Supporting supervisory control of safety-critical systems by optimizing visualizations on monitoring displays for fast and accurate perception

Marie-Christin Harre & Andreas Lüdtke
OFFIS Institute for Information Technology
Germany

Abstract

The amount of automation in technical systems continually increases e.g. autonomous driving or automatic failure detection in control rooms. The monitoring of a high amount of information becomes a major task of the human operator. Due to the rising quantity of information, this task becomes increasingly complex. Especially in safety-critical systems, it has to be ensured that the operator assesses critical system states fast and accurate to initiate countermeasures in time. Therefor the HMI has to be designed carefully. For this, we developed the Konect method that allows systematic derivation of efficient visualizations. The method combines knowledge from the human factors domain (e.g. task analysis, ecological interface design), the information visualization domain and knowledge about human perceptual skills. We validated the method in the automotive domain (for truck platooning) and in the maritime domain (with 17 designers creating designs, and 51 participants testing the designs in different laboratory studies). The results revealed that Konect designs performed significantly better than designs constructed with conventional methods ($p<0.001$) which reduced the amount of accidents by 81.8% (tested in driving simulator).

Introduction

The amount of automation in technical systems continually increases. Autonomous driving or automatic failure detection in control rooms represent just two examples. It is one of the ironies of automation, that an increased level of automation lies in higher demands for the human operator in monitoring the system instead of replacing the human operator 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). The human operator has to assess the state of the system continuously to estimate if the system is working correctly or if an anomaly occurs. Especially in the safety-critical domain, this monitoring task is a time-critical task, as counter-measures have to be taken as fast as possible in case an anomaly is detected. To monitor the system state, the human operator observes relevant information on a Human Machine Interface (HMI). To allow fast detection of critical system states, this HMI has to be designed carefully. For this, we developed the Konect method

In D. de Waard, K. Brookhuis, D. Coelho, S. Fairclough, D. Manzey, A. Naumann, L. Onnasch, S. Röttger, A. Toffetti, and R. Wiczorek (Eds.) (2019). Proceedings of the Human Factors and Ergonomics Society Europe Chapter 2018 Annual Conference. ISSN 2333-4959 (online). Available from http://hfes-europe.org

that allows systematic derivation of efficient visualizations. The method combines knowledge from the human factors domain (e.g. task analysis, ecological interface design), the information visualization domain and knowledge about human perceptual skills. The method is described in detail in the upcoming paper: The upcoming section starts with presenting related work about methods for visual HMI design. Thereafter, the method is described with a small example. The Konect method was evaluated in two different domains (automotive, maritime). The results revealed that HMI designs developed with Konect are significantly faster and more correct perceivable.

Related work

The optimization of HMIs to the extent that they are optimally adapted to the tasks of the operator has a long-lasting background in the HF domain:

The human centred design process as introduced by the international organization for standardisation (ISO) represents a well-established process for designing an HMI consisting of four different activities: (1) understand and specify the context of use, (2) specify the user requirements, (3) produce design solutions to meet user requirements and (4) evaluate the designs against requirements. Especially in the first step, task analysis methods are commonly applied. There exist different approaches for conducting a task analysis as proposed by Stanton et al. (Diaper & Stanton, 2003).

Ecological Interface Design (EID) is a framework introduced by Kim Vicente and Jens Rasmussen (Vicente & Rasmussen 1992). EID shifts the focus from the user centred perspective to a work domain-oriented perspective. This is based on EIDs aim of supporting the operator’s problem-solving capabilities in unforeseen problem situations. HMIs based on EID provide knowledge about the functioning of the system that is monitored so that the operator understands reasons for upcoming problems and can derive suitable countermeasures (Burns & Hajdukiewicz, 2013). There exist also approaches combining task analysis and EID (Jamieson et al., 2007).

The approaches previously presented focus on the derivation of information to be shown and on the structuring of information. The visualization of information plays a minor role. Konect combines both aspects – the well-established derivation of information and structure enhanced with systematic derivation of visual appearance of information elements.

With regard to the visual appearance, Petersen and May (2006) presented an approach for scale transformations and information presentation in supervisory control. *Scales* are used to describe the type of information to be presented (e.g. nominal, ordinal, interval, and ratio). To define the scale type, the authors present rules for mapping data being presented to the operator to a certain type of scale. To convert the information into a visual form, the authors apply a theoretical framework developed by Zhang et al. (1996). Zhang et al. presented a framework for describing properties and structures of relational information displays. Compared to Konect, the framework does not focus on fast and correct perception but is more oriented towards expressiveness.

The Konect Method

The Konect Method involves four basic steps as shown in Figure 1. The first step is the *information determination*, the second step the *idea box specification*, third, the *glyph sketching* and the last step is the *design composition*. Details for all steps are described in the upcoming text.

Figure 1. Steps of the Konect procedure.

Information determination

The first sub step is the information determination. This step ensures that the information shown on the HMI optimally supports the task of the human operator. In this regard it is important that relevant information needed during monitoring is shown and no essential information is missing. At the same time irrelevant information that overcrowds the interface and produce visual clutter should be avoided. This is often referenced as *information fitness* (Denker et al., 2014). Therefore, the essential information as well as the structure of the information (e.g. which information elements should be grouped together in order to avoid an extensive visual search of information within one task) is systematically derived. In this step, the connection between existing HF methods as task analysis and EID is established. These methods offer an engineering way for specifying the information to be shown on the HMI as well as the structure. For this, task analysis focuses on analysing the activities (tasks), the human operator conducts and grouping information elements according to these tasks (e.g. information that is needed in one task should be grouped together). EID shifts the focus from the human operator and his tasks to the work domain. Thus, a work domain analysis is conducted and structured according to an abstraction hierarchy. This is exemplarily shown in Figure 2 for a small example of a propulsion system: On the highest level, the functional purpose is specified. This is the main aim of the system analysed. In case of the small example, the main aim is that the *propulsion system operates in safe mode*. On the second level, the abstract function is described. This includes laws and principles existent in the underlying system e.g. *principle of conservation of energy*. After this, processes are described that are involved in the system (e.g. *combustion*) and the entities relevant in these processes (e.g. *engine*). On the lowest level, the physical form and parameters of these entities are described.

Before entering into step 2 activity of the Konect method, a decision has to be made which elements should be grouped together: Prior work has shown that information can be perceived faster and remembered better in case certain visual attributes (e.g. colour, length, shape) are integrated in one integrated visual form (Ware, 2004). These integrated visual forms are called *glyphs*. To allow fast perception of all information elements at one glance, the Konect method applies the concept of glyphs. The decision on which information to integrate can be done on the basis of a task analysis tree or the abstraction hierarchy (as common in EID and exemplarily shown in Figure 2). E.g. to estimate the engine state with one glance, the information about engine revolutions, torque, temperature and oil pressure should be grouped together in one glyph. For each glyph, one idea box is specified in the upcoming step 2 – the *idea box specification*.

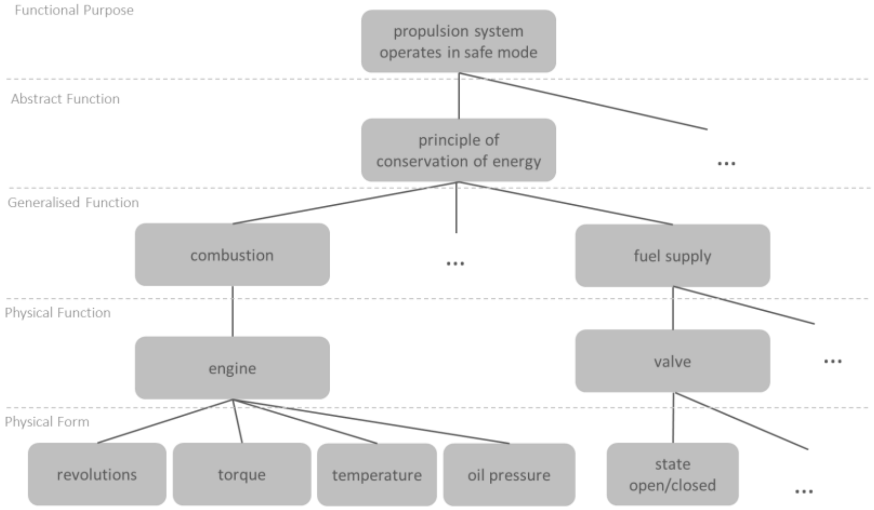

Figure 2. Extract of work domain analysis for engine monitoring example.

Idea Box specification

The second step is the idea box specification. The idea box is a core concept of the Konect method and provides a suitable format to collect all data relevant for informing the design process so that an optimization for fast and correct perception of chosen visual forms can take place. The idea box is a table with predefined columns. The columns are shown in Figure 3.

Importance ranking

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

Figure 3. Idea Box – Exemplary extract.

In the first column the *information* is added in the idea box. This is taken from the abstraction hierarchy (e.g. revolutions, torque, temperature, oil pressure). When defining which visualization is most efficient the so-called *insight* is important. The insight specifies why the human operator needs this information (e.g. the human operator wants to *perceive if the value is ok* or the human operator wants to *perceive the quantitative value*). We specified a predefined list of insights. Each insight is mapped to a visual efficiency ranking containing visual attributes e.g. colour, length. The full list of insights and the mapping to efficiency rankings of visual attributes can be found in Harre et al. (2018). The rankings are derived based on well-accepted empirical knowledge: Cleveland and McGill (1984) presented an empirically verified accuracy ranking for visual attributes for quantitative data (e.g. position is more accurate perceivable than volume). This was later extended by Mackinlay (1986) for different data types (nominal, ordinal, quantitative). Both works focus on accurate perception. To include the time factor, we added knowledge about preattentive perception (Healey et al., 1996): Some visual attributes e.g. colour can be perceived preattentively – in millisecond range. All insights that have this time factor (e.g. *perceive quantitative value (fast)*) do only consist of visual attributes that are perceived preattentively. Most insights can be perceived on low level vision. Low level vision focuses on the perception of single visual attributes as colour or length. But there exist also insights in which various data elements are included simultaneously (e.g. compare). This insight is only perceivable on higher level vision. High level vision deals with the perceptual organization of single visual attributes. The efficiency rankings for these insights are derived based on prior empirically verified knowledge about high level vision (Kosslyn et al., 1990), (Rensink, 2000), (Rensink, 2002).

The specification of insights is important as different visualisations are different efficient for different insights e.g. if the human operator wants to perceive if the engine revolutions are ok, colour is an appropriate choice. In case he or she wants to perceive the quantitative value of the engine revolutions, a length might be more efficient. The insight specification allows a mapping to different efficiency rankings as described in the previous paragraph for possible visual attributes for the information. The full ranking with mapping to the different insights is shown in Figure 4.

As described previously, all information elements specified in the idea box should be grouped together in one glyph. To offer possibilities on how to integrate visual attributes in one integrated form, the last column – the combination – offers possibilities on how to combine visual attributes. This is done via the well-established gestalt laws (e.g. symmetry, proximity) (Ware, 2004).

In a last step, all entries in the idea box should be ordered according to their importance – starting with the most important information and ending with least important information. In this respect the importance of an information depends on the influence this parameter has on the achievement of the overall goal (functional purpose). This can be either derived based on the work domain analysis in which the impact of parameters on the functional purpose is estimated or within an interview with a human operator who directly states which information is more important than another one for his or her monitoring task. This step is necessary to ensure that most important information is visualized most efficient with regard to human perceptual skills.

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)	(Cleveland & McGill, 1984), (Mackinlay, 1986)
perceive **quantitative value (fast)**	length (0), slope (1), volume (2), color hue (3)	(Cleveland & McGill, 1984), (Mackinlay, 1986), (Healy et al., 1996) ,(Ware, 2004)
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)	(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),	(Cleveland & McGill, 1984), (Mackinlay, 1986), (Healy et al., 1996) ,(Ware, 2004)
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)	(Cleveland & McGill, 1984), (Mackinlay, 1986)
perceive **ordered category/mode (fast)**	color hue (0), length (1), slope (2)	(Cleveland & McGill, 1984), (Mackinlay, 1986), (Healy et al., 1996) ,(Ware, 2004)
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),	(Kosslyn et al., 1990), (Rensink, 2000), (Rensink, 2002)

Figure 4. Mapping of insights to efficiency rankings.

Glyph sketching

The idea box specified in step 2, is now applied in step 3 to inform the design of glyphs. The designer of the HMI works with the idea box as follows: He or she starts with the first information (e.g. *revolutions* as shown in Figure 3). The information should be visualized once to estimate the quantitative value and additionally to estimate if the value is ok or not. According to the visual efficiency ranking, the most appropriate visual attribute for the first is *length*, and *colour* is the most appropriate for the latter. Similar applies for torque (length for quantitative value and colour for state (critical or not)), oil pressure and temperature. To create a glyph, these visual attributes have to be combined. Therefore, symmetry represents a suitable possibility to group all length variables in one visual form. This is exemplarily shown in Figure 5: The length of the quarter-circles represents the quantitative values of the parameters and the colour indicates if the parameter is within its acceptable limits (ok) or if it exceeds these limits (critical). Thereby, the overall state of the engine is fast perceivable.

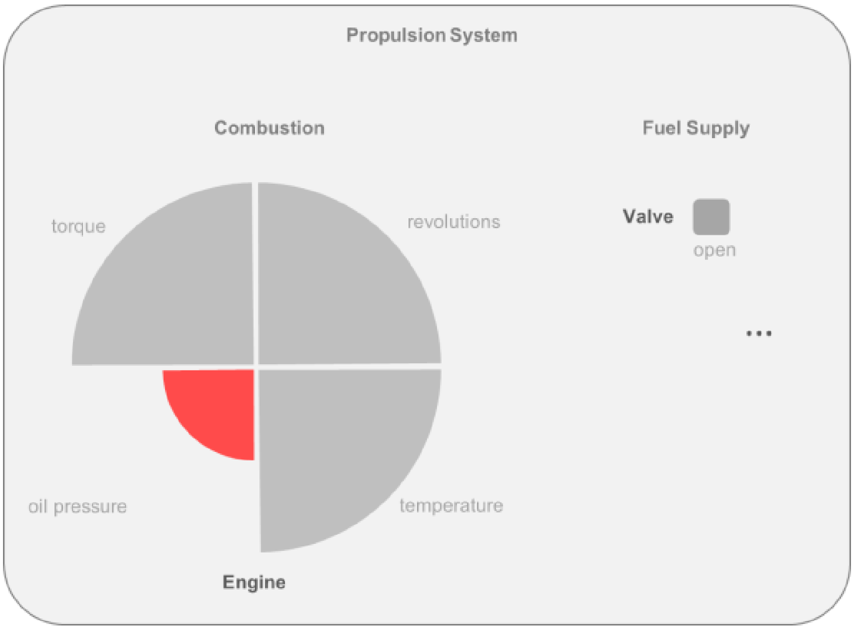

Figure 5. Example Glyph for engine.

Design Composition

In the glyph sketching phase different glyphs are designed separately from each other. As described previously, fast perception strongly relates to preattentive perceptual skills of the human operator. In this regard, there exist some prerequisites to obtain so that critical states produce a preattentive recognizable "pop-out" effect: It has to be ensured that glyphs – especially as they were designed separately – do not visually interfere with each other. For this the designer has to verify that the following guidelines are met (Harre et al., 2018):

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

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

Simplicity in Colours Reduce colours for elements that do not carry any information besides from structuring the interface.

Evaluation

The Konect method was evaluated in different domains (first, in the automotive domain for a truck platooning use case and second, in the maritime domain for vessel performance monitoring). The studies had a different focus: The truck platooning study was primarily used to compare designs derived with the Konect method compared to designs created with conventional methods, while the vessel performance monitoring study compared designs created after step 3 of Konect to designs after step 4 of Konect to further evaluate the guidelines for design composition. As conventional method, the human centred design process as described in the related work section was applied. This departs from the Konect method as no integration of specific prior knowledge about human perceptual abilities in a systematic step-by-step process is offered. Nevertheless, the human centred design process is a well-established standard that is widely applied for deriving HMI designs.

In both studies, a workshop was conducted as starting point. In this workshop, participants (HF experts with different background knowledge, UX professionals and designers) applied the method to create design solutions. In case of the truck platooning scenario, 5 designs have been created and in the maritime use case 12 designs were created. These designs were then tested in a laboratory study in front of the computer applying the following procedure: As starting point, the participants got a detailed explanation for the scenario and the different designs. This was followed by a training phase and a subsequent measurement phase. In the measurement phase (see Figure 6), the participants were asked to press the enter-Button as soon as they felt ready for estimating a situation. After pressing the button, a random design was shown presenting either a critical or a non-critical situation and a time-measurement started. The participants were asked to estimate as fast and accurate as possible if a shown situation was critical or not. As soon as they estimated the situation, they pressed the enter-Button and the time measurement stopped and the design disappeared. After this, the participant had to enter in a text-field if the situation shown before was critical or not. This answer has then been evaluated as correctness indicator for the percept. The study applied a within-subjects design to cancel out individual differences with regard to reaction times.

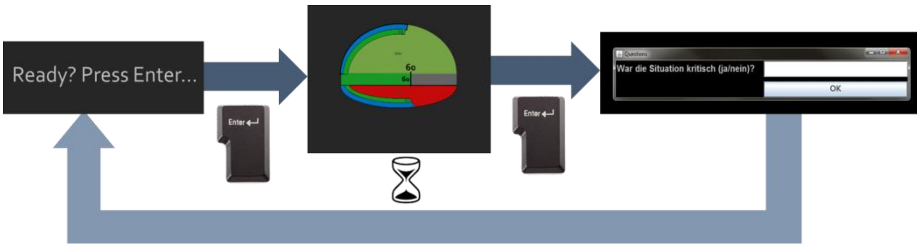

Figure 6. Procedure for measuring mean RT and mean assessment failure.

As these experiments were quite artificial, a driving simulator study was conducted additionally in which the participants were asked to drive in a simulated truck platooning scenario. Each participant drove about 40 minutes without having to react to any occurrence. After these 40 minutes drive, an ACC failure was simulated to which the participants react via braking to prevent an accident. For conducting this study, a between-subjects design was chosen (one group drove with a Konect design, the other group had a design created in a conventional user-centred design process). This was done to avoid a learning or accustoming effect for an ACC failure and to reproduce the real conditions with rare ACC failures as realistically as possible. The meters left to the truck in front when braking as well as the amount of accidents were measured.

Table 1. Overview for method evaluation.

	Participants	*Results*				*Further Details*
Truck Platooning (laboratory study)	33 (21f)		**Conventional**	**Konect**	**T-Test**	(Ostendorp et al., 2016a) (Ostendorp et al., 2016b)
		Mean Assessment Failure [%]	14.59 (SD=7.9)	5.43 (SD=3.77)	p<0.001	
		Mean RT [ms]	2122.86 (SD= 951.65)	1731.03 (SD= 772.31)	p<0.001	
Truck Platooning (driving simulator study)	23 (12f)		**Conventional**	**Konect**	**T-Test**	(Friedrichs et al., 2016)
		Meters left when braking [m]	1.21 (SD=1.4)	3.45 (SD=1.74)	p =0.002 < 0.05	
		Accident occurred [%]	50%	9.1%		
Vessel Performance Monitoring (laboratory study)	18 (14f)		**Konect (after Step 3)**	**Konect (after Step 4)**	**T-Test**	(Harre et al. 2018)
		Mean Assessment Failure [%]	7.72 (SD= 6.24)	3.09 (SD=2.73)	p < 0.001	
		Mean RT [ms]	1214.5 (SD=222.15)	1041.5 (SD=174.47)	p < 0.001	

All results of the different evaluation studies are summarized in Table 1. The results of the Truck Platooning laboratory study revealed that conventional designs led to a mean assessment failure of 14.59% (meaning that in nearly 15% of the cases, a situation was falsely assessed as being either critical or non-critical, although the opposite was correct). This was reduced to 5.43% with Konect designs. The T-Test showed that this difference is significant with $p<0.001$. With regard to the time needed to assess the situation, the participants needed around 2122.86ms with the conventional designs, compared to 1731.03ms with the Konect designs, which is again a significant result ($p<0.001$).

The results measured in the laboratory study were confirmed in the driving simulator study. When participants brake in case the ACC failure occurred, the mean meters left to the truck in front were 1.21m for conventional designs compared to 3.45m with the Konect designs. This strongly indicates that the increase of accuracy and time to perceive the situation lead to a better braking performance in critical situations. This is also reflected in the amount of accidents occurred. With the conventional designs every second participant had an accident, while with the Konect designs only 9.1% had a rear-end collision.

In the Vessel Performance Monitoring laboratory study, the influence of step 4 was analysed: The results showed that the mean assessment failure for estimating if a situation was critical or not was 7.72% with a design after step 3 compared to 3.09% after step 4. The reaction time for assessing the situation was reduced from 1214.5ms to 1041.5ms.

Summarizing, it can be said that the results revealed that Konects *Design Composition* step led to a significant improvement ($p<0.001$) and that Konect designs were significantly faster and more correct perceivable compared to non-Konect designs.

Conclusion

In the underlying paper, the Konect method was presented. Konect is a method for optimizing visualizations on monitoring displays for fast and accurate perception in the safety-critical domain. The method consists of four steps to be conducted: *Information determination*, *Idea Box Specification*, *Glyph Sketching* and *Design Composition*. For validation purposes, the method was applied in workshops in two different domains (automotive and maritime). The workshops revealed that Konect designs were significantly fast and more accurately perceived compared to designs created with conventional methods. In a driving simulator study, this led to a decrease of accidents from 50% to 9.1%.

References

Bainbridge, L. (1983). Ironies of automation. *Analysis, Design and Evaluation of Man–Machine Systems*, 129–135.

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

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

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*, 531–554.

Denker, C., Fortmann, F., Ostendorp, M.-C., Hahn, A. (2014). Assessing the Fitness of Information Supply and Demand during User Interface Design. In G. Di Bucchianico, A. Vallicelli, N.A. Stanton, S.J. Landry(Eds.), *Human Factors in Transportation*, Taylor and Francis.

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

Friedrichs, T., Ostendorp, M.-C., Lüdtke, A. (2016): *Supporting Truck Platooning: Development and Evaluation of Two Novel Human-Machine Interface*. In Proceedings of the 8th International Conference on Automotive User Interfaces and Interactive Vehicular Applications.

Harre, M.-C., Feuerstack, S., Wortelen, B. (2018): *A Method for Optimizing Complex Graphical Interfaces for Fast and Correct Perception of System States*. In Proceedings of the 7th International Working Conference on Human-Centered Software Engineering.

Healey, C.G., Booth, K. S., & Enns, J. T. (1996). High-speed visual estimation using preattentive processing. *ACM Transaction on Computer Human Interaction, 3,* 107–135.

International Organization for Standardization, (2006). *ISO 9241 ergonomics of human system interaction*.

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,* 887–905.

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,* 203–277.

Mackinlay, J. (1986). Automating the design of graphical presenta- tions of relational information. *ACM Transactions on Graphics*, *5*, 110–141.

Ostendorp, M.-C., Friedrichs, T., & Lüdtke, A. (2016a). *Supporting supervisory control of safety-critical systems with psychologically well- founded information visualizations*. In Proceedings of the 9th Nordic Conference on Human-Computer Interaction. New York, NY, USA: ACM.

Ostendorp, M.-C., Feuerstack, S., Friedrichs, T., & Lüdtke, A. (2016b). *Engineering automotive hmis that are optimized for correct and fast perception*. In Proceedings of the 8th ACM SIGCHI Symposium on Engineering Interactive Computing Systems (pp. 293–298). New York, NY, USA: ACM.

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

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

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

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

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

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