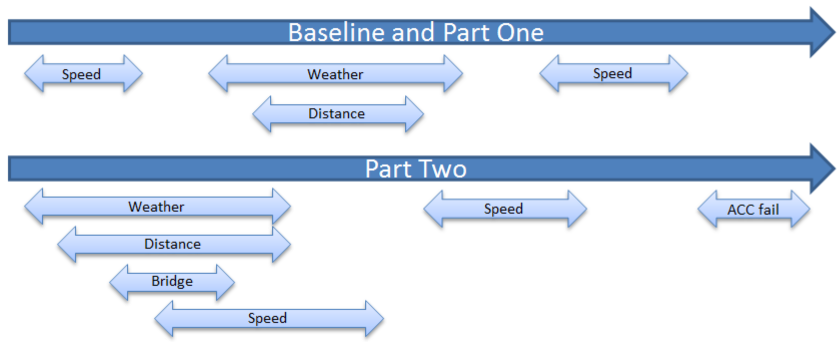

Figure 6.11: Order of the events during the simulation.

The beginning of the experiment was designed as follows: In each of the three driving conditions, the vehicle was placed on the road of a two-lane highway without any traffic. The lead vehicle was placed approximately 100 m in front of the vehicle and initially standing still. As soon as the accelerator pedal was engaged, the front truck also accelerated to the set speed of 85 km/h. The participants were told to accelerate to approximately 60 km/h, and if they reached this target speed, they pulled a lever on the left side of the steering wheel to enable the ACC. After this, the foot could be removed from the accelerator pedal and the vehicle closed the gap to the vehicle in front to an initial distance of about 11 m. Slowly after beginning the acceleration, some traffic was added to the road which behaved in a friendly way and did not influence the driving.
In the simulation, scripted platooning, road, and weather events were included. An overview of the order of the events is given in Figure 6.11. So, the events can overlap and exist simultaneously to further make the scenario realistic.

- **Plan speed**: Common change of the plan speed from 85 km/h to 75 km/h and back
- **Weather**: Bad weather conditions occur (heavy rainfall, low daylight)
- **Distance**: Inter-vehicle gap change from 0.3 s to 0.5 s and back
- **Bridge**: Heavy side wind on a bridge (wheel actuator mirrors side wind movements)
- **ACC fail**: The distance to the vehicle in front is decreased without stopping until the brake is applied

Changes in the planed speed reflect the behaviour of a platooning system where the individual planned speeds of the vehicles were adjusted remotely so that a platoon can be established in real traffic. In this way, the vehicles did not have to wait and could start driving at a planned time. Weather conditions can change in the real world at any time and are a reason to alter the current distances in a platoon or the planned speed. For example, if heavy rain appears, the distances are increased and the speed can be lowered so that the risk of an accident can be minimized due to an increased stopping distance. In the "bridge" situation, the vehicle passes a valley on a bridge where side winds appear so that the driving becomes more lively. At about two-thirds of the third part, the simulated ACC failure was induced. Beforehand, the participants were not informed that the ACC would fail. However, some participants asked whether the system could fail or could be somehow error-prone. In those cases, they got the answer that as in the real world, any system might fail and that it would be their responsibility to observe the system's function and to override the system in any case of hazard. After the ACC failure, the participants were asked to stop the vehicle on the shoulder of the road and they were told that the experiment was finished.

Results

In the experiment, it was measured how many meters between the vehicle and the vehicle in front were left at the time the first sensor value was registered from the brake pedal. If the participants were not able to break in time and caused an accident, the value was set to zero. The descriptive statistics and inferential statistics are shown in Figure 6.12. HMI A (the non-Konect design) resulted in an average distance of 1.21 m ($SD = 1.43$) left, while with HMI B (the Konect design) there were 3.45 m ($SD = 1.74$) left. The inferential statistics revealed that there was a significant difference of both conditions ($p < 0.001$) with a large effect (Cohens $d = 1.4, r = 0.57$). This large effect can be also seen in Figure 6.13 and in the amount of accidents occurred: With the non-Konect design, every second participant caused an accident. With the Konect design, this was reduced to 9.1%. Hence, with Konect, 90.9% of the participants were able to execute countermeasures in time. Thus, the null-hypothesis H0 can be rejected and the hypotheses H1 and H2 can be accepted.

Meters left when braking [m]

Descriptive Statistics		
Minimum	0	0
Maximum	3,67	5,43
Mean	1,21	3,45
SD	1,43	1,74
CI-95	0,70	0,85
Median	0,35	4,25

Inferential Statistics		
T-Test	p	0,0027
Cohen's d	d	1,41
Effect size	r	0,57

Figure 6.12: Driving simulator results: meters left when braking.

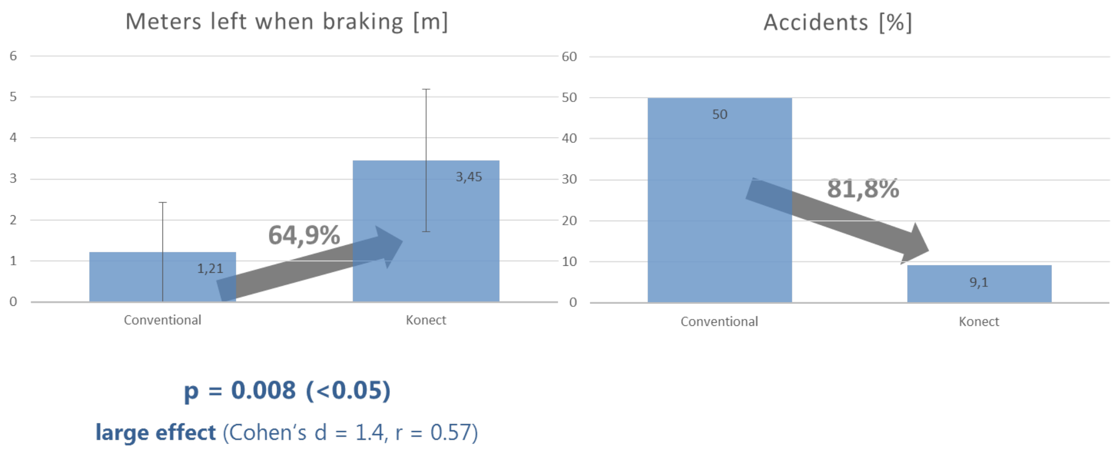

Figure 6.13: Driving simulator results: Mean meters left when braking and amount of accidents.

6.2 Application of Konect for Vessel Performance Monitoring

The truck platooning use case involves a limited amount of information elements (11 elements) and does only include **one** glyph. Thus, the fourth step (the *Design Composition)* of the Konect method played a minor to non-existent role. In a more complex scenario, this is quite different and the fourth step becomes more important. Hence, another experiment was conducted using a scenario of higher complexity. This scenario is situated in the maritime domain and deals with the surveillance of the fuel-efficient behaviour of a ship. This is called „Vessel Performance Monitoring". The task of vessel performance monitoring involves 25 information elements to be visualized. In the following text, the use case is described in detail (Section 6.2.1). This is followed by a detailed presentation of the study details with regard to the design creation in workshops (Section 6.2.2) and the evaluation of designs in a laboratory study (Section 6.2.3).

6.2.1 Use Case Description

The air quality in coastal cities is constantly getting worse. In the first quarter of 2017, the nitrogen oxides limit had been exceeded in the Hamburg harbour every two days [Kopp, 2017]. This results in a serious threat for the health of locals and other people. A large proportion of the air pollution is accounted for ships passing nearby the coast and entering the port: "Because nearly 70% of ship emissions are estimated to occur within 400 km of land [Endresen et al., 2003], ships have the potential to contribute significantly to air quality degradation in coastal areas. In addition, emissions are also generated while vessels are at berth, given that the main engines are not always switched off by all types of vessels [Meyer et al., 2008]" [Viana et al., 2014]. While the latter can be efficiently addressed by providing energy based on a power cable that connects the vessel to the port's energy distribution network (as it is also done with airplanes), the focus of this use case lies in addressing the former by optimizing the vessel performance monitoring.
Economic vessel navigation is an open issue in the maritime domain. According to studies published by the European Federation for Transport and Environment, the fuel consumption of ships actually increased by 10% between 1990 and 2013 [Transport & Environment, 2017b]. In 2016, the average design efficiency of ships was even worse compared to 2015 [Transport & Environment, 2017a]. Much of a ships' emissions arose close to the coast line and probably affected the air quality negatively [Viana et al., 2014]. To further identify the causes of fuel consumption of ships, Ando et al. [Ando, 2011] presented a breakdown analysis: A high amount of the consumption is caused by the ship's speed profile, the distances, and the trim. To optimize the total energy consumption and reduce emissions, some ships offer human machine interfaces (HMIs)

for vessel performance monitoring in order to be able to make right decisions to save fuel (e.g. use optimal speed, trim etc.).
Currently, such HMIs are difficult to use in critical situations as docking: In berthing or docking scenarios, information about the distance to the quay wall, the current, the position of tug boats, or the state of the thrusters is highly important for the task at hand as this directly affects the safety of the ship. Information on the secondary task—to save fuel and reduce emissions—has lower priority. Hence, as long as it is quite difficult for the operator to monitor these values, it will not be used in situations near land and port. Therefore, the idea was to design an HMI by depicting all relevant information for fuel-efficient operation that can be monitored with minor efforts while the operator performs the primary task (e.g. berthing or manoeuvring the ship).

A task analysis for the information determination step of the Konect method was conducted based on the information of two different data sources: regulatory information and an interview with a mariner. For the former, the Resolution MEPC.282(70) of the Marine Environment Protection Committee (MEPC) of the International Maritime Organization (IMO) was reviewed. Appendix 10 of that document deals with the development of a ship energy efficiency management plan. In its Section 5, it lists aspects that should be considered for fuel-efficient operation. This list was used as a first list of tasks relevant for fuel-efficient operation. Furthermore, an interview with a mariner was conducted to further clarify tasks and information elements that are relevant for fuel-efficient operation of vessels. As the use case deals with the monitoring of fuel-efficiency on board, only those tasks were selected that involve ship personnel during voyages. This resulted in a hierarchical task tree of 48 tasks for which each leaf task relates to one source of information. At the topmost level, under the goal of a fuel-efficient ship operation, three main tasks were identified: (1) *Speed Optimization*, (2) *Manoeuvring Optimization* and (3) *Trim and Draft Optimization*.

Speed Optimization: To save fuel during voyage, the speed, acceleration, and braking should be considered. Each ship has an optimal speed at which the fuel consumption is minimal. To estimate if the ship is driving at optimal speed, the actual speed must be known and compared to the optimal speed. Furthermore, the ship should reach the harbour at the right time for unloading cargo to avoid waiting time or problems with the place to berth. This is often called "just in time speed". This speed has also to be considered and should be compared with the actual speed. Finally, the acceleration is important for saving fuel. A more smooth and constant acceleration reduces fuel consumption. This can be seen with the acceleration trend and the shaft rpm trend—an indicator of the rotation speed of the propeller.
Maneuvering Optimization: Aspects influencing the manoeuvring can also lead to higher fuel consumption—e.g. headwind or high waves can lead to a higher resistance and thus to higher fuel consumption. Thus, the relative wind direction and speed, as

well as relative wave direction and speed, is relevant. Furthermore, the manoeuvring should be quite smooth to avoid high fuel consumption (similar to acceleration trend). Thus, the rudder angle trend is important and the autopilot state, as the autopilot can ensure smooth adaptation of the ships heading in accordance with a set course.
Draft and Trim Optimization: This includes the monitoring of trim (horizontal position of the ship), draft (the part of the ship below water), and the depth under keel (distance of the ship to the ground). For this, it should be noted that there exists an optimal trim and an optimal draft for each ship for having a minimal possible fuel consumption. This differs from ship to ship. The depth under the keel becomes important at a certain value at which the low depth can increase fuel consumption. So, sometimes the information that the depth under the keel is above or below this value is more important than the actual depth under the keel.

The information elements were systematically inserted into Konect idea boxes for three different glyphs—a speed optimization glyph, a manoeuvring optimization glyph, and a draft and trim optimization glyph.

6.2.2 Workshop 2

The creation of designs was done in different workshops—each composed of two participants. The workshops delivered the input designs for the subsequent laboratory study and tested the applicability of the Konect method.

Research Question

The following questions were of interest:

- How does the designs look like after Step 3 of the Konect procedure and how does the visual appearance change after Step 4 (Q1)?
- Do workshop participants have problems applying Konect(Q2)?

The focus of the study is on the visual appearance after Step 4 as the overall structuring of the design was already evaluated in previous work (e.g. [Burns & Hajdukiewicz, 2013]) as this strongly depends on the state of the art of available HF methods (EID, TA).

Method

Six workshops were organized, each of them with two human factors engineers, HMI designers, or industrial designers who collaboratively applied Step 3 (*Glyph Sketching*) of the Konect method. This was followed by the application of Step 4 of Konect (*Design Composition*). Groups of two experts were chosen to ease the observation of the discussion of the experts to get further insights into the reasons for choosing visual forms, the overall HMI design, and their way of working with the method and if problems occur (to answer Q2). Each workshop lasted about 3 hours.

Procedure

Within the workshop, the following procedure was applied:

As starting point, the designers read a textual description of the Konect method and the use case. Textual descriptions were used to avoid the differences between the information that the different experts obtained in the workshops and to control the effect of a potential bias caused by stating the instructions. Because of the limited amount of time and the complexity of the use case, the task analysis step and the creation of the idea box was excluded. Thus, the experts received already filled idea boxes and were asked to focus on the third step of the Konect method—the glyph sketching. In this part, each pair of experts created a design solution for the maritime use case. On average, the designers required around 2 hours to create the design based on Step 3 of the Konect method.

In the second part of the workshop, the experts received a second sheet of instructions with the description of Step 4, as specified in Section 5.2.4. They were asked to refine their designs according to this step. The experts needed around 1 hour to implement the guidelines to their designs.

Results

An exemplary sketch created in the workshops is shown in Figure 6.14. The sketches of all the participants were transferred to digital versions: The designs after Step 3 are shown in Figure 6.15. These designs changed to the designs shown in Figure 6.16 after the application of Step 4. During the application of the method, no problems occurred and the participants stated that the method was easy to apply.

6.2.3 Laboratory User Study 2

With the designs resulted from the workshop, a laboratory study was conducted in front of the computer to estimate the effect of the guidelines and Step 4.

Hypotheses

The following hypotheses were formulated:

(H0) There is no difference in RT and correctness of perceiving the situation between Konect designs after Step 3 compared to Konect designs after Step 4.

(H1) Konect designs after Step 4 can be perceived faster by the human controller than Konect designs after Step 3.

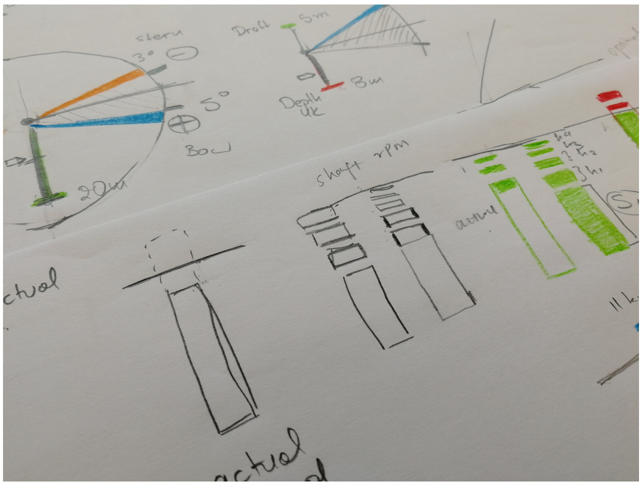

Figure 6.14: Exemplary extract of sketch created in workshop.

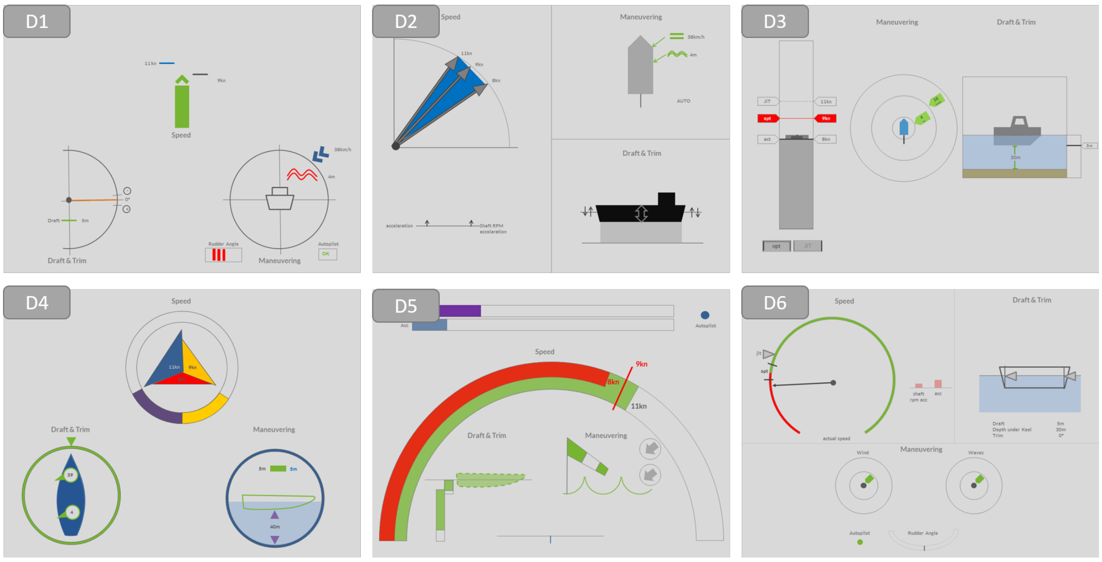

Figure 6.15: HMI Designs created in the workshops.

(H2) Konect designs after Step 4 can be perceived more correctly by the human controller than Konect designs after Step 3.

Method

Participants were recruited via a notice on the electronic bulletin board of the university. The study included 18 participants (14 women) whose ages ranged from 20 to 29 years (mean = 24.5, SD = 2.7). The participants received a reward of 15 euros.

Like the truck platooning laboratory study, a within-subjects design was chosen for the experiment. This was done to cancel out individual differences, especially with regard to individual reaction times. Thus, each participant worked with each design

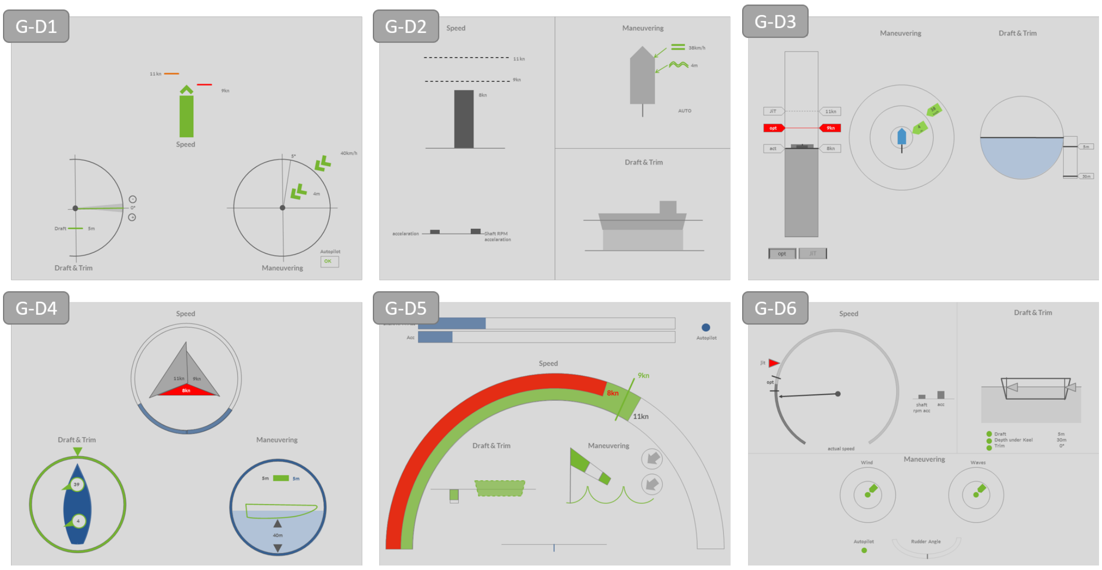

Figure 6.16: HMI Designs after application of guidelines.

(as shown in Figure 6.15 and 6.16). The exact procedure is described in the upcoming section.

Procedure

The procedure of the laboratory study is visualized in Figure 6.17. At first, the participants were given a description of all designs which they read carefully. After this, the participants were shown a series of figures. Each figure showed one of the 12 designs (6 initial designs + 6 guideline designs) in one of five different situations that are either critical or non-critical ($S1$: non-critical; $S2$: critical ship speed; $S3$: critical trim state; $S4$: critical (low) depth under keel; $S5$: critical wind condition). The task of the participants was to estimate as fast and accurately as possible whether the shown situation was critical or not. After pressing a key, the image disappeared immediately and the participants had to type their response. The correctness of the response and the reaction time between showing the image and hitting the key was measured.

The sequence of designs and situations was randomized. However, to avoid having the initial design and the guideline design of the same design concept (e.g. D1 and G-D1) in one sequence, the experiment was divided into two blocks (A and B) for each participant. Block A contained three initial designs and three guideline designs from different design concepts (e.g., D1, D2, G-D3, G-D4, D5, G-D6). Block B contained the six remaining designs (e.g. G-D1, G-D2, D3, D4, G-D5, D6). To eliminate the order effects, designs were randomly assigned to the blocks and balanced across participants. For each design, each of the four critical situations (S2–S5) were shown once and the non-critical situation (S1) twice. This was repeated three times, resulting in a sequence of $6 \times (4 + 2) \times 3 = 108$ stimuli shown in each block. To eliminate training effects, the

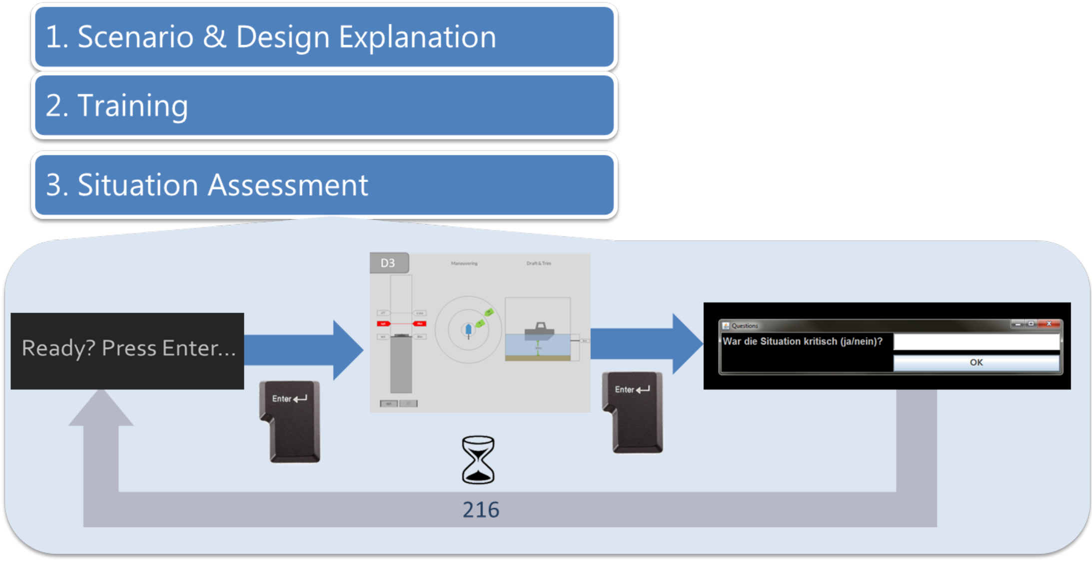

Figure 6.17: Procedure for the Vessel Performance Monitoring Laboratory Study.

blocks were iterated two times with pauses between them: A - B - A - B. Only data from the second iteration of Blocks A and B was analysed.

After the whole study, the participants were asked to assign a grade (1 to 6 based on the German school grade system) to the different designs to state how well they were able to execute their task.

Results

Time [ms]

Descriptive Statistics	after S3	after S4
Minimum	663,41	600,91
Maximum	1618,5	1374,08
Mean	1214,53	1041,52
SD	222,15	174,47
CI-95	108,85	85,49
Median	1220,82	1079,83

Inferential Statistics		
T-Test	p	3,64E-08
Cohen's d	d	0,87
Effect size	r	0,4

Assessment Failure [%]

Descriptive Statistics	after S3	after S4
Minimum	0,93	0
Maximum	26,85	9,26
Mean	7,72	3,09
SD	6,24	2,73
CI-95	3,06	1,34
Median	7,41	2,78

Inferential Statistics		
T-Test	p	0,00059
Cohen's d	d	0,96
Effect size	r	0,43

Subjective Evaluation

Descriptive Statistics	after S3	after S4
Minimum	1,5	1,33
Maximum	2,83	2,83
Mean	2,23	1,97
SD	0,41	0,43
CI-95	0,20	0,21
Median	2,33	1,92

Inferential Statistics		
T-Test	p	0,021
Cohen's d	d	0,63
Effect size	r	0,3

Figure 6.18: Statistics of Time, Assessment Failures, and Subjective Evaluation in VPM Laboratory Study.

The results of the laboratory study are shown in Figure 6.18 as a detailed description of correctness and reaction time measurements in the form of descriptive and inferential statistics. After Step 3 of the Konect method application, a mean correctness of 92.28% ($SD = 6.24$) was reached. The reworked design after the design composition step (Step 4) reached a mean correctness of 96.91% ($SD = 2.73$). With $p < 0.001$, a

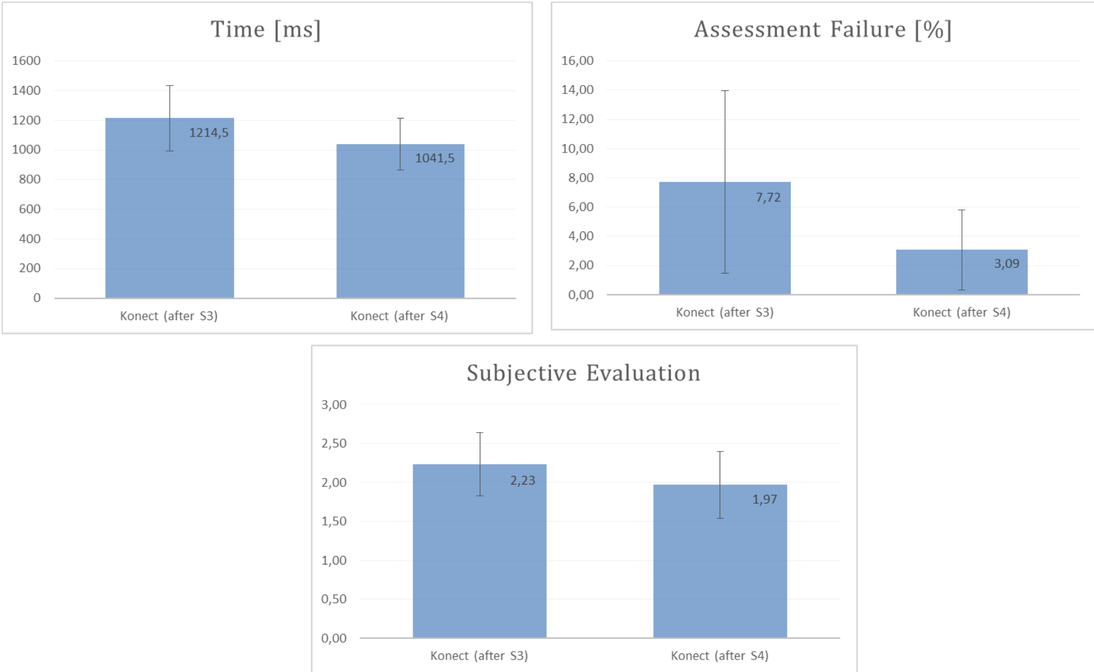

Figure 6.19: Mean Time, Assessment Failures, and Subjective Evaluation in VPM Laboratory Study.

significant difference was revealed, showing a medium to large effect regarding Cohen's d and effect size r (Cohens $d = 0.96, r = 0.43$). Thus, the application of the design composition step for complex designs was able to reduce assessment failures in mean by 4.6% (see Figure 6.19).
Regarding the time for perceiving the information, the results also revealed a significant difference ($p < 0.001$) with a medium to large effect (Cohens $d = 0.87, r = 0.4$). The designs after Step 3 reached a mean reaction time of 1214.53 ms ($SD = 222.15$), while the designs after Step 4 reached a mean reaction time of 1041.52 ms ($SD = 174$). This reveals a decrease in the time needed for perceiving the information of 12.4%.

In case of the subjective evaluation, the designs after Step 3 reached a mean grade of 2.23 ($SD = 0.41$), while the designs after Step 4 had a mean grade of 1.97 ($SD = 0.43$). The effect was again significant with $p < 0.05$. According to Cohen's d ($d = 0.63$) and effect size r ($r = 0.3$), a medium effect size was observed.

Thus, all in all, the null hypothesis can be rejected and H1 and H2 can be accepted.

6.3 Validation of the Konect Value

In Chapter 5.2.5, the Konect Value K was presented as the numeric indicator for estimating the efficiency of a design solution directly at the design time. Having the measured results for assessment failures and the time needed to perceive a critical system state for different design solutions for vessel performance monitoring (see Figure 6.15 and Figure 6.16) and truck platooning (see Figure 6.3), the calculated Konect Value K can be compared to these measured values for each design to validate that it represents a suitable metric.

Hypotheses

The following hypotheses with H0 as null hypothesis were formulated:

(H0) The Konect Value does not correlate with the measured values (reaction time, correctness, subjective evaluation) of Laboratory Study 1 and Laboratory Study 2.

(H1) The Konect Value correlates with the measured reaction time of Laboratory Study 1 and Laboratory Study 2.

(H2) The Konect Value correlates with the measured correctness of Laboratory Study 1 and Laboratory Study 2.

(H3) The Konect Value correlates with subjective evaluation of the designs of Laboratory Study 1 and Laboratory Study 2.

Method

To validate this, the Konect value K was calculated for each of the 19 design solutions presented previously by using the Konect tool. The data used for calculation has been saved as a .xml file, which can be opened directly with the Konect tool.

Procedure

For each design, the Konect Value K was calculated. Therefore, the information was inserted into the idea box using the Konect tool. For each piece of information, the visual efficiency for each chosen visual attribute was calculated and the amount of violations against design composition guidelines (inconsistencies, visual information elements that are not relevant to the task and produce clutter, simplicity in color as well as simplicity in shape) was counted and inserted in the Konect tool support, as described in Section 5.3. After this, the Pearson's moment correlation between the calculated Konect Value K and the measured reaction times and correctness was calculated.

Results

The resulted Konect Values K are listed in Figure 6.20. Besides the Konect Value K, the table lists the measured mean times in ms for the different design solutions, the measured assessment failures in %, and the subjective evaluation of the participants.

	K	Time [ms]	Assessment Failure [%]	Subjective
VPM D1	0,5	1613,5	20,1	3,1
VPM G-D1	0,17	1113,9	5,9	2,2
VPM D2	0,22	1114,8	2,8	2,6
VPM G-D2	0,24	1132,15	9	2,2
VPM G3	0,1	1008,35	0	1,8
VPM G-D3	0,04	1016,74	1,2	1,6
VPM G4	0,26	1062,75	4	1,6
VPM G-D4	0,13	951,5	1,2	1,2
VPM D5	0,31	1083,5	12,7	1,9
VPM G-D5	0,15	932,6	0,3	1,7
VPM D6	0,5	1404,3	7	2,5
VPM G-D6	0,22	1102,3	1	2,9
Truck D1	0,93	2348	17	3,95
Truck D5	0,83	2332	11	3,5
Truck D2	0,85	1784	12	3,2
Truck D7	0,72	1693	5	2,6
Truck D4	0,42	1408	7	2,5
Truck D6	0,12	1572	2	1,9
Truck D3	0,19	1439	3	2

Figure 6.20: Results overview.

To clarify in how far a correlation between the Konect Value K and the measured values exist, the Pearson's moment correlation was calculated. The resulted r values are shown in the table in Figure 6.21 and the scatterplots are showing the correlation in Figure 6.22. Here, it can be seen that there exists a high correlation between the calculated Konect Value K and the time measured ($r = 0.88$), the subjective evaluation of the participants ($r = 0.84$), and the assessment failures ($r = 0.71$). All correlations are significant with $p < 0.001$. Thus, H0 can be rejected and H1–H3 can be accepted, and therefore, the Konect Value K represents a suitable metric for estimating the efficiency of design sketches early.

	K	*Time [ms]*	*Assessment Failure [%]*	*Subjective*
K	1			
Time [ms]	0,8767	1		
Assessment Failure [%]	0,7095	0,6363	1	
Subjective	0,8448	0,8299	0,6913	1

Figure 6.21: Pearson's product-moment correlation between measured variables and Konect Value K.

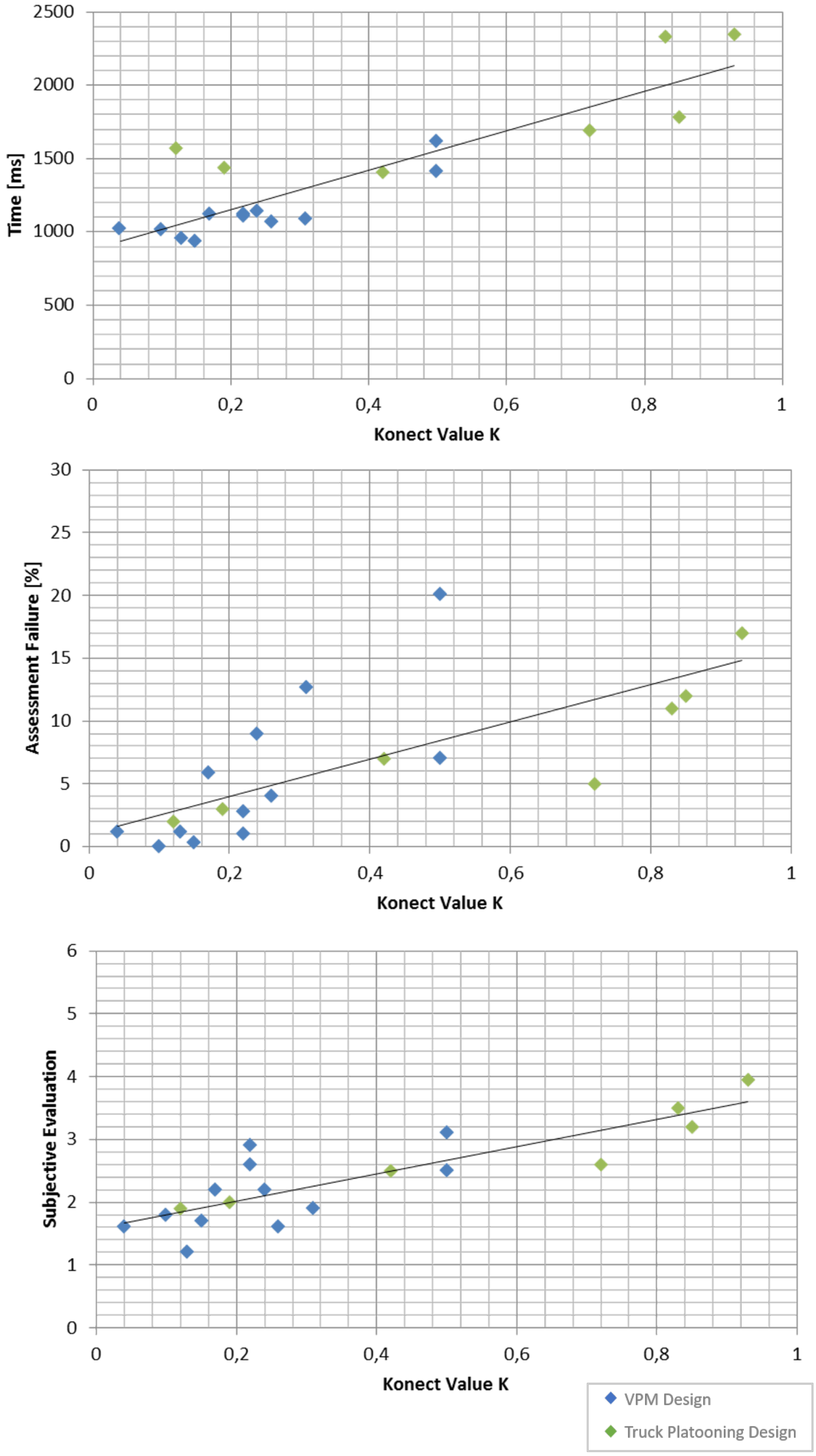

Figure 6.22: Scatterplots showing the correlation between Konect Value K and measured values.

7 Discussion

In the previous part of the dissertation, challenges and requirements have been described (cf. Chapter 3). Based on this, the Konect method was developed as a solution and outlined in detail in Chapter 5. To evaluate Konect, several experiments in two different domains (automotive, maritime) were carried out, and the results are shown in detail in Chapter 6. The upcoming chapter discusses the results achieved in the underlying dissertation and builds the bridge to the previously defined requirements. So, it is outlined in how far the method fulfil the requirements specified in Chapter 3. For this purpose, each requirement specified before is addressed in the subsequent sections, which also discuss to what degree Konect meets these specifications and where exactly weaknesses exist. The latter topic requires future research.

7.1 Problem-oriented and Industry Independent

The first requirement described in Chapter 3 was **R1**, stating that *Konect should work in a problem-oriented manner and thus be industry-independent for every design activity.*

During activities for creating the method, special attention was paid to the aspect that Konect does not use domain-dependent specifications or knowledge as a scientific basis. Instead, the method builds on knowledge about humans—especially human perception—in general. This results in a domain-independent working principle of Konect. The scientific basis of Konect has a problem-oriented view as it ensures fast and accurate perception of critical information. This has also been proven with the experiments conducted for the evaluation of the method: Once it has been applied in the automotive domain for a truck platooning use case, while for the second experiment the method has been applied in the maritime domain for systematically deriving information visualizations for a vessel performance monitoring use case. Thus, the operating principle of Konect is domain- and industry-independent. Instead, Konect works in a problem-oriented manner as designs support in both cases fast and accurate perception of critical system states.

7.2 Promotion of Invention and Knowledge

R2 stated that *Konect should promote invention and knowledge and thus facilitates the finding of optimal solutions.* This requirement has been further subdivided into the sub-requirements **R2.1 - R2.6**. Each of these sub-requirements will be discussed in the following text.

R2.1 Innovative Graphic Forms

R2.1 specified that *Konect should allow the creation of innovative graphic forms.* The workshops conducted for the truck platooning use case and the vessel performance monitoring use case revealed that the participants came up with quite new ideas for visualizing information. One example is the circular truck platooning design (see D7 in Figure 6.3). Compared to the conventional design D1 in Figure 6.3, this design is more innovative and unconventional; it, at the same time, avoids any single usage of text for encoding information (this was repeatedly stated by laboratory study participants). As both designs were created by the same person (once without Konect and once with Konect), this can be claimed to be a result of the method. During the experiments, it has also been revealed that the study participants first remarked that the circular Konect design was too innovative as it represented a quite uncommon visualization in the automotive domain. But after the execution of the study task (assessing critical states as fast and accurately as possible), the participants changed their opinions and stated that they would really like the circular design as it offered a better task support compared to the conventional design. This aspect also becomes obvious in the experiment outcome as D7 gained better results in subjective evaluation, time for assessing the situation, and in the correctness level of the assessment (see Figure 7.1).
During the experiments, no design was created which makes extensive usage of the text. All 19 designs developed by the workshop participants showed innovative graphic forms and made extensive usage of visualizations for encoding information. Thus, it can be claimed that **R2.1** is fulfilled by Konect.

R2.2 Fostering of Creativity

The fostering of creativity, as stated in requirement **R2** (*Konect should promote invention and knowledge, and thus, facilitate the finding of optimal solutions.*) was minded during the creation phase of the method in the form of the idea box. So, Konect borrows concepts fostering creativity from well-established research coming from this domain.
The application of the idea box was again tested in the workshops conducted for the experiments in the truck platooning scenario and the vessel performance monitoring use case. The workshops revealed that by opening up of the design space in a systematic way, the creativity of the workshop participants was fostered. The participants verbally

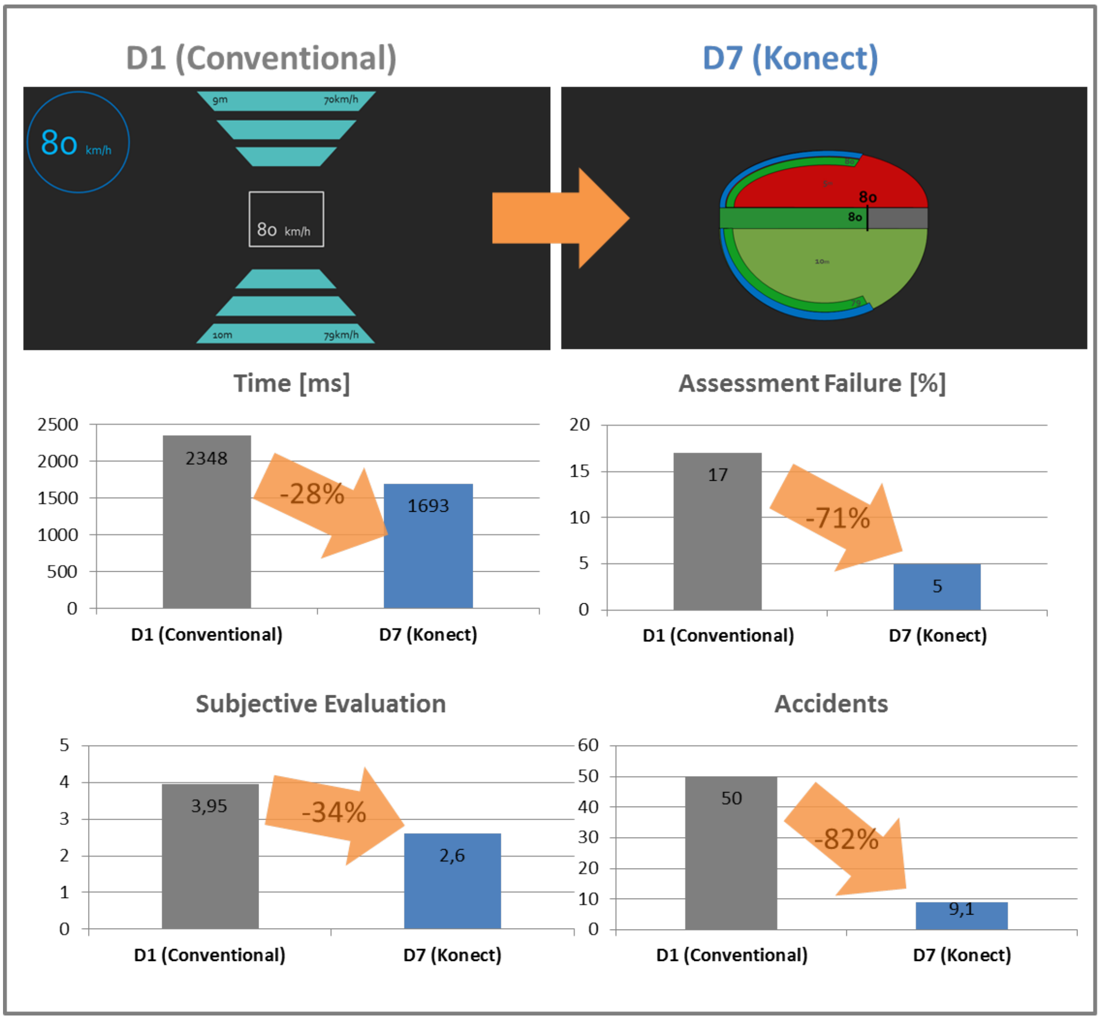

Figure 7.1: Comparison of designs made by the same designer with conventional method (user-centred design) and with Konect.

remarked that the method really helped in finding innovative solutions as it opens up a design space that can be searched systematically. In the truck platooning workshop, the subsequent questionnaire revealed that the designers had the impression that they could produce ideas faster (cf. section 6.1.2). This could also be observed during the workshop sessions: Even though most participants were not familiar with the presented use cases, all of them could derive efficient HMI concepts in just two hours for the considered task. Even though all design sketches were produced in a short period of time, most led to very good results for the measured time and correctness in the consecutive user study (cf. Section 6.1.3 and 6.2.3).

At the beginning of the workshops, the participants were asked to estimate their creativity on a 5-point Likert scale ranging from 1 (not creative) to 5 (totally creative). Even though no participant estimated him or herself as being not creative (1), all other values from 2 to 5 appeared (mean estimated creativity = 3.8 (SD = 1.13)). To assess to what extent the creativity influenced the quality of the design outcome beyond the

	K	Time	Correctness	Time/Correctness Ratio	Subjective Evaluation
Creativity	0,2237 (*p=0,2263*)	0,2245 (*p=0,2248*)	0,304 (*p=0,097*)	0,268 (*p=0,1451*)	0,0524 (*p=0,7794*)
HMI Design Expertise	0,278 (*p=0,13*)	0,052 (*p=0,783*)	0,19 (*p=0,3*)	0,098 (*p=0,6*)	0,335 (*p=0,065*)

Figure 7.2: Correlation between the stated creativity and HMI design expertise to Konect Value K and measured variables in the experiment (time, correctness, and subjective evaluation).

instruction of the Konect method, the correlation between the creativity of the designer and the resulted outcome (time, correctness, and subjective evaluation) was calculated. The results are given in Figure 7.2. For all cases, there exist only a minimal weak correlation and none of these correlations is significant.
Based on the combination of these facts—fast and similar creation time of designs for all designers (even though the estimated creativity differs) and nearly no correlation between the estimated creativity and the quality of design solution—it can be assumed that the design method successfully fosters creativity.

Further experiments might be helpful to especially examine the fostering of creativity. Since this aspect was not in the focus of the dissertation, no other experiments were conducted for further analysing this point. It was rather important that new innovative forms are fostered and that the application of the method does not „block" the designer in finding design solutions. This aspect did not happen in any case as rather the opposite case occurred: The designers were encouraged to develop innovative and creative solutions that are reflected in the different design solutions in Section 6.

R2.3 Optimization of Assessment Time and R2.4 Optimization of Assessment Correctness Level

R2.3 specified that *Konect should optimize the time needed to perceive a critical state.* This aspect has been studied in the laboratory experiments in the automotive and the maritime domain. As described in Section 6, designs created with the Konect method resulted in significant lower times to perceive a critical system state compared to designs that were created with conventional methods.

Requirement **R2.4** is quite similar to R2.3 and does address the second optimization objective of Konect: *Konect should optimize the accuracy of perceiving the criticality of a system state in terms of reducing the amount of overlooked critical information relevant for estimating the system's criticality level.* Like R2.3, this requirement was validated in the laboratory study via the measurement of assessment failures. The results revealed that assessment failures were significantly reduced with designs created with Konect compared to conventional designs.

Both results are causal conclusions based on the outcomes of the laboratory studies and the subsequent statistical evaluation. In such experiments, the validity of the results must be ensured: „Causal conclusions based on the outcomes of experiments are only possible if alternative explanations—i.e. threats to validity—are made implausible. Alternative explanations result if causal variables, which are not to be studied, influence the used effect variables or might have such influence. Such unwanted effect variables are called extraneous variables." [Krauth, 2000]. In empirical research, this aspect is often referred to as the *internal validity* of an experiment. For the design of the study, great importance was attached to ensuring a high internal validity of the results. For this reason, the effect of extraneous variables was reduced by applying different techniques for the study of the design:
It can be assumed that there are large individual differences in terms of reaction times. This might result from variables such as the age of the study participant or the level of fatigue. To cancel out the effect of different individual reaction times, a within-subjects design was chosen in case reaction times were measured. The same applies for the measurement of correctness levels. This means that each participant was assigned to each design condition. Furthermore, the order of designs and situations was randomized. Otherwise, the order could have had an impact on the results as the same person might respond differently to later treatments compared to former treatments due to fatigue or decreasing motivation [Krauth, 2000]. To cancel out this effect, the order was randomized. By this, the effects caused by the differences in „age, gender, body weight, intelligence, educational standard, social class, etc." were compensated. According to Krauth, randomization is one of the most important techniques to ensure internal validity: „In contrast to all other techniques, a randomization admits to control all potentially infinitely many known or unknown extraneous variables." [Krauth, 2000].
Another technique that should be considered during the study design to reduce the effect of extraneous variables is *constancy.* To eliminate the effect of surrounding aspects (e.g. elements in study room that might attract attention, devices used for measurement, material to explain designs, and persons and words used for design explanation), all of these elements were kept at a constant level (e.g. same room, same furniture, closed window with curtain in front of it, same explanation material, written explanation, same experimenter). So, a careful study design ensured that high internal validity exists.

The aspect that there exist no alternative explanation for the study results is further emphasized by the fact that there was a high correlation between the Konect Value K and the measured time and correctness levels (cf. section 6.3). This strongly indicates that the applied efficiency rankings and rules of the Konect method are the rational reason behind the times and correctness level for perceiving critical system states.

Regarding a high internal validity, the validity of the subsequent statistical evalua-

tion should also be considered. In Section 6, the results of the T-Test were presented. The T-Test is a parametric statistical test that is generally more powerful than the corresponding non-parametric tests (Mann-Whitney U, Wilcoxon) [Series, 2018, Riepl, 2018]. Non-parametric methods convert raw values to ranks and then analyse these ranks. Thus, they reduce the amount of information analysed and rather reveal tendencies. On the contrary, parametric tests can prove the existing differences as they use more information in the data [Riepl, 2018]. But parametric tests have some assumptions (dependent variables should be interval-scaled and data should be normally distributed). If an assumption is not met, this might lead to false conclusions when applying the test, even though it is very robust against such violations [Bortz, 1999, Riepl, 2018]. In such cases, it is a discretionary decision if a non-parametric test is applied instead of the parametric counterpart.
To ensure the validity of the statistical results, the assumptions have been checked. For this reason, all data was plotted. In most cases, the data nearly results in a normal distribution (bell-shaped distribution curve). Furthermore, the Shapiro–Wilk test (statistical test for testing normal distribution) was conducted. In some cases, the Shapiro–Wilk test indicated that the data is not normal distributed (this evaluation has to be considered carefully as for sample sizes less than 100, there exists quite a high risk of a Type II error [false negative] with this test). Nevertheless, to be absolutely sure that the differences between the Konect and the non-Konect designs are statistically significant, the non-parametric counterpart to the T-Test (Wilcoxon) was also conducted in these cases. All of them resulted in significant differences and revealed that Konect designs perform significantly better regarding the time and correctness to perceive critical system states. Hence, the validity of the statistical evaluation is also given.

Besides *internal validity*, the *external validity* of the experiment has to be taken into account. External validity „asks the question of generalizability" [Campbell & Stanley, 1963]. In this case, it has to be considered that the participants were assigned to conditions that do not resemble the real situation. This has been done to have a controlled environment that cancels out the effects of confounding or extraneous variables and ensures a high level of internal validity of the study. In a more realistic set-up, the context of use is slightly different as the influence of a secondary task exists, which has to be executed, or other distracting elements as noise, lighting conditions etc. For this reason, the driving simulator experiment was conducted (see Section 6.1.4) to estimate the transferability of the results to a more realistic set-up. The results revealed that the effect remains the same, even though a secondary task or distracting elements exists in the field of view (cf. Section 6.1.4). In this case, the reduced time and increased correctness for perceiving a critical state led to a reduction of accidents by 81.8%. This strongly indicates that the necessity of using efficient visual forms becomes even more important in case of distracting tasks and other elements.

R2.5 Fitness to Task

In the requirements section, it has been specified that *Konect should tailor the HMI to the operators tasks* (**R2.5**). This was considered in integrating prior HF methods as task analysis and ecological interface design in the information determination step of Konect. Furthermore, the tailoring was considered via the specification of insights for different information elements. This ensures that chosen visualizations are optimal with regard to the required kind of information needed for conducting the task at hand and consider the expressiveness of graphical elements (see section 5.1.3).
In the laboratory studies conducted in the evaluation phase of Konect, the study participants were asked how well they were able to execute their task. The results revealed that designs developed with Konect were evaluated as being significantly better for task execution performance compared to the designs developed using conventional methods (cf. 6).
Nevertheless, it has to be said that the focus of the dissertation lies on one specific task: Fast and accurate perception of critical system states. If it comes to other tasks, such as a comparison between two temperature values, no perfect statement can be made. Even though other tasks have been considered in the theoretical framework of Konect via the insights and expressiveness of graphic forms, the conducted experiment focused on perceiving and assessing critical states. Thus, further experiments might be helpful to analyse this aspect in more detail. As other tasks were not in the focus of the dissertation, no further experiments were conducted to analyse this aspect. But this might be an interesting point for future work.

7.3 Compatibility with Terms, Methods and Findings of Other Disciplines

Requirement **R3** specified that *Konect should be compatible with terms, methods and findings of other disciplines.* This requirement is directly based on the requirements for a constructive method. In case of Konect, this has been further subdivided into the sub-requirements **R3.1** to **R3.3**.

R3.1 defined that *Konect should represent an extension of existing HF methods or allow compatibility with them.* This requirement was recognized during the creation of the Konect method. The existent HF methods are applied to the information determination step of the Konect procedure. For the evaluation part of Konect, a task analysis was conducted to obtain all the information elements needed in the execution of the tasks.

R3.2 specified that *Konect should consider prior knowledge coming from the data visualization domain and the way of working in this domain.* Section 5.1 and 4 showed that

Konect is extensively based on knowledge coming from the data visualization domain. It was important that Konect should not only mind the knowledge coming from the data visualization domain, but also the way of working in this domain. This is necessary to include knowledge coming from this domain and additionally for being able to later adapt or extent the method based on new findings in this area. This aspect was recognized with regard to the abstraction level: The Konect method offers help for choosing visual attributes on the level of *color*, *position*, *length* (e.g. deciding between *color*, and *length* as the visualization option and not on the level of the instantiation (e.g. *red vs. blue*)). As this is the abstraction level most works focus on (see section 2), it will be possible to adapt or extend the knowledge base of the Konect method accordingly.

R3.3 determined that *Konect should be compatible to guidelines and standards existent in the HMI design for safety-critical systems.* In this regard, it was important that requirements coming from the currently existing standards (e.g. NASA-STD-3000 or ISO-9241) can be fulfilled and do not come into conflict with the instructions given by the Konect method. Based on the literature review, the existing standards are rather abstract (e.g. giving the hint that a design should offer suitability for the task [ISO-9241], or that a simple design should be preferred [NASA-STD-3000]), or very concrete (e.g. that for alert flashes no more than three to five flashes should be used per second (MIL-STD-1472F) or that red should be always used as the color code for an alarm [ISA-5.5-1985]). In both cases, the requirements coming from the standards can be included in Konect: Most of the abstract rules are directly considered in the theoretical framework of Konect (e.g. simplicity, suitability for the task). In case the abstract rules do not give any relationship to the monitoring task but rather influence the interaction design (e.g. suitability for individualization or feedback for interactions), they can directly be applied as this aspect is excluded in Konect. The concrete ones are also applicable as part of Konect, since they address the instantiation and can be easily included in the glyph sketching phase of the method, as described in Section 5.2.3.

In the vessel performance experiment, the designers were asked to fill in a skill and knowledge matrix (shown in Figure 7.3). All the workshop participants had different experiences. None of them had a problem in including prior knowledge and expertise in the process, as no contradiction between this knowledge and the instructions given in the Konect method exists.

Thus, all in all, it can be stated that the compatibility with terms, methods, and findings from other disciplines is fulfilled because this aspect was considered in the development of the method and that nothing has been recognized otherwise during the workshops.

	P1 (f)	P2 (f)	P3	P4	P5	P6	P7 (f)	P8	P9 (f)	P10 (f)	P13	P14	Mean
task analysis	5	3	4	4	4	5	4	4	5	4	3	4	**4,1**
HMI design	5	4	5	5	4	5	3	5	5	5	5	5	**4,7**
information visualization	4	3	4	5	4	4	3	5	5	4	4	5	**4,2**
preattentive visual cues	3	4	4	4	2	2	2	4	4	1	4	5	**3,25**
ISO 9241	3	1	2	2	2	1	2	4	5	5	4	5	**3**
structural information theory	3	2	2	2	2	1	1	2	4	4	2	3	**2,3**
shneiderman's 8 golden rules	3	3	4	5	2	1	3	5	5	5	4	4	**3,7**
garners patterns	2	2	2	1	2	1	3	3	5	1	1	2	**2,1**
gestalt laws	4	4	4	3	2	1	5	5	5	5	3	5	**3,8**

1 never heard of
2 heard about
3 know
4 applied/done
5 often applied/done

Figure 7.3: Prior skills and knowledge of participant workshops.

7.4 Systematic Creation of Designs

Requirement **R4** further establishes the strong engineering background of the method. R4 specified that *Konect should not create solutions by chance.* The method instead aims for creating design solutions that are rationally justified. Requirement R4 has been further subdivided into the requirements R4.1–R4.4.

R4.1 defined that *Konect should work with rational constraints* to have a rational justification for choosing a certain visualization. This was fully considered in the creation of the method in Section 5. The information shown in the idea box–especially the efficiency rankings enhanced with the visual efficiency value VE–provide a basis for rationally choosing and justifying visualizations. These rankings are based on actual knowledge of human perceptual skills (see section 5 for details), thus fulfilling the requirement **R4.2** that *Konects rational constraints should offer compatibility with perceptual and cognitive skills.* The knowledge was incorporated into the theoretical framework, which was described and reasoned in detail in Section 5. Hence, Requirement **R4.3** (*Konect should provide a theoretical framework for rationally supporting decision-making for visual forms during the design phase*) is covered.
The last sub-requirement was **R4.4** stating that *Konects theoretical framework should offer help for synthesizing visual elements appropriately.* This requirement was fulfilled with Step 4 of the Konect procedure (see Section 5.2.4). The more complex the monitoring task, the more important this step. The truck platooning experiment and especially the correlation between the Konect Value K and the measured values revealed that the rational justification mentioned in R4.1–R4.3 is correct. For the validation of R4.4, the vessel performance experiment is of higher importance as this focuses on the synthesizing of visual elements for scenarios with a higher level of complexity. The experiment revealed that after the synthesizing step of the Konect method, the designs were significantly improved regarding the time needed to perceive a critical state, the reduction of assessment failures, and the subjective evaluation of task performance possible with the HMI design solution.
So, all in all, the requirement R4 can be seen as fulfilled and validated.

7.5 Transferability of Results

Requirement **R5** deals with the transferability of design solutions to related tasks. Therefore, it has been specified that *Konects theoretical framework should be based on the perceptual and cognitive skills of humans in general and thus be domain-independent* (**R5.1**) and that *Konects procedure should work on a partially abstract level that generates generally valid reusable solution documents* (**R5.2**).

As mentioned previously (cf. Section 7.1), Konect offers a domain- and industry-independent working principle due to the alignment of Konect scientific knowledge basis to human perception in general. Thus, Konect is applicable to human operators in different domains regardless of their expert knowledge or expert skills. This was also shown by the experiments as they were situated in two different domains. By this, the requirement R5.1 is fully met.
With regard to R5.2, Konect generates the idea box as the solution document (see section 7.8 for details). Owing to the insights column, this artefact works on an abstract level. The name of the information connected to the insight and the resulting efficiency ranking is easily exchangeable (especially when working with the edit function of the Konect tool, as presented in Section 5.3). The efficiency rankings combined with the given insight is generally valid and can be used in different domains and for different tasks.
The fulfilment of both requirements (R5.1 [domain-independent theoretical framework as the scientific basis] and R5.2 [generally valid reusable solution documents on the partially abstract level]) leads to the aspect that Konect allows easy transferability of design solutions to all related tasks.

7.6 Teachable and Learnable Characteristic

R6 specified that *Konect should be teachable and learnable.* This aspect has been validated in various studies:

In the workshop conducted in the context of the truck platooning use case, no workshop participant had problems applying the method and all agreed that Konect was easy to apply (see Section 6.1.2). The same is valid for the workshop conducted for the vessel performance monitoring use case: All 12 workshop participants learned the method quickly via reading a textual manual about the method. The learning process took about half an hour to complete.
In addition to the workshops described previously, further empirical feasibility tests were conducted:

The Konect method was taught to master's students in computer science as part of the lecture „Inf374 – Einführung in das Cognitive Engineering". The lecture was followed by an accompanying tutorial. In this tutorial, the students had the exercise to create a design for a simplified air traffic control monitoring task by applying the Konect method to the Konect tool support. All the participants were able to easily install the tool and work with the method accordingly. No problems occurred.

Furthermore, the method was applied in the European project „MeBeSafe" in a workshop conducted in Oldenburg for an automotive HMI design that reveals danger (e.g. an approaching cyclist) at hazardous intersections so that the human driver can adapt his or her speed and react in time. In the workshop, research associates from Volvo Cars, FIAT, BMW, Cygnify, TNO (Organization for applied scientific research situated in the Netherlands), and Virtual Vehicle and ika (Institut für Kraftfahrzeuge, RWTH Aachen) participated. All the participants received an introduction to the method and afterwards split up in subgroups of three persons each. All participants gave positive feedback and had no problems in applying the Konect method.

Thus, all in all, the teachable and learnable characteristic of the Konect method was validated and tested in different domains (automotive, maritime, aeronautics) with people having different backgrounds (master's students, HMI design and HF experts, and experienced experts from the economics background (Volvo, FIAT, BMW)).

7.7 Numeric Indicator System

R7 stated that *Konect offers a numeric indicator system for roughly comparing alternative solutions* and that *Konects numeric indicator system should reveal deficiencies of a design solution* (**R7.1**).

The numeric indicator system of the Konect method (Konect Value K) was described in detail in Section 5.2.5 and validated in Section 6.3. The high correlation between the measured values and the calculated Konect Value validates the correctness of the calculation and the numeric indicator system. This indicator system also reveals the deficiencies of a design solution quite obviously in the form of the single values VE and the amount of different violations to the guidelines provided for synthesizing the HMI (inconsistencies, additional information, simplicity in color, and simplicity in shapes). So, it is directly revealed where the deficiencies of a design solutions lie. Furthermore, it is indicated how the design solution can be improved:
This aspect can be clarified by having a deeper look at the results achieved in the experiments conducted in the dissertation: In the vessel performance monitoring workshop, the results revealed that all designs remained the same or have been approved after Step 4 (see Figure 7.4). Only the design D2 received worse results regarding the measured time and correctness. When having a deeper look at the Konect idea boxes and the

numeric indicator system, the problem is directly revealed (see Figure 7.5): The idea boxes show that the amount of violations were reduced due to the application of guidelines. However, the designers totally removed the visual attribute for presenting the information that actual speed complies with just-in-time speed (with insight *perceive if value is ok (fast)*) and for presenting if actual speed complies with planned speed (with insight *perceive if value is ok (fast)*). This is indicated by the least efficient VE value of 1.0 for the values that are both marked as missing. This fact leads to a worse Konect Value of 0.236 for D2-G compared to 0.22 for D2. Thus, especially regarding the correct estimation of the actual speed information (compared to just in time speed and optimal speed), a deterioration has to be expected. This can be approved when having a deeper look at the detailed reaction time measured for the different critical situations for the designs (see Figure 7.6). The reaction time for assessing a critical ship's speed regarding the vessel performance decreased about 200ms for D2-G compared to the design D2.

Based on the results shown in Section 6.3 and the detailed examination of the Konect value indicates the reason as to why a certain HMI performs better or worse, **R7** and **R7.1** can be seen as validated.

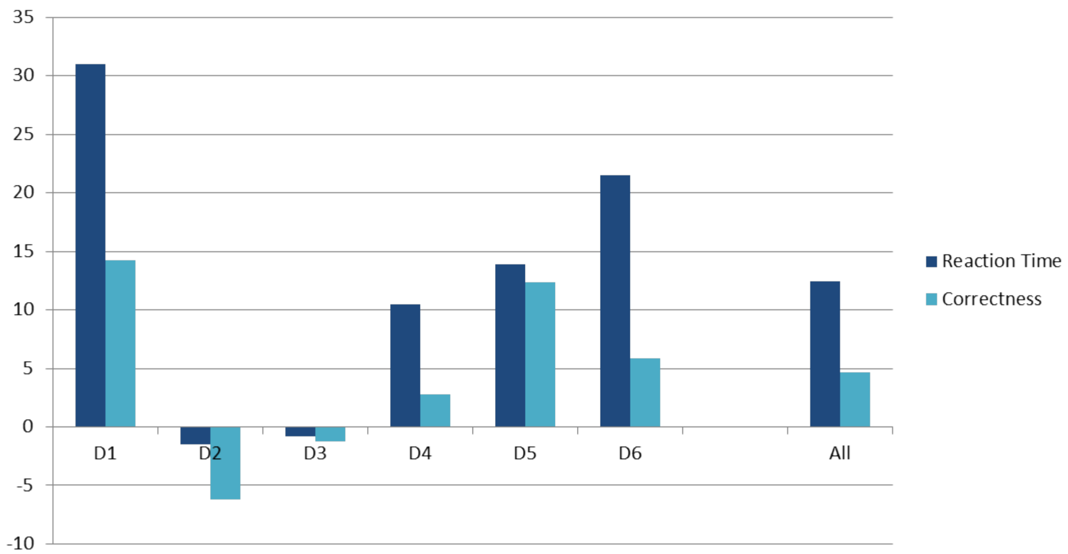

Figure 7.4: Percentual improvement or deterioration of designs before and after step 4 in the vessel performance monitoring experiment.

7.8 Solution Document

The last requirement **R8** defined that *Konect should lead to a solution document that is usable as input for a software engineering process.*

The Konect procedure, as described in the underlying dissertation, leads to two main

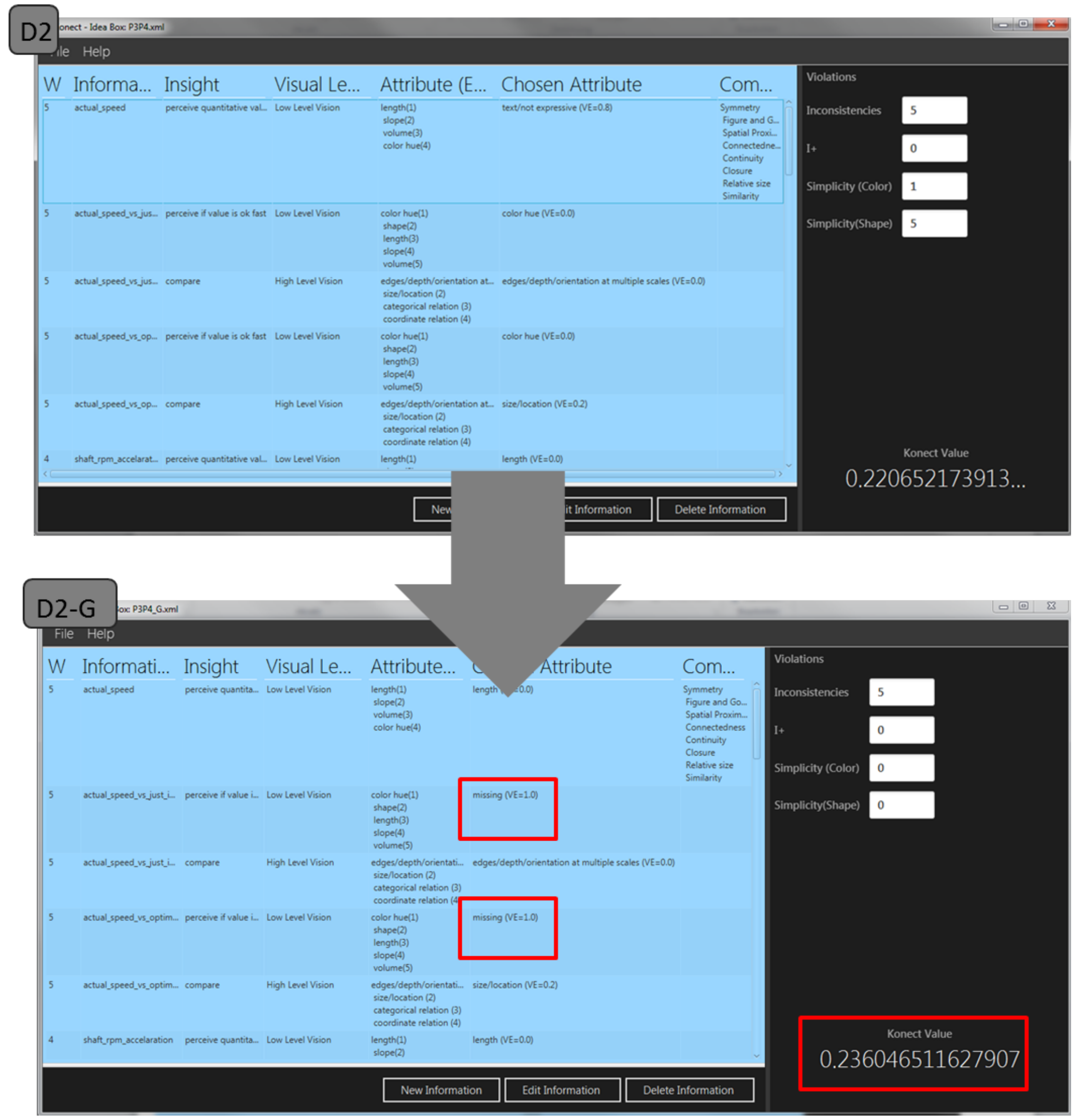

Figure 7.5: Reason for Deterioration of D2 indicated by Konects numeric indicator system.

outputs: The idea box, which reveals the rational justification for single information visualization, and the design mockup, which is the direct output from the visual attribute instantiation in Step 3 and the reworking in Step 4.

As previously mentioned, Konect leads to quite innovative and complex visualizations. In this context, visualizations cannot be specified as typical widgets available in common programming languages (e.g. labels, buttons, checkboxes, choiceboxes, textareas etc.) in most cases. The technology chosen to realize the visual interface might have certain limitations because not all offer possibilities for total innovative visual forms. Possible platforms that allow a high degree of freedom in realizing visual HMIs are, for instance, JavaFX, D3js (based on SVG, CSS and javascript) or qt.

Both outputs (mockup and idea box) allow the systematic implementation of the GUI:

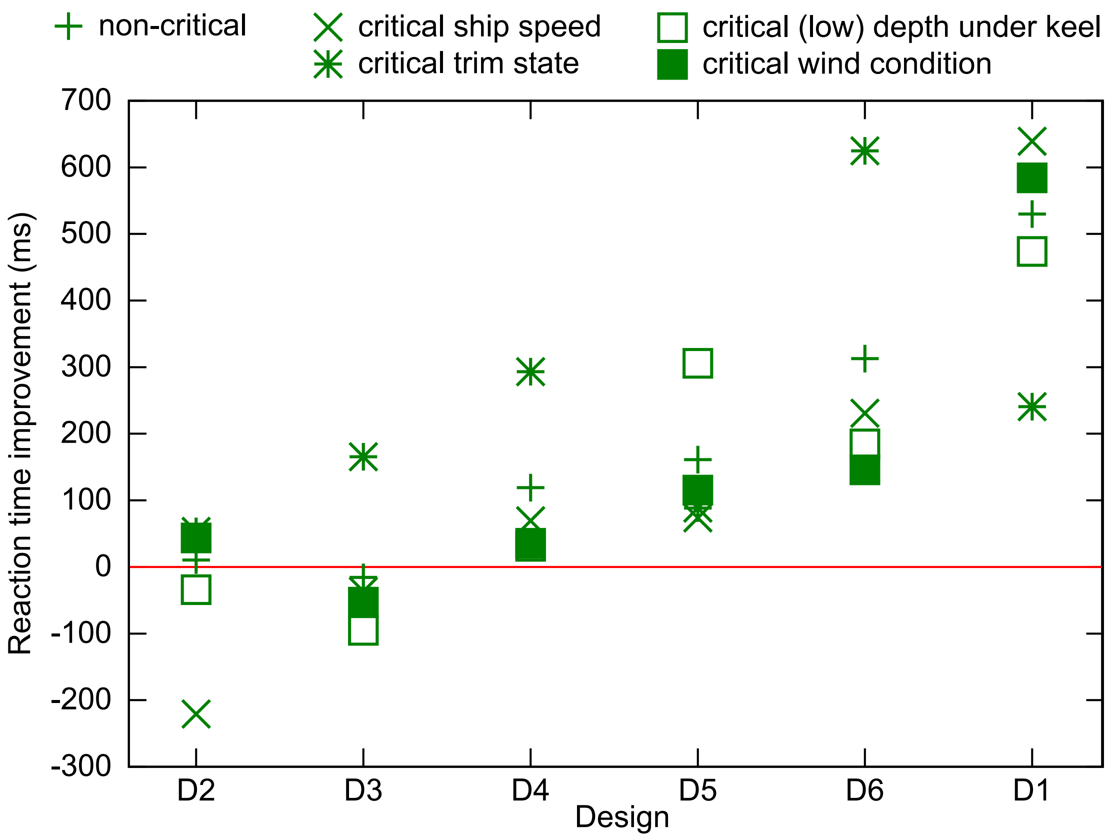

Figure 7.6: Improvement of detection of different situations.

The mockup provides an overview of how the HMI looks like. In case an adjustment has to be made due to the technology chosen for realizing the visual interface, the idea box offers help. In the idea box, it is stated which aspect has to be absolutely considered during implementation (e.g. the information should be visualized via *length* and the mockup shows a bar with rounded corners. In case the technology does not allow a bar with rounded corners, a bar with sharp corners can also be used as long as a length is applied to encode the information). With this aspect, the functional validation of the interface, aside from concrete graphical decisions in detail, is ensured. In addition to guaranteeing functional validation, the idea box also offers a systematic instrument for ensuring traceability in a V&V activity, as it reveals the reason why a certain visual attribute was chosen. In case problems occur (e.g. that some certain critical information is often overlooked), the idea box reveals alternative visual attributes and directly presents it in an efficiency ranking, which happens to be applicable for further reasoning of a choice for an alternative visual attribute. Therefore, it might be helpful to have a mapping document linking the visual elements in the mockup to the entries in the idea box.

In the experiments conducted, the mockups and idea boxes for the truck platooning use case were used as input for the implementation phase, as two different HMIs

were implemented in JavaFX for being used in the driving simulator study.
In future, derivative work might be of interest for integrating such solution documents in the state of the art of currently existing software engineering processes.

7.9 Summary

The overall goal of the dissertation that it **should provide a constructive method that allows a systematic derivation of information visualizations optimized for fast and accurate perception** was achieved. For this reason, several sub-requirements needed to be fulfilled. The fulfilment of each requirement and the internal and external validity of experiment results were discussed in detail in the underlying section. A summary is shown in Figure 7.7. So, the figure shows if the requirement was fulfilled and the validation level for this fulfilment (ranging from green = validated over yellow = partly validated to red = not validated). There was no requirement that had not been validated at all. Some requirements were marked as „partly validated":

1*) : The aspect was considered during the creation phase of the method. But as it was not in the focus of the dissertation, no further experiments were conducted for validation purposes.

2*) : The validation was fully done for the task that lies in the focus of dissertation; further experiments might be helpful for analysing totally different tasks (different tasks were out of scope of dissertation).

3*) : Validation not based on any experiment, but to the best of current knowledge (literature review).

4*) : Solution documents can be further tested and further integrated in a subsequent software development activity.

	Requirement	Fulfilled	Validation Level
R1	*Konect should work on a problem-oriented manner and thus be industry-independent for every design activity.*		
R2	*Konect should promote invention and knowledge and thus should facilitate the finding of optimal solutions.*		
R2.1	*Konect should allow creation of innovative new graphic forms.*		
R2.2	*Konect should foster creativity of the constructor/designer.*		1*)
R2.3	*Konect should optimize the time needed to perceive a critical system state.*		
R2.4	*Konect should optimize the accuracy of perceiving criticality of a system state in terms of reducing the amount of overlooked critical information relevant for estimating the systems criticality level.*		
R2.5	*Konect should tailor the HMI to the operators tasks.*		2*)
R3	*Konect should be compatible with terms, methods, findings of other disciplines.*		
R3.1	*Konect should represent an extension of existing HF methods or allow compatibility with them.*		
R3.2	*Konect should mind prior knowledge coming from the data visualization domain and the way of working in this domain (e.g. abstraction level).*		3*)
R3.3	*Konect should be compatible to guidelines and standards existent in the HMI design for safety-critical systems.*		3*)
R4	*Konect should not create solutions by chance.*		
R4.1	*Konect should work with rational constraints.*		
R4.2	*Konects rational constraints should offer compatibility with perceptual and cognitive skills.*		
R4.3	*Konect should provide a theoretical framework for rationally supporting decision making for visual forms during design phase.*		
R4.4	*Konects theoretical framework should offer help for synthesizing visual elements appropriately.*		
R5	*Konect should allow easy transferability of design solutions to related tasks.*		
R5.1	*Konects theoretical framework should be based on perceptual and cognitive skills of humans in general and thus be domain-independent.*		
R5.2	*Konects procedure should work on a partially abstract level that creates generally valid, reusable solution documents.*		4*)
R6	*Konect should be teachable and learnable.*		
R7	*Konect offers a numeric indicator for roughly comparing alternative solutions.*		
R7.1	*Konect should lead to a solution document that is usable as input for a software engineering process.*		
R8	*Konect should lead to a solution document that is usable as input for a software engineering process.*		4*)

Figure 7.7: Overview of requirements and fulfillment.

8 Conclusion and Future Work

This dissertation has contributed a constructive method that would allow a systematic derivation of information visualizations optimized for fast and accurate perception of critical system states. By this, an existing pain point in the state of the art of designing human machine interfaces, which serves the monitoring tasks in safety-critical systems, has been addressed.

The dissertation started by clarifying the motivation, challenges, and the broad objectives of the problem considered in the first chapter. After this first introductory part, the dissertation provided a deeper analysis of the current problem by presenting the state of the art and basic principles. Based on this deeper analysis, a concrete specification of requirements was created, thereby ensuring a systematic object-oriented way of working to methodically develop a problem solution. Chapter 4 differentiates the method from related works. Chapter 5 describes the problem solution—in form of the new Konect method— in detail. Konect provides two core elements to ensure the systematic derivation of rationally justified visualizations. These are the *Konect theoretical framework* (c.f. Chapter 5.1) and the *Konect Procedure* (c.f. Chapter 5.2). The Konect theoretical framework establishes the scientific basis for the whole method. This includes not only scientific knowledge of the procedures (e.g. the working principle for deriving HMI designs) and fostering of creativity (to design the procedure and its artefacts itself), but also knowledge of human perceptual skills (to enhance the Konect procedure with knowledge that steers the design in such a way that optimal design solutions can be found). The Konect procedure is based on this knowledge (as far as it concerns fostering creativity and procedures for designing HMIs in the safety-critical domain) or directly includes the knowledge in the design activity itself. This is, for instance, done by opening up the design space via efficiency rankings. The Konect procedure consists of four steps: *Information Determination*, *Idea Box Specification*, *Glyph Sketching*, and *Design Composition.* The two artefacts developed in the underlying dissertation handle the previously described challenges (*C1*: How does an appropriate search space for efficient visual forms look like corresponding to findings of prior scientific works? and *C2*: How does an engineering procedure for visual forms for monitoring HMIs in the safety-critical domain look like?). This was further evaluated in different experiments conducted as part of the dissertation. The empirical evaluation is described in detail in Chapter 6. In this regard, the Konect method

was applied to two different domains— the automotive domain (truck platooning use case) and the maritime domain (vessel performance monitoring use case). A total of 45 different persons applied and tested the Konect method in different circumstances (17 experts in HF and HMI designs under laboratory conditions, 18 master students in computer science in a lecture, and 10 professional industry partners in a workshop for the European project MeBeSafe). The upcoming designs were measured and empirically evaluated in different studies. So, a total of 74 different study participants tested the resulting designs (33 under laboratory conditions in the truck platooning use case, 23 in a more realistic set-up in the driving simulator, and 18 under laboratory conditions in the vessel performance monitoring study). The results revealed that the application of Konect leads to designs that were significantly faster and more correctly perceivable compared to conventional designs or designs that do not apply the whole range of Konect's guidance.
The study results as well as the fulfilment of previously stated requirements in Chapter 3 were discussed in detail in Chapter 7. This revealed that the Konect method meets all requirements demanded for a constructive engineering method (c.f. Section 3). Thus, it can be summarized that the Konect method developed in the underlying dissertation provides an engineering approach for systematically derived rationally justified information visualizations in any HMI design activity in the safety-critical domain (for optimizing fast and accurate perception of critical system states).

8.1 Future Work

In the dissertation, it was shown that the Konect method optimizes the reaction time and reduces assessment failures for assessing critical system states in monitoring tasks via efficient visualization. Further aspects might be interesting for future work:

- The optimization currently focuses on **fast** and **accurate** perception of critical system states to increase safety in monitoring tasks. But there exist also other optimization objectives that might be interesting—e.g. increasing the **intuitive understanding** of visual forms to diminish the learning curve or that the visualization is **graphically appealing**. For the latter, the gestalt laws already offer a basic direction in the current version of Konect. In future investigations more can be included in the instantiation of visual attributes in Step 3 (*Glyph Sketching*) of the Konect procedure.

- The Konect method focuses on visual displays involved in the monitoring task. In control rooms, it is often important to include more media (e.g. sound, haptics) for the overall design, especially to support better multi-tasking (c.f. [Wickens, 2002]). Furthermore, Konect focuses on monitoring and does not include interaction. To involve knowledge of interaction with the system—e.g. to take countermeasures in time—might also be interesting to further optimize systems.

- Regarding the overall design (structure) of the control room, the Konect method strongly builds on the current state of the art (EID, TA). In future research, it might also be interesting to investigate the distribution of information to different human operators monitoring the system concurrently.

Bibliography

[Abend, 2008] Abend, G. (2008). The meaning of 'theory'. *Sociological Theory*, 26(2), 173–199.

[Ando, 2011] Ando, H. (2011). Performance monitoring and analysis for operational improvements. International Conference on Ship Efficicency.

[Baas et al., 2015] Baas, M., De Dreu, C., & Nijstad, B. (2015). *The Cognitive, Emotional and Neural Correlates of Creativity:*. Frontiers Research Topics.

[Bainbridge, 1983] Bainbridge, L. (1983). Ironies of automation. In *Analysis, Design and Evaluation of Man–Machine Systems 1982* (pp. 129–135). Elsevier.

[Balzert & Balzert, 2004] Balzert, H. & Balzert, H. (2004). *Lehrbuch der Objektmodellierung: Analyse und Entwurf mit der UML 2*. Spektrum Akademischer Verlag.

[Beer, 2008] Beer, B. (2008). Methode, methodik und methodologie in der ethnologie. *Ethnoscripts*, 10(2), 8–23.

[Bell & Holroyd, 2009] Bell, J. & Holroyd, J. (2009). *RR679 – Review of human reliability assessment methods*. Technical report, Health and Safety Executive (HSE).

[Bennett & Flach, 2011] Bennett, K. & Flach, J. (2011). *Display and Interface Design: Subtle Science, Exact Art*. CRC Press.

[Bertin, 2011] Bertin, J. (2011). *Semiology of Graphics: Diagrams, Networks, Maps*. ESRI Press.

[Biederman, 1987] Biederman, I. (1987). Recognition-by-components: a theory of human image understanding. *Psychological review*, 94(2), 115.

[Boff et al., 1986] Boff, K., Kaufman, L., & Thomas, J. (1986). *Handbook of Perception and Human Performance, Volumes 1 & 2*. Handbook of Perception and Human Performance. Wiley.

[Borojeni et al., 2016] Borojeni, S. S., Friedrichs, T., Heuten, W., Lüdtke, A., & Boll-Westermann, S. (2016). Design of a human-machine interface for truck platooning. In *CHI 2016: Proceedings of the 34th Annual ACM Conference on Human Factors in Computing Systems*.

[Bortz, 1999] Bortz, J. (1999). *Statistik für Sozialwissenschaftler: mit 247 Tabellen.* Springer-Lehrbuch. Springer.

[Brazier, 2010] Brazier, A. (2010). Managing the risks of control room operations. url: http://www.methodenberatung.uzh.ch (24-07-2018).

[Breslow et al., 2009] Breslow, L., Trafton, J. G., & Ratwani, R. M. (2009). A color perceptual-process approach to selecting color scales for complex visualizations. *Journal of Experimental Psychology: Applied*, 15(1), 25–34.

[Broadbent, 1958] Broadbent, D. (1958). *Perception and Communication.* London: Pergamon Press.

[Bruce et al., 2003] Bruce, V., Green, P., & Georgeson, M. (2003). *Visual Perception: Physiology, Psychology, & Ecology.* Psychology Press.

[Burns & Hajdukiewicz, 2013] Burns, C. & Hajdukiewicz, J. (2013). *Ecological Interface Design.* CRC Press.

[Campbell & Stanley, 1963] Campbell, D. T. & Stanley, J. C. (1963). Experimental and quasi-experimental designs for research. *Handbook of research on teaching. Chicago, IL: Rand McNally.*

[Card et al., 1999] Card, S., Mackinlay, J., & Shneiderman, B. (1999). *Readings in Information Visualization: Using Vision to Think.* Interactive Technologies Series. Morgan Kaufmann Publishers.

[Carpendale, 2003] Carpendale, M. S. T. (2003). *Considering Visual Variables as a Basis for Information Visualisation.* Technical report, University of Calgary, Calgary, AB.

[Casner, 1991] Casner, S. M. (1991). Task-analytic approach to the automated design of graphic presentations. *ACM Trans. Graph.*, 10(2), 111–151.

[Cavanagh, 2011] Cavanagh, P. (2011). Visual cognition. *Vision research*, 51(13), 1538–1551.

[Cherry, 2018] Cherry, K. (2018). Introduction to psychology research methods. url: https://www.verywellmind.com/ (1-08-2018).

[Cleveland & McGill, 1984] Cleveland, W. S. & McGill, R. (1984). Graphical perception: Theory, experimentation, and application to the development of graphical methods. *Journal of the American Statistical Association*, 79(387), pp. 531–554.

[Commission, 2002] Commission, U. N. R. (2002). Nureg-0700 human-system interface design review guidelines.

[Commission, 2013] Commission, U. S. N. R. (February 2013). Backgrounder on the three mile island accident. url: https://www.nrc.gov/reading-rm/doc-collections/fact-sheets/3mile-isle.html (14-07-2017).

[Cottam et al., 2012] Cottam, J. A., Lumsdaine, A., & Weaver, C. (2012). Watch this: A taxonomy for dynamic data visualization. In *IEEE VAST* (pp. 193–202).: IEEE Computer Society.

[Darrigol, 2012] Darrigol, O. (2012). *A History of Optics from Greek Antiquity to the Nineteenth Century*. OUP Oxford.

[Day, 2016] Day, A. (2016). Gnome human interface guidelines. url: https://people.gnome.org/ fpeters/hig3.pdf (15-07-2016).

[Denhardt et al., 2015] Denhardt, R., Denhardt, J., & Aristigueta, M. (2015). *Managing Human Behavior in Public and Nonprofit Organizations*. SAGE Publications.

[Denker et al., 2014] Denker, C., Fortmann, F., Ostendorp, M.-C., & Hahn, A. (2014). Assessing the fitness of information supply and demand during user interface design. In G. Salvendy (Ed.), *Proc.of AHFE'14*, Advances in Human Factors and Ergonomics: CRC Press.

[Diaper & Stanton, 2003] Diaper, D. & Stanton, N. (2003). *The Handbook of Task Analysis for Human-Computer Interaction*. CRC Press.

[Dickinson & Pizlo, 2013] Dickinson, S. & Pizlo, Z. (2013). *Shape Perception in Human and Computer Vision: An Interdisciplinary Perspective*. Advances in Computer Vision and Pattern Recognition. Springer London.

[Dutch & the Environment, 2016] Dutch, M. o. I. & the Environment (2016). European truck platooning challenge website.

[Eder & Hosnedl, 2007] Eder, W. & Hosnedl, S. (2007). *Design Engineering: A Manual for Enhanced Creativity*. CRC Press.

[Ehrlenspiel & Meerkamm, 2013] Ehrlenspiel, K. & Meerkamm, H. (2013). *Integrierte Produktentwicklung: Denkabläufe, Methodeneinsatz, Zusammenarbeit*. Hanser Fachbuchverlag.

[Eilers et al., 2015] Eilers, S., Martensson, J., Pettersson, H., Pillado, M., Gallegos, D., Tobar, M., Johansson, K., Ma, X., Friedrichs, T., Sadeghian Borojeni, S., & Adolfson, M. (2015). Companion - towards co-operative platoon management of heavy-duty vehicles. In *18th International Conference on Intelligent Transportation Systems, 2015 IEEE*.

[Elektronik, 2015] Elektronik, A. (2015). Seacat – hybrid autonomous underwater vehicle system. url: http://www.seacat-auv.com (24-07-2018).

[Endresen et al., 2003] Endresen, ., Sørgård, E., Sundet, J., Dalsøren, S., Isaksen, I., Berglen, T., & Gravir, G. (2003). Emission from international sea transportation and environmental impact. *Journal of Geophysical Research: Atmospheres (1984–2012)*, 108.

[Engineering, 2015] Engineering, B. H. (2015). What is ship collision? url: http://www.brighthubengineering.com/seafaring/36193-what-is-ship-collision/ (1-09-2015).

[Equipment & Association, 2007] Equipment, E. & Association, M. U. (2007). *Alarm Systems: A Guide to Design, Management and Procurement*. EEMUA publication. E E M U A (Engineering Equipment & Materials Users Association).

[Feldhusen & Grote, 2013] Feldhusen, J. & Grote, K. (2013). *Pahl/Beitz Konstruktionslehre: Methoden und Anwendung erfolgreicher Produktentwicklung*. Springer Berlin Heidelberg.

[Feuerstack & Wortelen, 2017] Feuerstack, S. & Wortelen, B. (2017). The human efficiency evaluator - a tool to predict and analyse monitoring behaviour; kognitive systeme. *Kognitive Systeme*, ISSN 2197-0343(1-2017).

[Few, 2009] Few, S. (2009). *Now You See it: Simple Visualization Techniques for Quantitative Analysis*. Analytics Press.

[Fiset, 2009] Fiset, J. (2009). *Human-machine Interface Design for Process Control Applications*. Instrumentation, Systems, and Automation Society.

[Gillan & Callahan, 2000] Gillan, D. J. & Callahan, A. B. (2000). A componential model of human interaction with graphs: Vi. cognitive engineering of pie graphs. *Human factors*, 42(4), 566–591.

[Grandjean, 1980] Grandjean, É. (1980). *Fitting the task to the man: an ergonomic approach*. Taylor & Francis.

[Griffin & Morrison, 2010] Griffin, W. & Morrison, D. (2010). *The Creative Process Illustrated: How Advertising's Big Ideas Are Born*. F+W Media.

[Grots & Pratschke, 2009] Grots, A. & Pratschke, M. (2009). Design thinking—kreativität als methode. *Marketing Review St. Gallen*, 26(2), 18–23.

[Gruhn, 2011] Gruhn, P. (2011). Human machine interface (hmi) design: The good, the bad, and the ugly (and what makes them so).

[Gutierrez et al., 2008] Gutierrez, M., Vexo, F., & Thalmann, D. (2008). *Stepping into Virtual Reality*. Springer London.

[Halik, 2012] Halik, Ł. (2012). The analysis of visual variables for use in the cartographic design of point symbols for mobile augmented reality applications. *Geodesy and Cartography*, 61.

[Hallinan, 2010a] Hallinan, J. (2010a). *Errornomics: Why We Make Mistakes and What We Can Do To Avoid Them*. Ebury Publishing.

[Hallinan, 2010b] Hallinan, J. (2010b). *Why We Make Mistakes: How We Look Without Seeing, Forget Things in Seconds, and are All Pretty Sure We are Way Above Average*. Broadway Books.

[Haught-Tromp, 2017] Haught-Tromp, C. (2017). The green eggs and ham hypothesis: How constraints facilitate creativity. *Psychology of Aesthetics, Creativity, and the Arts*, 11(1), 10.

[Healey, 2015] Healey, C. (2015). Perception in visualization. url: http://www.csc.ncsu.edu/faculty/healey/PP/ (2015-12-9).

[Healey et al., 1996] Healey, C. G., Booth, K. S., & Enns, J. T. (1996). High-speed visual estimation using preattentive processing. *ACM Trans. Comput.-Hum. Interact.*, 3(2), 107–135.

[Hegarty, 2011] Hegarty, M. (2011). The cognitive science of visual-spatial displays: Implications for design. *topiCS*, 3(3), 446–474.

[Hegarty et al., 2010] Hegarty, M., Canham, M. S., & Fabrikant, S. I. (2010). Thinking about the weather: How display salience and knowledge affect performance in a graphic inference task. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 36(1), 37.

[Hennessey & Amabile, 2010] Hennessey, B. A. & Amabile, T. M. (2010). Creativity. *Annual Review of Psychology 61*, (pp. 569–598).

[Hinkelmann, 2015] Hinkelmann, K. (2015). How to choose a research methodology. url: http://knut.hinkelmann.ch/lectures/project2013/p1_5_how-to-choose-a-research-methodology.pdf (16-03-2015).

[Hoffman, 2000] Hoffman, D. (2000). *Visuelle Intelligenz: wie die Welt im Kopf entsteht*. Klett-Cotta.

[Hollifield et al., 2008] Hollifield, B., Dana, O., Nimmo, I., & Habibi, E. (2008). *The High Performance HMI Handbook: A Comprehensive Guide to Designing, Implementing and Maintaining Effective HMIs for Industrial Plant Operations*. PAS.

[Hussey, 1999] Hussey, A. (1999). Patterns for safer human-computer interfaces. In *International Conference on Computer Safety, Reliability, and Security* (pp. 103–112).: Springer.

[ISA, 1985] ISA (1985). Isa-5.5-1985, graphic symbols for process display.

[ISO, 1999] ISO, I. O. f. S. (1999). Iso 13407 human-centred design processes for interactive systems.

[ISO, 2006] ISO, I. O. f. S. (2006). Iso 9241 ergonomics of human system interaction.

[Jamieson et al., 2007] Jamieson, G. A., Miller, C. A., Ho, W. H., & Vicente, K. J. (2007). Integrating task-and work domain-based work analyses in ecological interface design: A process control case study. *IEEE Transactions on Systems, Man, and Cybernetics-Part A: Systems and Humans*, 37(6), 887–905.

[Kasparov & Greengard, 2017] Kasparov, G. & Greengard, M. (2017). *Deep Thinking: Where Machine Intelligence Ends and Human Creativity Begins*. PublicAffairs.

[Kennedy, 1971] Kennedy, R. S. (1971). A comparison of performance on visual and auditory monitoring tasks. *Human Factors*, 13(2), 93–97.

[Kerren et al., 2008] Kerren, A., Stasko, J., Fekete, J., & North, C. (2008). *Information Visualization: Human-Centered Issues and Perspectives*. Lecture Notes in Computer Science. Springer Berlin Heidelberg.

[Kirwan, 1994a] Kirwan, B. (1994a). *A Guide To Practical Human Reliability Assessment*. Taylor & Francis.

[Kirwan, 1994b] Kirwan, B. (1994b). *A guide to practical human reliability assessment*. CRC press.

[Kirwan, 1996a] Kirwan, B. (1996a). The validation of three human reliability quantification techniques—therp, heart and jhedi: Part 1—technique descriptions and validation issues. *Applied ergonomics*, 27(6), 359–373.

[Kirwan, 1996b] Kirwan, B. (1996b). The validation of three human reliability quantification techniques—therp, heart and jhedi: Part 1—technique descriptions and validation issues. *Applied ergonomics*, 27(6), 359–373.

[Knight, 2002] Knight, J. C. (2002). Safety critical systems: Challenges and directions. In *Proceedings of the 24th International Conference on Software Engineering*, ICSE '02 (pp. 547–550). New York, NY, USA: ACM.

[Kockrow & Hoppe, 2014] Kockrow, R. & Hoppe, A. (2014). Gestaltungsempfehlungen für Operatorarbeitsplätze – Ableitung aus einer Eye-Tracking Studie. *13. Symposium Energieinnovation*.

[Kopp, 2017] Kopp, M. (2017). Dicke Luft im Hafen. *Hamburger Abendblatt*.

[Kornhauser et al., 2009] Kornhauser, D., Wilensky, U., & Rand, W. (2009). Design guidelines for agent based model visualization. *Journal of Artificial Societies and Social Simulation*, 12(2), 1.

[Kosslyn, 2006] Kosslyn, S. (2006). *Graph Design for the Eye and Mind*. Oxford University Press.

[Kosslyn et al., 1990] Kosslyn, S. M., Flynn, R. A., Amsterdam, J. B., & Wang, G. (1990). Components of high-level vision: A cognitive neuroscience analysis and accounts of neurological syndromes. *Cognition*, 34(3), 203–277.

[Krauth, 2000] Krauth, J. (2000). *Experimental Design: A Handbook and Dictionary for Medical and Behavioral Research*. Techniques in the Behavioral and Neural Sciences. Elsevier Science.

[Leeuwenberg & Van der Helm, 2012] Leeuwenberg, E. & Van der Helm, P. (2012). *Structural Information Theory: The Simplicity of Visual Form*. Cambridge University Press.

[MacEachren et al., 2012] MacEachren, A. M., Roth, R. E., O'Brien, J., Li, B., Swingley, D., & Gahegan, M. (2012). Visual semiotics & uncertainty visualization: An empirical study. *IEEE Transactions on Visualization and Computer Graphics*, 18(12), 2496–2505.

[Mackinlay, 1986] Mackinlay, J. (1986). Automating the design of graphical presentations of relational information. *ACM Transactions on Graphics TOG*, 5(2), 110–141.

[Marr, 2015] Marr, B. (2015). *Big Data: Using SMART Big Data, Analytics and Metrics To Make Better Decisions and Improve Performance*, volume 1. John Wiley & Sons.

[Marr, 1982] Marr, D. (1982). *Vision. A Computational Investigation into the Human Representation and Processing of Visual Information*. W.H. Freeman, New York.

[Mazza, 2009] Mazza, R. (2009). *Introduction to Information Visualization*. Computer science. Springer London.

[Meirelles, 2013] Meirelles, I. (2013). *Design for Information: An Introduction to the Histories, Theories, and Best Practices Behind Effective Information Visualizations*. EBSCO ebook academic collection. Rockport Publishers.

[Meixner et al., 2011] Meixner, G., Paternò, F., & Vanderdonckt, J. (2011). Past, present, and future of model-based user interface development. *i-com*, 10(3), 2–11.

[Meskens et al., 2008] Meskens, J., Vermeulen, J., Luyten, K., & Coninx, K. (2008). Gummy for multi-platform user interface designs: Shape me, multiply me, fix me, use me. In *Proceedings of the Working Conference on Advanced Visual Interfaces*, AVI '08 (pp. 233–240). New York, NY, USA: ACM.

[Messerschmid et al., 2013] Messerschmid, E., Freyer, T., & Bertrand, R. (2013). *Space Stations: Systems and Utilization*. Springer Berlin Heidelberg.

[Meyer et al., 2008] Meyer, P. D., Maes, F., & Volckaert, A. (2008). Emissions from international shipping in the belgian part of the north sea and the belgian seaports. *Atmospheric Environment*, 42(1), 196 – 206.

[Micallef et al., 2017] Micallef, L., Palmas, G., Oulasvirta, A., & Weinkauf, T. (2017). Towards perceptual optimization of the visual design of scatterplots. *IEEE transactions on visualization and computer graphics*, 23(6), 1588–1599.

[Nemeth, 2004] Nemeth, C. (2004). *Human Factors Methods for Design: Making Systems Human-Centered*. CRC Press.

[Nielsen, 1994] Nielsen, J. (1994). *Usability Engineering*. Interactive technologies. Morgan Kaufmann.

[Nielsen & Molich, 1990] Nielsen, J. & Molich, R. (1990). Heuristic evaluation of user interfaces. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, CHI '90 (pp. 249–256). New York, NY, USA: ACM.

[Nimmo, 2012] Nimmo, I. (October 2012). Best practices in high-performance hmi design. url: http://www.controlglobal.com/articles/2012/nimmo-best-practices-high-performance-hmi-design/ (11-05-2017).

[Norman, 2002] Norman, D. A. (2002). *The Design of Everyday Things*. New York, NY, USA: Basic Books, Inc.

[North, 2006] North, C. (2006). *Information Visualization*, (pp. 1222–1245). John Wiley & Sons, Inc.

[Novick & Catley, 2007] Novick, L. R. & Catley, K. M. (2007). Understanding phylogenies in biology: the influence of a gestalt perceptual principle. *Journal of Experimental Psychology: Applied*, 13(4), 197.

[Olshannikova et al., 2015] Olshannikova, E., Ometov, A., Koucheryavy, Y., & Olsson, T. (2015). Visualizing big data with augmented and virtual reality: challenges and research agenda. *Journal of Big Data*, 2(1), 22.

[Opto22, 2014] Opto22 (2014). Building an hmi that works: New best practices for operator interface design.

[Ostendorp, 2014] Ostendorp, M.-C. (2014). Entwicklung eines Interfaces zur Unterstützung von Hafenmanövern nach dem Ecological Interface Design Ansatz. Master's thesis, University of Oldenburg.

[Ostendorp et al., 2016a] Ostendorp, M.-C., Feuerstack, S., Friedrichs, T., & Lüdtke, A. (2016a). Engineering automotive hmis that are optimized for correct and fast perception. In *Proceedings of the 8th ACM SIGCHI Symposium on Engineering Interactive Computing Systems*, EICS '16 (pp. 293–298). New York, NY, USA: ACM.

[Ostendorp et al., 2016b] Ostendorp, M.-C., Friedrichs, T., & Lüdtke, A. (2016b). Supporting supervisory control of safety-critical systems with psychologically well-founded information visualizations. In *Proceedings of the 9th Nordic Conference on Human-Computer Interaction*, NordiCHI '16 (pp. 11:1–11:10). New York, NY, USA: ACM.

[Oswald, 2006] Oswald, D. (2006). Design methods. Master's thesis, University of Applied Science Constance.

[Oulasvirta, 2017] Oulasvirta, A. (2017). User interface design with combinatorial optimization. *IEEE Computer*, 50(1), 40–47.

[Pashler & Yantis, 2004] Pashler, H. & Yantis, S. (2004). *Stevens' Handbook of Experimental Psychology, Sensation and Perception*. Stevens' Handbook of Experimental Psychology. John Wiley & Sons.

[Peebles & Cheng, 2003] Peebles, D. & Cheng, P. C.-H. (2003). Modeling the effect of task and graphical representation on response latency in a graph reading task. *Human Factors*, 45(1), 28–46.

[Petersen & May, 2006] Petersen, J. & May, M. (2006). Scale transformations and information presentation in supervisory control. *International journal of human-computer studies*, 64(5), 405–419.

[Pfeffers et al., 2007] Pfeffers, K., Tuunanen, T., Rothenberger, M., & Chatterjee, S. (2007). A design science research methodology for information systems research. *J. Manage. Inf. Syst.*, 24(3), 45–77.

[Popova, 2015a] Popova, M. (2015a). A 5-step technique for producing ideas crica 1939. url: http://www.brainpickings.org/2012/05/04/a-technique-for-producing-ideas-young/ (2-09-2015).

[Popova, 2015b] Popova, M. (2015b). The art of thought: Graham wallas on the four stages of creativity, 1926. url: http://www.brainpickings.org/2013/08/28/the-art-of-thought-graham-wallas-stages/ (2-09-2015).

[Questions & Answers, 2016] Questions, B. & Answers (2016). The parts and function of the human eyes.

[Rae, 2007] Rae, A. (2007). Helping the operator in the loop: Practical human machine interface principles for safe computer controlled systems. In *Proceedings of the*

Twelfth Australian Workshop on Safety Critical Systems and Software and Safety-related Programmable Systems - Volume 86, SCS '07 (pp. 61–70). Darlinghurst, Australia, Australia: Australian Computer Society, Inc.

[Rautenbach et al., 2015] Rautenbach, V., Coetzee, S., & Schiewe, S. andColtekien, A. (2015). An assessment of visual variables for the cartographic design of 3d informal settlement models. In *Proceedings of the ICC 2015*.

[Rensink, 2000] Rensink, R. A. (2000). The dynamic representation of scenes. *Visual cognition*, 7(1-3), 17–42.

[Rensink, 2002] Rensink, R. A. (2002). Change detection. *Annual review of psychology*, 53(1), 245–277.

[Riepl, 2018] Riepl, W. (2018). T-test oder u-test? url: http://statistik-dresden.de/archives/232 (16-05-2018).

[Ritchey, 1998] Ritchey, T. (1998). Problem structuring using computer-aided morphological analysis. *Journal of the Operational Research Society*.

[Rogers, 2010] Rogers, K. (2010). *The Eye: The Physiology of Human Perception*. The human body. Britannica Educational Pub.

[Rose, 2012] Rose, G. (2012). *Visual Methodologies: An Introduction to Researching with Visual Materials*. SAGE Publications.

[Rosenholtz et al., 2007] Rosenholtz, R., Li, Y., & Nakano, L. (2007). Measuring visual clutter. *Journal of vision*, 7(2), 17–17.

[Sadeghian Borojeni et al., 2016] Sadeghian Borojeni, S., Friedrichs, T., Boll, S., Heuten, W., & Lüdtke, A. (2016). Design of a human-machine interface for truck platooning. In *CHI 2016: Proceedings of the 34th Annual ACM Conference*.

[Sahu & Subudhi, 2014] Sahu, B. K. & Subudhi, B. (2014). Adaptive tracking control of an autonomous underwater vehicle. *International Journal of Automation and Computing*, 11(3), 299–307.

[Series, 2018] Series, B. R. S. (2018). Non-parametric tests. url: http://biostat.mc.vanderbilt.edu/wiki/pub/Main/AnesShortCourse (16-05-2018).

[Sherman & Craig, 2003] Sherman, W. R. & Craig, A. B. (2003). *Understanding Virtual Reality: Interface, Application, and Design*. San Francisco, CA, USA: Morgan Kaufmann Publishers Inc.

[Shneiderman et al., 2016] Shneiderman, B., Plaisant, C., Cohen, M., Elmqvist, N., Jacobs, S., & Diakopoulos, N. (2016). *Designing the User Interface: Strategies for Effective Human-Computer Interaction*. Pearson Education, Limited.

[Spence, 2001] Spence, R. (2001). *Information Visualization*. ACM Press Books. Addison-Wesley.

[Stanciulescu et al., 2005] Stanciulescu, A., Limbourg, Q., Vanderdonckt, J., Michotte, B., & Montero, F. (2005). A transformational approach for multimodal web user interfaces based on usixml. In *Proceedings of the 7th international conference on Multimodal interfaces* (pp. 259–266).: ACM.

[Stanton et al., 2004] Stanton, N., Hedge, A., Brookhuis, K., Salas, E., & Hendrick, H. (2004). *Handbook of Human Factors and Ergonomics Methods*. CRC Press.

[Stanton et al., 2006] Stanton, N. A., Salmon, P. M., Walker, G. H., Baber, C., & Jenkins, D. P. (2006). *Human Factors Methods: A Practical Guide for Engineering And Design*. Brookfield, VT, USA: Ashgate Publishing Company.

[Stevens et al., 1946] Stevens, S. S. et al. (1946). *On the theory of scales of measurement*. Bobbs-Merrill, College Division.

[Stone et al., 2017] Stone, N., Chaparro, A., Keebler, J., Chaparro, B., & McConnell, D. (2017). *Introduction to Human Factors: Applying Psychology to Design*. CRC Press.

[Thompson et al., 2011] Thompson, W., Fleming, R., Creem-Regehr, S., & Stefanucci, J. K. (2011). *Visual perception from a computer graphics perspective*. CRC Press.

[Tidwell, 2010] Tidwell, J. (2010). *Designing Interfaces: Patterns for Effective Interaction Design*. O'Reilly Media.

[Tognazzini, 2016] Tognazzini, B. (2016). First principles of interaction design. url: http://asktog.com/basics/firstPrinciplesOldEdition.html (15-07-2016).

[Tory & Moller, 2004] Tory, M. & Moller, T. (2004). Human factors in visualization research. *IEEE transactions on visualization and computer graphics*, 10(1), 72–84.

[Transport & Environment, 2017a] Transport, E. F. & Environment (2017a). The efficiency of new ships is falling, study finds. url: https://www.transportenvironment.org/ (17-07-2017).

[Transport & Environment, 2017b] Transport, E. F. & Environment (2017b). Fuel consumption changes 1990-2013. url: https://www.transportenvironment.org/ (17-07-2017).

[Transportation & A/S, 2007] Transportation, A. S. & A/S, R. (2007). Uss user manual. url: https://www.eso-io.com (24-07-2018).

[Treisman, 1985] Treisman, A. (1985). Preattentive processing in vision. *Computer Vision, Graphics and Image Processing*, 31(2), 156–177.

[Tufte, 1997] Tufte, E. (1997). *Visual Explanations: Images and Quantities, Evidence and Narrative.* Graphics Press.

[Tufte, 1990] Tufte, E. R. (1990). *Envisioning Information.* Cheshire, Connecticut: Graphics Press.

[Ullman et al., 1996] Ullman, S. et al. (1996). *High-level vision: Object recognition and visual cognition*, volume 2. MIT press Cambridge, MA.

[USC, 2018] USC, U. o. S. C. (2018). Organizing your social sciences research paper: Theoretical framework. url: http://libguides.usc.edu/writingguide/theoreticalframework(1-08-2018).

[Viana et al., 2014] Viana, M., Hammingh, P., Colette, A., Querol, X., Degraeuwe, B., de Vlieger, I., & van Aardenne, J. (2014). Impact of maritime transport emissions on coastal air quality in europe. *Atmospheric Environment*, 90, 96 – 105.

[Vicente, 2006] Vicente, K. (2006). *The Human Factor: Revolutionizing the Way People Live with Technology.* Taylor & Francis.

[Vicente & Rasmussen, 1992] Vicente, K. & Rasmussen, J. (1992). Ecological interface design: theoretical foundations. *Systems, Man and Cybernetics, IEEE Transactions on*, 22(4), 589–606.

[von Helmholtz, 1866] von Helmholtz, H. (1866). *Handbuch der physiologischen Optik.* Allgemeine Encyklopädie der Physik. Voss.

[Wallas, 1926] Wallas, G. (1926). *The art of the thought.* New York, Harcourt, Brace and Company.

[Ware, 2004] Ware, C. (2004). *Information Visualization: Perception for Design.* Interactive Technologies. Elsevier Science.

[Ware, 2010] Ware, C. (2010). *Visual Thinking: for Design.* Morgan Kaufmann series in interactive technologies. Elsevier Science.

[Weber, 2017] Weber, W. (2017). Show. Don't tell. Vom Zeigen und Sichtbarmachen. *Doing Applied Linguistics: Enabling Transdisciplinary Communication*, (pp. 145).

[Wertheimer, 1923] Wertheimer, M. (1923). Untersuchungen zur Lehre von der Gestalt. II. *Psychologische forschung*, 4(1), 301–350.

[Wickens et al., 2015] Wickens, C., Hollands, J., Banbury, S., & Parasuraman, R. (2015). *Engineering Psychology & Human Performance.* Taylor & Francis.

[Wickens, 2002] Wickens, C. D. (2002). Multiple resources and performance prediction. *Theoretical issues in ergonomics science*, 3(2), 159–177.

[Wolfe, 1994] Wolfe, J. M. (1994). Guided search 2.0 a revised model of visual search. *Psychonomic Bulletin & Review*, 1(2), 202–238.

[Woods, 1984] Woods, D. D. (1984). Visual momentum: a concept to improve the cognitive coupling of person and computer. *International Journal of Man-Machine Studies*, 21(3), 229–244.

[Wördenweber et al., 2007] Wördenweber, B., Wallaschek, J., Boyce, P., & Hoffman, D. (2007). *Automotive Lighting and Human Vision*. Springer Berlin Heidelberg.

[W.R. & Clement, 1963] W.R., G. & Clement, D. E. (1963). Goodness of pattern and pattern uncertainty. *Journal of verbal learning and verbal behaviour*.

[Young, 2003] Young, J. (2003). *A Technique for Producing Ideas*. A McGraw-Hill advertising classic. Mcgraw-hill.

[Zhang, 1996] Zhang, J. (1996). A representational analysis of relational information displays. *International Journal of Human-Computer Studies*, 45(1), 59–74.

[Zürich, 2018] Zürich, U. (2018). Methodenberatung. url: http://www.methodenberatung.uzh.ch (16-05-2018).

[Zwicky & Wilson, 1967] Zwicky, F. & Wilson, A. (1967). *New Methods of Thought and Procedure: Contributions to the Symposium on Methodologies*. Springer Berlin Heidelberg.

Glossary

control room a room from which a system (often containing a high amount of physical equipment) can be monitored and controlled.

design describes the activity of creating an HMI (including HMI conceptualisation as well as graphical appearance).

development the activity of creating the HMI including the design, but also the technical implementation.

ecological interface design (EID) a framework developed by Kim Vicente and Jens Rasmussen to design an HMI from a work-domain oriented perspective. HMIs are optimized for detection of problems and support problem-solving capabilities of the operator.

global design the overall HMI design consisting of overall structure (e.g. position of graphical forms), display hierarchy.

glyph several visual attributes integrated into one graphical form.

HMI Human Machine Interface; in the dissertation the term HMI only refers to the visual display. Further components as physical interaction elements (e.g. buttons, switches) are not included.

information data that contains valuable meaning for the task at hand (e.g. speed, temperature of a certain equipment).

insight is „an instance of apprehending the true nature of a thing, especially through intuitive understanding"[1]. In connection with the Konect method, insight defines what the human operator should intuitively apprehend when looking at the visual form e.g. *quantitative value* of an information, *certainty* of an information or to which *category or mode* the information belongs.

method allows a systematic procedure enhanced with knowledge for achieving several objectives; in the underlying dissertation the Konect method consists of the Konect procedure (defining steps and order of this steps) and the Konect theoretical framework (that establishes the knowledge base).

[1]https://www.dictionary.com/

operator the personnel sitting in front of the display and that is responsible for the monitoring task; user of the HMI.

procedure specifies several steps or actions performed in a particular order.

phase „any distinct or characteristic period or stage in a sequence of events or chain of development"'[2].

task an identifiable and essential action of the whole work of the human operator .

task analysis (TA) the task analysis is used to analyse the whole work the human operator conducts and break this work into smaller pieces of actions (tasks).

theoretical framework consists of concepts and offers a structure to show key concepts minded and the connections established between different well-accepted theories. The theoretical framework is strongly based on current literature and provides the scientific basis for the method presented in the dissertation. This theoretical framework ensures that chosen visualizations are rationally justified and the designer works towards an optimal design solution with regard to time needed to perceive the criticality level of a system and concerning reduction of assessment failures for such states.

visual attribute in literature sometimes called *visual variable*; describing entities of visualizations e.g. *color*, *shape*, *length*.

visual or graphical forms instance of one or more visual attributes e.g. a red dot, a bar or filled square.

visual efficiency means a graphical form can be perceived better or worse with regard to certain performance indicators (e.g. in the underlying dissertation the performance indicators are time and correctness): „Unlike expressiveness, which only depends on the syntax and semantics of the graphical language, effectiveness also depends on the capabilities of the perceiver" [Mackinlay, 1986].

visual expressiveness means that a graphical form exactly encodes the information needed by the operator and does not allow less or more (e.g. missing information or misinterpretations).

[2] https://www.dictionary.com/

Affirmation

I hereby affirm that I have written this work independently and used only the sources and resources indicated. I also assure that I followed the general principles for scientific work and publication, as specified in the guidelines for good scientific practice at Carl von Ossietzky University of Oldenburg.

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