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Spatial Attention Guidance for Deck Officers on Ship Bridges

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Abstract

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Abstract

Over 90% of the world's trade is transported by sea. Most of the resulting traffic is confined to highly trafficked waterways. That is why collisions and groundings still constitute the biggest number of maritime accidents, endangering the life of the ship's crew, the life of others, the cargo, and the environment. This makes these accidents not only costly but also really severe. Looking into the causes of these accidents, the majority of them are caused by a lack of Situation Awareness as the responsible operators did either notice important information too late or not at all. With increasing ship size and capacity, the handling becomes more and more challenging and the time it takes to successfully implement an evasion maneuver gets longer. This reduces the available time for decision making which is why it is very important to have a complete overview of the current situation at any given point in time.

Literature shows that the perception of information is the bottleneck for gaining good Situation Awareness. Work in other domains shows that attention guidance helps to improve the perception of information in demand for attention. The goal of this thesis is to provide design guidelines and strategies for spatial attention guidance of nautical operators to information in demand for attention filling potential information gaps. Further, we propose a system for the selection of guidance cues based on the current context and estimated workload. Combined with already existing related work that identifies information in demand for attention, this results in a fully functional monitoring assistance system.

We make the following contributions to assistance systems for guiding attention. Through Accident Report Analysis using natural language processing techniques, we compiled a ranking of human factors that impede Situation Awareness in maritime accidents. For the ecological validity of our study results three combineable apparatuses for lab testing were implemented, which simulate the visual, auditory, and tactile properties of a real-world ship bridge. In lab experiments using eye-tracking and standardized questionnaires, we created a set of visual, auditory, and tactile cues for spatial attention guidance on ship bridges. From the experiments and literature research, we composed a list of design guidelines for spatial attention guidance cues.

Keywords:

Attention guidance, eye tracking, situation awareness, maritime

Räumliche Aufmerksamkeitslenkung für Deckoffiziere auf Schiffsbrücken

Zusammenfassung

Über 90% des Welthandels werden auf dem Seeweg abgewickelt. Der größte Teil des daraus resultierenden Verkehrs beschränkt sich auf stark befahrene Wasserstraßen. Deshalb stellen Kollisionen und Grundberührungen nach wie vor die größte Zahl von Seeunfällen dar, die das Leben der Schiffsbesatzung, das Leben anderer, die Fracht und die Umwelt gefährden. Das macht diese Unfälle nicht nur kostspielig, sondern auch sehr schwerwiegend. Betrachtet man die Ursachen dieser Unfälle, so ist die Mehrheit davon auf mangelndes Situationsbewusstsein zurückzuführen, da die verantwortlichen Schiffsführer entweder zu spät oder gar nicht auf wichtige Informationen aufmerksam wurden. Mit zunehmender Schiffsgröße und -kapazität wird das Manövrieren immer anspruchsvoller und die Zeit, die benötigt wird, um ein Ausweichmanöver erfolgreich durchzuführen, wird länger. Dadurch wird die verfügbare Zeit für Entscheidungen verkürzt, weshalb es sehr wichtig ist, einen vollständigen Überblick über die aktuelle Situation zu jedem Zeitpunkt zu haben.

Die Literatur zeigt, dass die Wahrnehmung von Informationen der Flaschenhals für ein gutes Situationsbewusstsein ist. Die Arbeit in anderen Bereichen zeigt, dass die Aufmerksamkeitslenkung dazu beiträgt, die Wahrnehmung von Informationen zu verbessern, die Aufmerksamkeit erfordern. Das Ziel dieser Arbeit ist es, Designrichtlinien und Strategien für die räumliche Aufmerksamkeitslenkung von nautischen Offizieren zu Informationen zu liefern, die für die Schließung potenzieller Informationslücken erforderlich sind. Darüber hinaus schlagen wir ein System für die Auswahl der Hinweisreize vor, das auf dem aktuellen Kontext und der geschätzten Arbeitsbelastung basiert. In Kombination mit bereits bestehenden verwandten Arbeiten zur Bestimmung des Aufmerksamkeitbedarfs, ergibt sich daraus ein voll funktionsfähiges Assistenzsystem.

Wir leisten die folgenden Beiträge zu Assistenzsystemen zur Steuerung der Aufmerksamkeit. Durch die Analyse von Unfallberichten unter Verwendung von Techniken der linguistischen Datenverarbeitung haben wir ein Ranking der menschlichen Faktoren erstellt, die das Situationsbewusstsein bei Seeunfällen beeinträchtigen. Für die ökologische Validität unserer Studienergebnisse wurden drei kombinierbare Apparaturen für Laborversuche implementiert, die die visuellen, auditiven und taktilen Eigenschaften einer realen Schiffsbrücke simulieren. In Laborexperimenten mit Eyetracking und standardisierten Fragebögen haben wir eine Reihe von visuellen, auditiven und taktilen Hinweisen für die räumliche Aufmerksamkeitslenkung auf Schiffsbrücken entwickelt. Aus den Experimenten und der Literaturrecherche haben wir eine Liste von Gestaltungsrichtlinien für diese Hinweise zusammengestellt.

Schlüsselwörter:

Aufmerksamkeitslenkung, Eyetracking, Situationsbewusstsein, maritim

Contents

Abstract I

1 Introduction 1

1.1 Challenges . . . 3
1.2 Research Objectives & Contributions . . . 4
1.3 Publications . . . 8
1.4 Outline . . . 9

2 Background 11

2.1 Situation Awareness . . . 11
2.2 Overt Attention . . . 13
2.3 Attention Tracking using an Eye Tracker . . . 15
2.4 Spatial Attention Guidance . . . 16
2.5 Maritime User Interface and Working Environment Regimentations . . . 18
2.6 Summary . . . 19

3 Requirements and Approach 21

3.1 Methodology . . . 21
3.2 Context of Use . . . 23
3.3 Problem Analysis . . . 29
3.4 Approach . . . 37
3.5 Summary . . . 41

4 Apparatus 43

4.1 Transportable Ship Bridge Simulator . . . 44
4.2 Audio Lab and Acoustic Scene of a Ship Bridge . . . 52
4.3 Platform for Simulation of Environmental Vibration on a Ship . . . 54
4.4 Measurement Apparatus for Tracking of Overt Attention . . . 58
4.5 Summary . . . 59

5 Guidance Cues 61

5.1 Design Space of Spatial Guidance Cues . . . 61
5.2 Light-controlled Attention Guidance for Multi-Monitor Environments 63
5.3 Exploring Peripheral and Vibrotactile On-body Cues . . . 73
5.4 Use of Pneumatic On-body Cues to Encode Directions . . . 87
5.5 Comparison of Moved and Static Acoustical Pointers . . . 95
5.6 Summary . . . 107

6 Context-aware Guidance Control 109
6.1 Spatially Distributed Information of Heterogeneous Complexity . . 109
6.2 Concept for Context-aware Guidance Cue Selection 118
6.3 Summary 120

7 Conclusion 121
7.1 Summary 121
7.2 Contributions 123
7.3 Reliability and Validity 127
7.4 Future Work 128
7.5 Closing Remarks 130

Figures 131

Tables 133

Bibliography 135

1 Introduction

As Technology evolves, it finds its way into many different domains, offering support and enabling growth. Often, this changes the way of working in these domains. Today, many working environments consist of vast number of different technical systems and that are connected and constantly exchange information. This connection of previously independent systems, called a cyber-physical system, offers new possibilities of operation. For example, the connection of a navigation system and environmental sensors with vehicle controls enables autonomous driving. Tasks that were previously actively performed by a human operator, now are controlled by a machine, changing the role of the human from an operator to an observer that only operates on demand, e.g. in high traffic density or on system failure. This increase in automation frees time for the operator to perform other tasks, but also comes with the challenge of keeping him or her in the loop, in case he or she has to take over.

Therefore, monitoring and safe operation of large cyber-physical systems is a challenging task. The operator becomes a component of a socio-technical system, that will fail if he or she fails. A representative example of such systems is the bridge of a ship. Multiple persons interact with multiple systems, and the environment to ensure safe maneuvering through highly trafficked waterways as well as on long distances with low traffic density. Unsurprisingly, this results in highly different workload conditions. Phases with extreme high workload and need for unconfined attention and phases with low workload, that allow for divided attention are the case. Both of which come with their own challenges to the human operator.

Seafaring is an old profession that mostly relied on skills and experience for centuries, recently more and more assistant systems were introduced into the maritime domain supporting seafarers to safely operate ships of increasing size and capacity in highly trafficked waterways. While ships are still not fully autonomous, today the task of the seafarer changed from active to passive navigation. Collision and grounding avoidance are major parts of safe maneuvering, requiring continuous monitoring of the status of ship systems and the ship's surroundings. Monitoring tasks often require the observation and assessment of the overall system status based on information, which in many cases is located on different spatially separated information displays. This is the common case on ship bridges.

Although the percentage decreased from 85% in 2005 [BM05] to about 62% in 2016 [Eur16], the majority of maritime accidents still are caused by Human Error. As intensive analyses of accident reports show, up to 71% of Human Error caused accidents were caused by a lack of Situation Awareness [GHS02, HFM06, SB16]. The majority of these accidents are collisions and grounding accidents, which can cause severe damage to people, and the environment [Fed20, Eur20, All20].

Figure 1.1: Collision of *Marti Princess* and *Renate Schulte* off Bozcaada Island on 27th of June 2009. The picture was taken from the corresponding investigation report of the German Federal Bureau of Maritime Casualty Investigation [Fed12].

The following scenario was inspired by the events leading to the collision between the Maltese registered general cargo ship *Marti Princess* and the German registered container ship *Renate Schulte* off Bozcaada Island on 27th of June 2009 [Fed12]. The before-named accident is a classical example of a lack of Situation Awareness leading to an accident. Figure 1.1 shows both ships after their collision. Fortunately, neither injuries nor pollution were reported as an outcome of this accident.

Imagine you are a nautical officer on watch on a 15,000 GT container vessel of about 200 meters in length. It is a dark night without moonlight and you are underway on a coastal waterway with high traffic density on the Aegean Sea close to Bozcaada island. The visibility is reasonably good and you are concentrating on a vessel passing in front of you. While the other vessel's stern passes you safely, you are getting called over VHF by the local VTS station. Busy talking with them another vessel approaches on counter course. An attention shift to the ARPA or the ECDIS indicating the position, speed, and course of the approaching vessel is vital in this situation to be able to react early enough to the actions of the approaching vessel and to safely pass each other. As changes in course and speed on a ship of this size take several minutes to take an effect a collision cannot be avoided without a timely shift of attention to this information and an appropriate reaction based on it.

This scenario visualizes that the timely perception of relevant information, which directly affects the correctness of our current Situation Awareness, contributes to safe maneuvering, which could mitigate or even avoid accidents. The goal of this thesis is to support the timely perception of relevant information through spatial attention guidance and thereby ensuring a sufficient Situation Awareness of the decision maker. On ships, this person is the Officer of Watch (OOW).

1.1 Challenges

The following paragraphs describe general challenges in this thesis and how they were addressed.

Problem Space

The scope of this thesis is to help the Officer of Watch (OOW) on a ship bridge to maintain Situation Awareness. This comes with several challenges that have to be addressed. First, the size of the bridge room and the spatial extent of interfaces in it, combined with the free movement of the OOW forms a challenge on cue placement. Second, the information density, heterogeneous information complexity, and redundancy of information form a challenge of how the information is transported to the OOW or vice versa, when the information can be acknowledged as perceived and to which information the OOW should be guided. Third, some information is derived from the context, e.g. the current can be monitored by watching the difference of the speed over ground (GPS based) and the speed through water (Log based). We performed a thorough requirement analysis, including accident report analyses, contextual inquiries, interviews, and first-hand simulator training to ensure accurate capture of the context, activities, and confounding variables.

Experiments in Target Context

Performing field studies on on-duty ships brings several challenges. First, there is a logistical challenge, since they are underway most of the time (moving between different harbors), which narrows the reachable time-frame. Second, the interference with active onboard systems is not allowed for safety reasons, limiting the study apparatus. Third, to reach the necessary sample size for statistically significant results in experiments, several sessions on different ships would be necessary stretching the time frame of an experiment enormously, as the maximum number of deck officers onboard a vessel is three to four persons. Therefore, the next best option for ensuring a high ecological validity of experiments is a training simulator. These allow for realistic scenarios and tasks in experiments, which help to evaluate designs in the right context. However, the focus of these simulators lies in the accurate simulation of ship controls and learning workflows, hence, the emulation of the modal properties of ship bridges, such as environmental vibration, and the reverberation characteristics of large scale rooms with metal walls are not properly emulated. Therefore, we implemented three simulators to cope with these challenges: A modular transportable ship bridge setup that be used to setup maneuvering simulators of varying configuration and size in laboratory environments and potentially enables field studies without interference with active onboard systems in the future, an acoustic scene of a ship bridge that emulates reverb and acoustics of a ship bridge in an anechoic special lab, and a vibrating platform that can emulate vibrational noise on a ship bridge based on engine noise emulation.

Experiments with Target Group

The access to active maritime personal for on-shore experiments is limited. Typical experiments with users run in a time-frame of two weeks, while mariners are on-duty for different not necessary overlapping weeks or months-long time-frames, which makes the acquisition of study participants as well as the scheduling of sessions extremely challenging. This can partly be addressed by including nautical students after their first practical experience, retired mariners, pilots, and nautical researchers. Further, some experiments require no nautical background, therefore we fall back to including laymen for these.

1.2 Research Objectives & Contributions

The overarching objective of this thesis is to contribute to the safety of seafaring. We identify the problem of a lack of Situation Awareness, induced by the insufficient perception of relevant situational information, as the main contributor to human errors in maritime accidents. In the subsequent research, we investigate visual, tactile, and auditory attention guidance techniques to support the perception of relevant situational information. We take special care of the ecological validity of the before-mentioned techniques by creating and using sophisticated simulations of the ship bridge environment, reassembling its visual, vibrational, and auditory characteristics, as well as the tasks performed during shifts. Further, we adjusted an existing monitoring assistance system to the special needs on a ship bridge by mapping to the spatial extent and introducing additional metrics for information complexity. Finally, we linked this system with our attention guidance techniques. In this thesis, we contribute to the following five research questions:

RQ1: What are the main factors for a lack of attention that lead to maritime accidents?

Prior Work by Grech et al. identified the perception of information as a bottleneck leading to insufficient Situation Awareness causing maritime accidents [GHS02], however, the main causes for this lack in attention were unclear. Therefore we asked ourselves what are the factors that led to the lack of attention. We took a systematic approach to identify the deeper causes by analysis of full-text accident reports. Our results confirm that Situation Awareness Level 1 is the most prominent source of Human Error in maritime accidents. Likewise, it is the most prominent one of the three levels of Situation Awareness. All in all, the SA Demons with the highest proportion in the investigated sample were *WOFAS* with fatigue as the main cause, *errant mental models*, and *attention tunneling*. We were not able to find accidents caused by *requisite memory trap*, *misplaced salience* or *complexity creep*, however we still think that these exist. Unfortunately detecting these SA Demons in maritime accident investigation reports will remain difficult, unless it becomes part of the investigation itself. We advise taking special care of the SA Demons *WOFAS*, *errant mental models*, *data overload* and *attention tunneling* when designing new interfaces for ship bridges. Our findings might also be beneficial for the design of user interfaces for Vessel Traffic Management (VTM) centers.

RQ 2: How can we simulate a ship bridge including its visual, auditory, and tactile noise conditions in a lab environment?

As stated in the Challenges section before, field studies in the maritime domain bring limitations Existing training simulators offer scenario simulations, and realistic controls and systems. However, they are designed for training and not focused on realistic simulation of sensory noise, therefore, we asked how we could mimic the sensory noise conditions on a ships bridge in lab experiments. We contribute three simulator systems, each targeting a different modality: a mobile ship bridge system, an artificial acoustic scene of a ship's bridge, and a vibration platform and engine vibration signal. These simulators specifically mimic realistic visual, acoustic, and tactile properties of a ship's bridge, ensuring a high ecological validity of results. As our apparatuses are based on real ship characteristics from our reference ship, a 2999 GT bulk carrier, and were developed complying with the relevant standards (cf. Section 2.5), we find our apparatuses and the way we combined them in the chapters (Chapter 5 and Chapter 6) to offer a higher ecological validity for the respective experiment objectives than training simulators.

RQ 3: What is the design space of guidance cues for exogenous orienting of overt attention?

As result of our first research question, we found that certain human factors contributed the most to the lack of attention that led to missed perception of critical information for the current situation, resulting in accidents. Spatial Attention Guidance is the spatial reorientation of overt attention (cf. Section 2.2) triggered and guided by cues. We focus on cues that utilize exogenous orienting (cf. Section 2.4), as these cope better with human factors such as fatigue. The design space of Spatial Guidance Cues is limited to the three modalities visual, tactile, and auditory, as they are the only cue modalities, that allow for spatial localization or mapping in 3D space. Concerning cue placement, we distinguish between cues placed onbody and cues placed in the environment.

According to the Guidelines on Ergonomic Criteria for Bridge Equipment and Layout (MSC/Circ.982) by the International Maritime Organization (IMO), the preferred viewing area (+/-15° horizontally) and the immediate field of view (+/-35° horizontally) are reserved for information from displays and should not be occluded [Mar00]. Figure 2.3 in Section 2.5 visualizes these areas. Not blocking the foveal vision is also important in other domains. That is why we decided to investigate visual cues in the peripheral field of view. Peripheral vision comes with different characteristics than foveal vision. The color perception is more limited, there is no sharp vision, and the perception of changes and motions is stronger than the perception of details. Therefore we focused on investigating visual cues rendered by low resolution light displays.

Tactile cues are widely used for conveying directions for navigation [TY04, MMUW15, HHBP08], which shows their high potential for successfully conveying spatial information. There are different ways to implement tactile cues, we focused on vibro-tactile cues (vibration) and pneumatic cues (pressure). For the highest effectiveness, the placement of tactile cues should be limited to positions that allow for simple direction mapping. Further, close proximity to intimate body areas should be avoided, to avoid unpleasant user experiences.

Auditory cues are spatially locatable by humans, however, the quality of 3D audio is limited by hardware. There are two ways to render 3D audio, either through a surround-sound speaker setup or through headphones. Headphones have the disadvantage of physically limiting the perception of environmental sounds, such as face-to-face communications, VHF radio calls, and environmental sounds. Bone conduction speakers are alternative speaker hardware that allows for the simultaneous perception of environmental sounds. Unfortunately, they are not technically suitable for rendering 3D audio, as the sound does not travel through the outer ear but rather through a bone to the inner ear. That is why we decided to focus on auditory cues rendered in the environment through a surround-sound speaker setup, to ensure 3D localization of sounds while maintaining high speech intelligibility.

RQ 4: What are effective visual, auditory, and tactile cue implementations for cuing onbody or in the environment?

After defining the design space, the task remains to find effective solutions inside the design space, which is what this question aims at. In Section 5.3, we looked into visual and vibro-tactile onbody cues. We found that the combination of visual and tactile cues led to increased workload and should be avoided in situations and environments, where the workload is already high. Instead of the concurrent combination of modalities, we propose to combine modalities consecutively and use vibration for attention arousal and peripheral light for the shift. As for the use of single modalities, tactile cues tend to have a faster total response time than visual cues. Further, on-body cues should be paired with cues at the target position to allow for accurate localization, as we found in pre-tests and implemented in our study setups.

In Section 5.5, we observed that static and moving conditions triggered different behavior in our participants. Static acoustical pointers led to a more chaotic gaze pattern and head movements searching for the source of the signal, whereas moving patterns led to a more stable and smooth head and gaze movement towards the target. This is also reflected in the shorter target acquisition times for moving acoustical pointers. That is why we recommend using moving acoustical pointers rather than static acoustical pointers.

In Section 5.2, we presented three different guidance strategies (trace, call, pickup) for spatial attention guidance in multi-monitor systems. We implemented and compared these strategies through the example of a ship bridge using a light display. Our findings indicate that ambient guidance cues that begin at the current focus of the user are faster in guiding the user to a target in the periphery than ambient guidance cues in the peripheral vision of the user. Combined with our findings from Section 5.5, we recommend for visual and auditory cues in the environment to begin guidance at the current focus of attention and guide continuously towards the target.

RQ 5: When should guidance cues be triggered?

As the goal of this thesis is to cope with the factors that induce a lack in attention, it is important to ensure that the guidance cues do not contribute to these factors. Therefore, we propose to cue only when necessary, which leads to the question, when guidance cues should be triggered. We found that on ship bridges some information has to be perceived once, some has to be checked in a fixed interval and for some information it depends on the situation (e.g. distance to other ships), how frequent it demands attention (see Table 6.1). Therefore, we decided together with domain experts to base the frequency for the latter on the Time to Closest Point of Approach (TCPA), a common time distance measure from the maritime domain.

Fortmann et al. defined the *demand for attention* (DfA) [FM14] based on Wickens SEEV-Model [WM07]. They further presented a tool called MAS, that calculates and ranks the *demand for attention* of multiple areas of interest (AOIs) online based on live eye tracking data. As the goal is to support regular monitoring, the neglect time, the time since the last check of the information, is taken into account for the calculation of the DfA score. Therefore, the DfA of an *information element* is calculated based on the task-relevance of an information element, a value between zero and one, the maximal neglect time for the monitoring interval of the information element, and the actual neglect time, as measured by eye tracking. For further details on the calculation, see Fortmann and Mengeringhausens paper [FM14].

On ship bridges, the complexity of information varies drastically between displays (e.g. radar or turn rate indicator), therefore we introduce two new parameters to the MAS tool: The *fixation quotient*, which reflects the number of fixations on the display and the *fixation duration quotient*, which reflects the duration of the visual inspection of the display by the operator. Both parameters were introduced to cope with the complexity of the displays, as van de Merwe et al. found, that the fixation rate and dwell time are good indicators for situation awareness [vdMvDZ12]. Depending on the complexity of a display, there are more areas of interest (AOIs) on it, and the time to comprehend the information on it might be longer. The information of an information display is recognized as ”perceived” by the system, if either the *fixation quotient* or the *fixation duration quotient* reaches a value of one. This is to cope with measurement errors of the eye tracker and to avoid unnecessary cues.

We found that guidance cues should be triggered on a regular basis, but based on the current situation and context rather than on a fixed interval. Further, we recommend considering the information complexity as a relevant factor for monitoring intervals.

1.3 Publications

Parts of this thesis have been previously published as conference and journal papers [SB16, SSBHB18, SLG+18, SGS+18, SBB19, SKB19]. We provide references to these publications at the beginning of each chapter. Further, papers on related topics have been published, which contributed to the overall idea, and objective of this thesis [LBS+17, GSB+18]. In the following we list all core publications, ordered by their publication date in descending order.

- Tim Claudius Stratmann and Susanne Boll. Demon Hunt - The Role of Endsley’s Demons of Situation Awareness in Maritime Accidents. In Cristian Bogdan, Jan Gulliksen, Stefan Sauer, Peter Forbrig, Marco Winckler, Chris Johnson, Philippe Palanque, Regina Bernhaupt, and Filip Kis, editors, *Human-Centered and Error-Resilient Systems Development*, Lecture Notes in Computer Science, pages 203–212. Springer International Publishing, August 2016

- Tim Claudius Stratmann, Shadan Sadeghian Borojeni, Wilko Heuten, and Susanne C.J. Boll. ShoulderTap - Pneumatic On-body Cues to Encode Directions. In *Extended Abstracts of the 2018 CHI Conference on Human Factors in Computing Systems*, CHI EA ’18, pages LBW130:1–LBW130:6, New York, NY, USA, 2018. ACM

- Tim Claudius Stratmann, Andreas Löcken, Uwe Gruenefeld, Wilko Heuten, and Susanne Boll. Exploring Vibrotactile and Peripheral Cues for Spatial Attention Guidance. In *Proceedings of the 7th ACM International Symposium on Pervasive Displays*, PerDis ’18, pages 9:1–9:8, New York, NY, USA, 2018.

ACM

- Tim Claudius Stratmann, Uwe Gruenefeld, Julia Stratmann, Sören Schweigert, Axel Hahn, and Susanne Boll. Mobile Bridge - A Portable Design Simulator for Ship Bridge Interfaces. *TransNav, the International Journal on Marine Navigation and Safety of Sea Transportation*, 12(4):763–768, 2018
- Tim Claudius Stratmann, Dierk Brauer, and Susanne Boll. Supporting the Perception of Spatially Distributed Information on Ship Bridges. In *Proceedings of Mensch Und Computer 2019*, MuC'19, pages 475–479, New York, NY, USA, 2019. ACM
- Tim Claudius Stratmann, Felix Kempa, and Susanne Boll. LAME: Light-controlled Attention Guidance for Multi-monitor Environments. In *Proceedings of the 8th ACM International Symposium on Pervasive Displays*, PerDis '19, pages 7:1–7:5, New York, NY, USA, 2019. ACM

1.4 Outline

This thesis is structured into seven chapters. The first two chapters cover the introduction and background of the research presented in this thesis. Chapters three to six cover the conducted research. The last chapter concludes the thesis, states our contributions to the research questions, and gives an outlook. Figure 1.2 illustrates the structure of this thesis.

Chapter 1 motivates the work by illustrating the addressed problem and stating the challenges of the presented research. The chapter introduces our research objectives as well as summarizes our contributions.

In Chapter 2, we introduce concepts and related work on which this work is based on.

Chapter 3 describes the general approach of this thesis. Starting with a brief description of the applied methodologies, we follow up with a description of the context of use, problem analysis and end with a structured description of our approach.

In Chapter 4, we introduce three simulator systems that we implemented for the development and evaluation of multi-modal assistance systems on ship bridges.

In Chapter 5, we investigate visual, tactile, and auditory cue designs and cueing strategies for spatial attention guidance for onbody and environmental placement.

Chapter 6 proposes an implementation of an assistance system that can utilize attention guidance cues as described in Chapter 5. Further, we propose model adaptations to an existing attention demand model for the ship bridge environment and propose a model for context-aware cue selection.

In Chapter 7, we summarize our work and contributions and discuss the reliability and validity of our work. Finally, we give directions and highlight attachment points for future work.

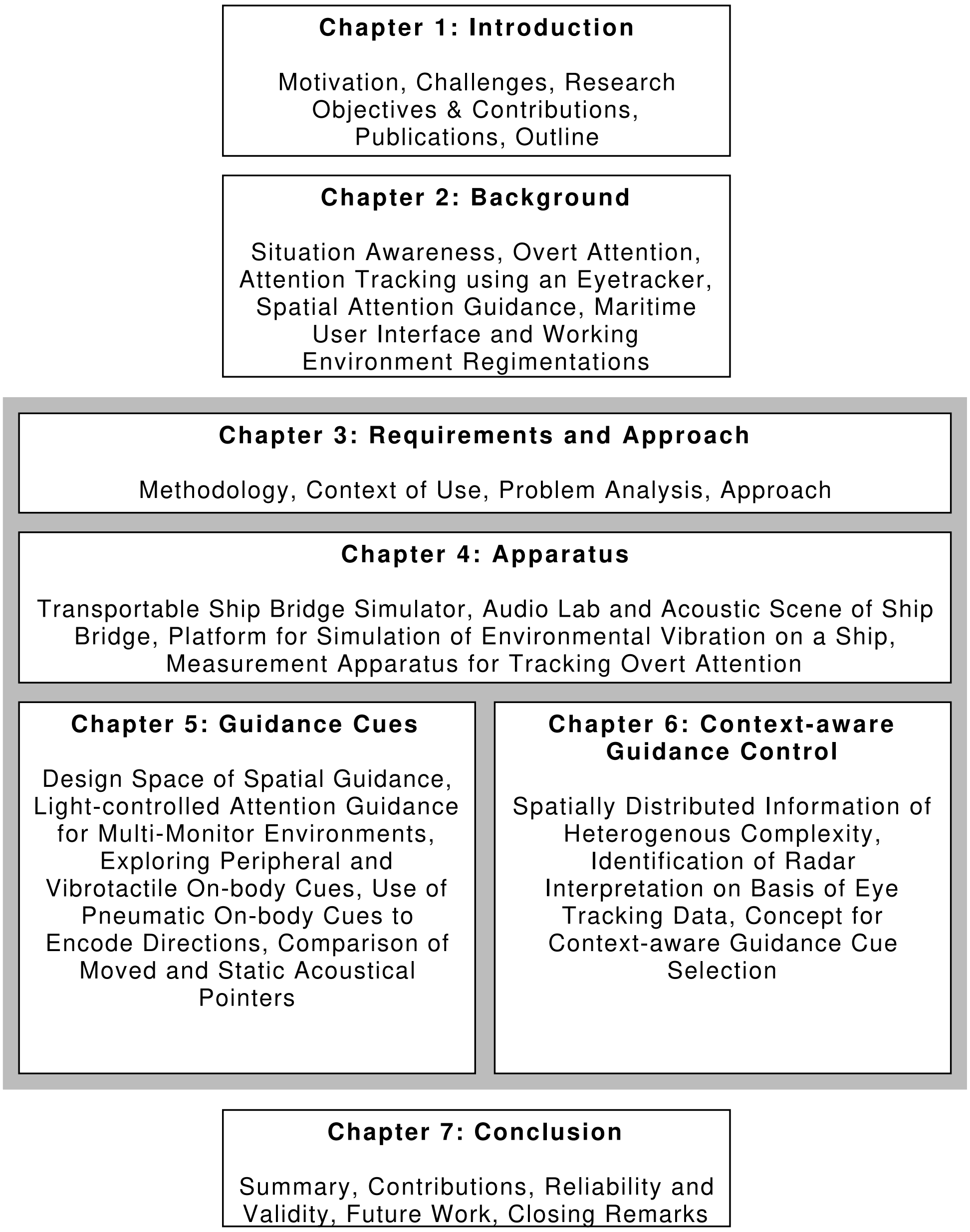


Figure 1.2: Overview of the thesis structure.

2 Background

This chapter introduces concepts and related work on which this work is based on. Starting with a definition of Situation Awareness, followed by models of attention, and how attention can be tracked, the chapter closes with related work about attention guidance and relevant regimentations in the maritime domain.

2.1 Situation Awareness

Stanton et al. state that there are three perspectives on Situation Awareness (SA), a psychology, engineering, and systems ergonomics perspective [SSWJ10]. According to them, the psychology perspective is that SA only exists in the minds of people in an system, which means it is the SA of the individual, where the SA of a team would be the sum of their individual SAs (cf. [End95]). The engineering perspective puts situation awareness in the world, which means it is represented in the objects that people interact with. The systems ergonomics perspective proposes that SA works like a distributed cognition of interaction between people and their artefacts in the world. Stanton et al. further conclude that that the distributed cognition perspective of SA offers the most comprehensive explanation of the phenomena observed in socio-technical systems.

The ship bridge is a socio-technical system and the concept of Distributed Situation Awareness [SSH$^+$06] has been applied in the maritime domain before [Den15]. However, the focus of this work is to increase the SA of the decision maker. Further, Kozlov et al. found that in situations, where the an external representation of the knowledge of an collaborator is available, it is faster to obtain the knowledge from it than through interaction with the collaborator [KEBH15]. Therefore, we consider the concept of individual SA, which will be further elaborated in the following.

The current Situation Awareness (SA) of an operator is defined by his or her monitoring of the situation. Mica R. Endsley defined Situation Awareness as "the *perception* of the elements of the environment within a volume of time and space, the *comprehension* of their meaning, and the *projection* of their status in the near future" [End95, p. 36]. "It is a state of knowledge about a dynamic environment" [End00, p. 25]. Endsley also presents a model for Situation Awareness based on three consecutive levels (see Figure 2.1). The model was reviewed in 2000 by herself, and in 2008 by Christopher D. Wickens, who found that "Situation awareness is a viable and important construct that still possesses some controversy over measurement issues" [Wic08]. As Situation Awareness is a state of knowledge at a point in time, it is hard to measure, therefore measurement methods vary from real-time probe techniques such as the Situation Present Assessment Method (SPAM) [DHT$^+$98], over freeze freeze probe techniques such as the Situation Awareness Global Assessment Technique

(SAGAT) [End17] to posthoc questionnaries such as the Situation Awareness Rating Technique (SART) [Tay90].

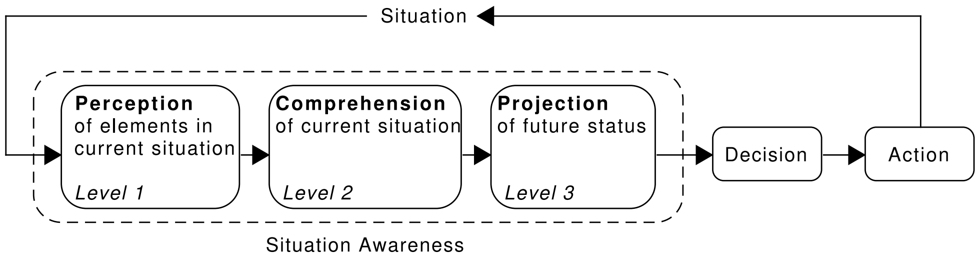


Figure 2.1: Situation Awareness as part of the dynamic decision making process.

Since the levels of Situation Awareness build on each other, level 1, i.e. the perception of all relevant elements in the environment in context, is the most important factor for Situation Awareness in Endsley's model. If the elements are not perceived, they cannot be understood. Level 2 contains the understanding of the elements in the environment. This also includes the understanding of the connections between different information. Only if the elements are understood correctly, a prediction of their state in the near future (level 3) is possible. This is an important aspect for making decisions that promise the best possible result for the future.

According to Endsley, time is an important factor for the Situation Awareness of levels 2 and 3. For example, this is important when an operator has to assess when an approaching object plays a role in the situation. Furthermore, it is important to know the maximum time interval at which information needs to be updated so that it is still sufficiently up-to-date. In addition, dynamic systems often have time-dependent events.

The Situation Awareness can be seen as an internal image that the operator forms of the situation. It, therefore, plays an important role in making decisions. Nevertheless, Endsley has consciously separated decision-making from Situation Awareness in her model. This is justified by the fact that bad decisions can also be made although a perfect Situation Awareness exists. On the other hand, it is also possible that good decisions are made despite inadequate Situation Awareness, even if this only happens by a happy coincidence.

Demons of Situation Awareness

In 1999 Endsley introduced a taxonomy of Situation Awareness errors [End99]. This taxonomy later led to the definition of the so-called Demons of Situation Awareness (SA Demons) [EJ11]. The SA Demons stand for eight common causes for a lack of Situation Awareness. They address all three levels of Situation

Awareness. The following list[1] describes each SA Demon and states the Situation Awareness levels it affects.

SAD 1 **Attention Tunneling** *(SA level 1)*
Good Situation Awareness is dependent on switching attention among multiple data streams. Locking in on certain data sources and excluding others is attention tunneling.

SAD 2 **Requisite Memory Trap** *(SA level 2)*
The working memory processes and holds chunks of data to support Situation Awareness level 2. The working memory is a limited resource. Systems that rely on robust memory do not support the user.

SAD 3 **Workload, Anxiety, Fatigue, and other Stressors** *(SA level 1 and 2)*
Stress and anxiety are likely issues in the warning environment. *WAFOS* taxes attention and working memory.

SAD 4 **Data Overload** *(SA level 1)*
There is more data available than can be processed by the human ”bandwidth”.

SAD 5 **Misplaced Salience** *(SA level 1)*
Salience is the ”compellingness” of a piece of data, often dependent on how it is presented.

SAD 6 **Complexity Creep** *(SA level 1, 2 and 3)*
Complexity slows down the perception of information and it undermines the understanding and the projection of information.

SAD 7 **Errant Mental Models** *(SA level 2 and 3)*
Wrong mental model may result in incorrect interpretation of data.

SAD 8 **Out-of-the-loop syndrome** *(SA level 1)*
For example: Automated systems that do not involve the human until there is a problem.

2.2 Overt Attention

Overt attention is defined as a person's attention that is in the range of what the person is looking at. Covert attention means that a person looks at something but the attention is on something else [Pos80]. Michael Posner defined attention as a spotlight ([PRSJD80]). This theory states that visual attention is limited only to a certain area of defined size (also called *location-based attention* or *spatial*

[1] based on: `http://web.archive.org/web/20170829043555/http://www.au.af.mil/au/awc/awcgate/noaa/anti_situation_awareness.pdf`

attention). Within this cone of light, attention is particularly efficient, stimuli can be processed quickly and accurately. An alternative proposed by Eriksen and St. James is the zoom-lens metaphor [ESJ86] which suggests that the attentional focus is variable in size. The gradient model [LB89] theorizes that the attentional focus gradually decreases the further away from the center of the attentional focus a stimulus appears.

In his work "Selective Attention and the Organization of Visual Information" (see [Dun84]) in 1984 John Duncan for the first time provided evidence that a *object-based attention* also exists. He states that attention can also be directed to a single object instead of to a spatial surface.

A third type is *dimension-based attention*. This theory states that selection is limited by differences between dimensions of attributes (e.g. shape and color). Building on this theory, the dimension weighting approach was developed by Müller et al. (see [HJM95]). Accordingly, it is possible to assign a weight to object dimensions, whereby the total amount of weight is limited. If, for example, the shape dimension is highly weighted, it is easier to process the shapes for all objects. The processing of other object attributes (such as color), on the other hand, is impaired because the total weight is limited and therefore only a subordinate role remains.

SEEV Model of Selective Attention

The SEEV model by Wickens et al. is a model of selective attention [WHG+01]. SEEV stands for salience, effort, expectancy, and value. Salience is the bottom-up attention-capturing property of events, such as bright flashes or sounds. Effort in the model means the effort of moving attention across longer distances, e.g. bigger scans, and head movements. Expectancy means the likelihood of seeing an event at a particular location, it is a top-down cognitive factor that is calibrated to the frequency of occurrence of events that happen at that location. Value is the top-down importance of tasks served by the attended event, as well as the relevance of the event to the valued task. From these four factors, the SEEV model can calculate a probability of attending a certain AOI.

Multiple-Resource Theory

Wickens' Multiple-Resource Theory(MRT) [Wic91] states that humans have several different pools of cognitive resources. Figure 2.2 visualizes the resource pools. The capability of humans to process information is limited. According to Wickens' MRT, this leads to errors and slower task performances, if resources from the same pool of cognitive resources are used by several tasks simultaneously. For the design of guidance cues, this means that cues should use different pools of cognitive resources than the typical tasks of an operator to mitigate potential errors or performance reductions due to overload.

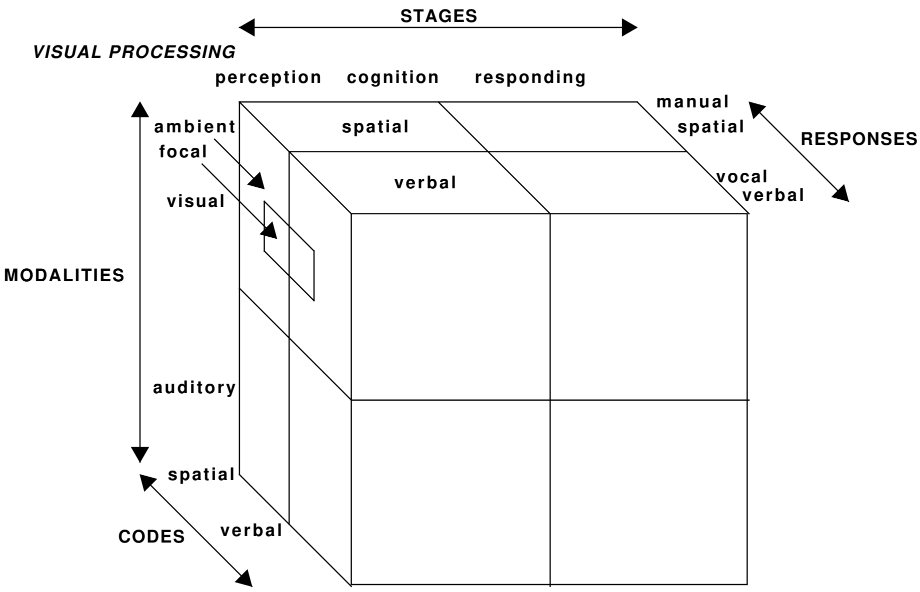


Figure 2.2: Three-dimensional representation of the structure of multiple resources. The fourth dimension (visual processing) is nested within visual resources (cf. [Wic91]).

2.3 Attention Tracking using an Eye Tracker

Eye trackers are camera-based devices that track the gaze of a person in a scene. There are two common types of gaze trackers, head-worn and stationary systems.

2.3.1 Eye-Mind-Hypothesis

A person's eye movements can be recorded by an eye tracker to evaluate his or her attention distribution. It is assumed that the person also perceives the information he or she fixates on. This assumption is called *Eye-Mind Hypothesis* [GLCR06]. Through this method, situational perception, i.e. the perception of the elements in the environment, can be assessed. This has, as already described in Section 2.1, a strong influence on the whole Situation Awareness. The certainty that the *Eye-Mind Hypothesis* applies in every case is not given. The fixation of an element without actually perceiving it is called *looked-but-failed-to-see-phenomen* [Bro02], compare covert attention as mentioned earlier. However, information gaps can be uncovered in any case, since the operator cannot perceive information if he does not fixate it.

2.3.2 Attention Tracking

Our gaze reveals our overt attention. Tracking the gaze of a user allows us to objectively measure if, in which order, and how fast something is perceived. An eye tracker can be used to measure fixations and saccades. A fixation is a condition in which the eyes are almost still while information is being recorded. This state lasts about 200 to 300 ms [Ray98]. A saccade, on the other hand, refers to the rapid movement of the eyes between two fixations. Further information on various metrics that can be derived from fixations and saccades can be found in Poole and Ball [PB06]. To derive information from fixations and saccades, Areas of Interest (AOI) can be defined. AOI are areas from which certain information can be derived when a fixation is detected. For example, a visual display that represents information can be defined as AOI. If a fixation is recognized in this, then it can be assumed that the corresponding information was perceived (*Eye-Mind Hypothesis*, see Subsection 2.3.1). Another information that can be obtained by using an eye tracker is the dwell time. The dwell time describes the duration of a gaze dwelling within an AOI. The time to first fixation (TTFF) is another common gaze metric, it measures the time between stimulus onset and the first fixation in the targeted AOI. Further, the gaze path, the chronological path between fixations can reveal patterns and the sequence of AOIs in the gaze path can give insights into subconscious workflows.

Poole and Ball also point out limitations of eye tracker technologies [PB06]. For example, the calibration, especially of head-mounted eye trackers, is typically quite sensitive and may need to be recalibrated during a scenario. Also, glasses or contact lenses can cause problems with pupil detection. Eye trackers are also not arbitrarily accurate, so the readings from different devices may differ. Because eye trackers produce large amounts of data, data filtering should be automated to save time and avoid errors.

2.4 Spatial Attention Guidance

Spatial Attention Guidance is the spatial reorientation of overt attention (cf. Section 2.2) triggered and guided by cues. Orienting attention can be controlled through exogenous or endogenous processes. Exogenous orienting is being under control of a stimulus by a reflexive reaction to sudden change in the periphery [MDRS04]. Endogenous orienting on the other hand is the intentional allocation of attention to a predetermined location or space. Findings by Trujillo et al. showed that 24 hours of sleep deprivation affected exogenously driven selective attention to a lower degree than it affected endogenously driven selective attention [TKS09]. Therefore, exogenous cues have a higher chance at succeeding in guiding the selective attention of fatigued operators than endogenous cues.

In the following, we will list and describe related work dealing with systems and strategies to guide and spatially reallocate attention. Each section in Chapter 5 and Chapter 6 that is linked to a publication, contains an own related work subsection, as these include work that is especially relevant to the respective topic. The same applies to Subsection 3.3.1.

Name/Reference	Modality	Cue location
Guiding Attention in Controlled Real-world Environments [BSM+13]	visual	environment
Ambient Light As Spatial Attention Guidance in Indoor Environments [TLTLH16]	visual	environment
Attention guiding techniques using peripheral vision and eye tracking for feedback in augmented-reality-based assistance systems [RP17]	visual	onbody
Subtle gaze guidance for immersive environments [GSEM17]	visual	onbody
HapticHead: A Spherical Vibrotactile Grid Around the Head for 3D Guidance in Virtual and Augmented Reality [KR17]	tactile	onbody
Good Vibrations: Tactile Feedback in Support of Attention Allocation and Human-Automation Coordination in Event-Driven Domains [SS99]	tactile	onbody
Guiding Visual Search Tasks Using Gaze-contingent Auditory Feedback [LRZP14]	auditory	onbody
Investigating Different Modalities of Directional Cues for Multi-task Visual-searching Scenario in Virtual Reality [CWZ18]	visual, auditory, tactile	onbody

Table 2.1: Overview of related work for spatial attention guidance and design space classification.

Table 2.1 offers an overview of the related work for spatial attention guidance categorized by modality and cue location. Note that the cue location reflects the actual physical location the cue is rendered at. This takes the limitations of display technologies into account. For example, current head-worn Augmented Reality (AR) devices do not allow for correct accommodation of the eye, as all virtual content is rendered on a display at a fixed distance to the eye. Therefore, the cue location on these head-worn AR devices is always onbody, in contrast to projected AR.

In recent years, there has been a body of work researching attention guidance in Virtual Reality (VR). Many of these works are motivated by the technical limitations of today's VR technology, such as a small field of view. In addition to the demand for guidance strategies in VR applications, such as games and VR cinema, VR also offers a large design space for various approaches that are not transferable to the real world. Some examples for such strategies are forced rotation [NMH+16], blurring everything but the target region [ST13], and rendering target objects only on one eye [KCWK19]. However, these strategies are not transferable to the real world. In the following, we will only discuss related work in VR, if the results are technically transferable to the real world, especially the maritime domain.

2.5 Maritime User Interface and Working Environment Regimentations

The International Maritime Organization[2] (IMO) laid down rules for maritime user interfaces, systems, and assistance systems, e.g. night view mode for displays and defined parameters for the working environment, e.g. noise limits. Most of these rules are documented in IMO Resolutions by the Maritime Safety Committee (MSC). We identified the following relevant resolutions for multimodal attention guidance: Guidelines on Ergonomic Criteria for Bridge Equipment and Layout [Mar00], Bridge Navigational Watch Alarm System (BNWAS) [Mar02], and Noise Levels on Board Ships [Mar12]. Further, we found the ISO Standard 6954 - Mechanical vibration – Guidelines for the measurement, reporting and evaluation of vibration with regard to habitability on passenger and merchant ships [ISO00] and the report Ship Vibration and Noise – Guidance Notes by the Lloyd's Register [Fil06] of relevance. As of December 2016, ISO 6954 has been deprecated and merged as Part 5 into ISO 20283 [ISO16]. However, as the measurements by the Lloyd's Register are based on it, and there were no relevant changes, we kept to it.

We derived the following parameters from these regimentations: cue placement, noise limits, vibration strength, dim-able lights, audio signal max volume, and speech intelligibility (cf. Chapter 5).

[2] `http://www.imo.org/en/Pages/Default.aspx`, last retrieved: July 5, 2021

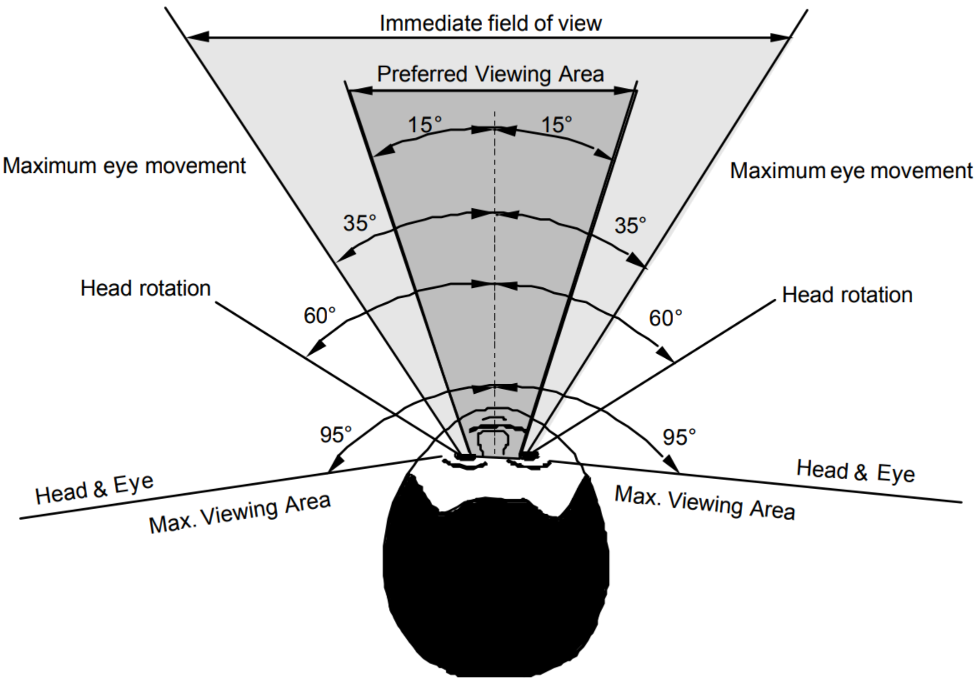


Figure 2.3: The preferred viewing area and the immediate field of view are reserved for information from displays and should not be occluded [Mar00, Fig. 5.1].

2.6 Summary

In this chapter, we provided an introduction to the relevant basics and concepts that are necessary to fully comprehend the presented work. We elaborated the concepts of Situation Awareness, overt attention, and spatial attention guidance. Further, we explained how attention can be tracked using an eye tracker and referenced relevant maritime user interface and working environment regimentations and standards.

3 Requirements and Approach

This chapter is partly based on the following publication:

- Stratmann, Tim Claudius, and Boll, Susanne. ”Demon Hunt - The Role of Endsley’s Demons of Situation Awareness in Maritime Accidents”. Proceedings of the 8th International Working Conference on Human Error, Safety, and System Development. Springer International Publishing, 2016.

3.1 Methodology

In this work, we follow a mix of methodologies. However, we mainly follow a user-centered approach using methods from the Human-Centered and Activity-Centered Design approaches. Both methodologies implement the scientific process (requirements, design, implementation, evaluation). Further, we always applied a systematic approach using widely established methods, such as contextual inquiry, goal-directed-task-analysis (GDTA) [EBJ03], activity analysis, scenario, Wizard of Oz, experimental research (experimental HCI), user studies, interviews, and questionnaires. We make use of established standardized questionnaires, such as the System Usability Scale (SUS) [Bro96], the NASA Task Load Index (NASA-TLX) [Har06], and the Situation Awareness Rating Technique (SART) [Tay90].

3.1.1 Human-Centred-Design (HCD)

Human-Centred-Design (HCD) is a standardized approach documented in ISO 9241-210:2019: Ergonomics of human-system interaction - Part 210: Human-centred design for interactive systems [ISO19]. HCD evolved from the first user-centered design approaches presented in 1986 by Donald A. Norman and Stephen W. Draper in their book ”User Centered System Design: New Perspectives on Human-computer Interaction” [ND86]. It follows a circular design process consisting of four phases: specify context of use, specify requirements, produce design solutions, and evaluate designs. The most important part of HCD is the user participation in every step of the process, e.g. through participative design.

Our main source of insights are lab experiments with human participants. A further method in human-computer interaction that we use in some of these experiments is the Wizard of Oz prototype, where the functionality of the system is mocked and controlled be a human. This is hidden to the Participant, who interacts with the system as though it would be fully implemented. This method has the advantage that interactions between humans and computer systems can be evaluated without spending time on the implementation of these, which allows for faster iterations and improvements of the design befor the actual implementation.

In 2015, the Maritime Safety Committee (MSC) of the International Maritime Organization (IMO) has approved the "MSC.1/Circular.1512 - Guideline on Software Quality Assurance and Human Centred-Design for E-Navigation" [Mar15] that recommends a Human-Centred-Design Cycle for the development of maritime applications and systems.

One of the critiques of HCD come from Donald A. Norman himself [Nor05]. He states that HCD has a limited view of design and that it should take a larger view focusing more on the entire activity of the user. To cope with his concerns, we couple our HCD approach with methods from Activity-Centered-Design and perform task analyses. These give insights into workflows, goals, involved tools, actors, rules, and necessary information.

3.1.2 Activity-Centered-Design (ACD): Activity Analysis

From the methodology of Activity-Centered-Design (ACD), we mainly use the activity analysis approach to complement our HCD approach. To assess what actors, tools, and rules are involved in the activities of collision avoidance and grounding, as well as, how the community is structured and how tasks are divided between actors, we applied the concept of activity analyses from the activity-centered design approach [GH04]. Figure 3.1 shows a template for an activity diagram, displaying the interactions between the aforementioned factors. Table 3.1 lists the corresponding questions asked in the process of activity analysis that are used to fill the diagram.

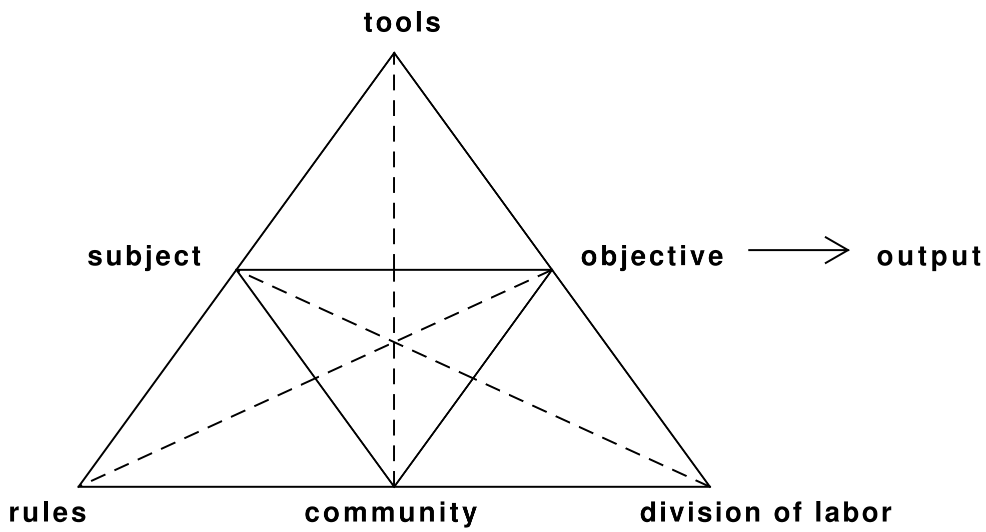


Figure 3.1: Activity diagram template (cf. [GH04]).

activity	What sort of activity?
object(ive)	Why is the activity taking place?
subjects	Who is involved?
tools	What means are used in performing the activity?
rules and regulations	Are there any cultural norms, rules or regulations?
division of labor	Who are responsible for what and are those roles organised?
community	What is the environment in which this activity is being carried out?
outcomes	What is the desired outcome?

Table 3.1: corresponding questions asked in the process of activity analysis that are used to fill the diagram.

Further, we applied goal-directed task analysis (GDTA) [EBJ03] to gain insights into the hierarchy of goals, decisions and related information requirements of the decision maker for a given scenario. The goal of this method is to identify the Situation Awareness requirements of a scenario through cognitive task analysis.

3.2 Context of Use

The Assessment of the context of use is an essential part of the HCD Methodology. Therefore, we combined multiple sources of knowledge to get an adequate assessment. We started with a literature and completed with first-hand experience in simulator training, an contextual inquiry on a 2999 GT bulk carrier, and a focus group with maritime HCI and human factors experts.

3.2.1 Analysis of Systems and Workflows on Ship Bridges

In the following a short insight into the maritime environment and in particular into the ship bridge is given. In this context, important sources of information as well as the duties and responsibilities of the watch officer are presented. The aim is to create an understanding of the working environment on a ship's bridge.

According to Gauss and Kersandt [GK05] the main tasks of a watch officer are *planning*, *communication*, *management*, and *navigation/nautics*. The *planning* includes the preparation of a voyage plan taking into account ship characteristics, crew, cargo, the state of the environment as well as time and financial restrictions. The *communication* includes the exchange of information with other ships as well as within the ship. The *management* includes monitoring, control and steering operations. Furthermore, it includes risk assessment as well as the resulting decisions and their implementation. The *navigation/nautics* contains the monitoring of traffic, environment as well as the planned shipping route.

In the context of this work the tasks of the *communication*, the *management* and the *navigation/nautics* are of importance above all, since these are accomplished by the watch officer during his guard. To perform these tasks, the watch officer needs appropriate information that can be taken from different sources of information. In Figure 3.2 the ship bridge of the Research Vessel Sikuliaq is exemplarily represented. The following is a brief overview of the most important sources of information on a ship bridge according to Gauss and Kersandt.

Figure 3.2: The ship's bridge of research vessel Sikuliaq
(`https://commons.wikimedia.org/wiki/File:Bridge_of_the_RV_Sikuliaq.jpg`)

Radar Dynamic information such as positions of other ships, buoys, and coastlines can be taken from the radar. It can, however, be disturbed by external influences such as the weather.

Sea charts & ECDIS Sea charts contain static information about areas such as water depths, sailing areas, and the positions of tons. Nowadays electronic nautical charts are often used, which offer additional functions compared to classical nautical charts. These electronic charts are part of the Electronic Chart Display and Information System (ECDIS) that combines zoomable charts with additional environmental information and sensor data, such as position, heading, speed from GPS or sonar, and can sometimes even overlay radar data.

Window Despite many technical possibilities, windows are still one of the main sources of information on a ship's bridge. For example, information about the condition and position of other ships, navigation marks, coastlines, and the movement of one's ship can be taken from them. In contrast to all other information sources on the ship's bridge, the window offers direct information that does not have to be processed electronically or mechanically.

Radiotelephony (VHF) Radiotelephony enables communication with other ships, with the port, and with other interlocutors.

Central console Information such as course, speed, wind, turning speed, and rudder angle can be taken from the central console.

Steering position The steering position shows the desired and actual course, as well as the rudder angle and the rate of turn. The steering position also contains the autopilot, which displays the currently programmed course.

It should be noted that the instruments and screens on a ship's bridge are often not located directly next to each other. Rather, they are distributed over the entire bridge. Accordingly, the watch officer sometimes has to move to be able to perceive various information.

Controlling a ship is the interaction between operators (humans), controls and information displays of the ship bridge (machine). Figure 3.3 sketches an overview of the situation on a ship bridge.

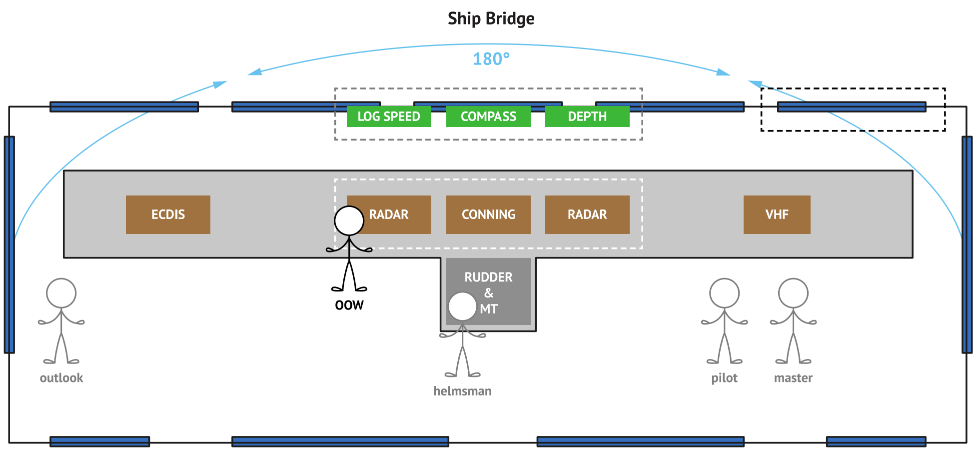


Figure 3.3: Ship bridge, maximum personnel, marked example entities per information location: (1) white box; (2) black box; (3) gray box.

OOW As the decision-making process on ships still follows a strongly hierarchical structure, only one person, the officer of the watch (OOW) makes decisions, therefore he or she has to have a full overview of the situation. The OOW could either be a mate or the master, depending on the situation and work shift. The OOW on a ship bridge can move around freely. His position may differ from time to time, nevertheless, there are areas he inhabits more often and regularly. Besides his position, his orientation may also differ, e.g. when looking outside a window at the side or back of the bridge.

Helmsman The Helmsman is responsible for steering and controlling the ships speed. It is his or her responsibility the change and maintain heading and speed of the vessel as instructed by the OOW.

Outlook The outlook watches the ships environment in situations where the OOW is already visually occupied or cannot be in a suitable location and reports the observed situation verbally to the OOW. Often the communication channel is radiotelephony.

Pilot The pilot is an expert for a certain coastal area that comes on board the ship to assist the passage of the respective area. After the passage he or she leaves the ship again.

Master/Mate The master bears the ultimate responsibility for the safety of his or her ship, crew, and the causes of implemented actions. Meanwhile, the mate only bears this responsibility during his or her shift.

Ship Bridge The ship bridge is a large and wide room that is typically the same width as the beam of the ship. Currently, the largest container vessel has a beam of 60 meters. On modern ships, the information that has to be monitored by the operator is located in three different groups: (1) information displays in the integrated bridge, (2) the bridges' windows, (3) displays above front windows (cf. Figure 3.3). There are confounding variables in the environment: Changing lighting conditions (e.g. glaring sun, day/night), auditory and vibrational noise (e.g. ship engine, weather). Further, there is subordinate personnel on the bridge. Acoustical alarms and radio communications happen from time to time.

Information Displays We define information displays as any visual source of information, that is relevant for the safe maneuvering of the ship. This includes windows for lookout, displays with high information complexity, such as the radar or ECDIS, and displays with low information complexity, such as the compass.

Training to avoid Human Error The second attachment to the International Convention on Standards of Training, Certification, and Watchkeeping for Seafarers (STCW) from 1978 in 2010 introduced Bridge Resource Management into the mandatory minimum requirements for certification of officers in charge of a navigational watch on ships of 500 gross tonnage or more [Int10, Reg. A-II/1]. According to the STCW, the knowledge of Bridge Resource Management principles includes the allocation, assignment, and prioritization of resources; effective communication; assertiveness and leadership; obtaining and maintaining situational awareness; and the consideration of team experience. Although, making this training mandatory was a good step in the right direction, its effectiveness and its impact on the number of accidents caused by human error is still unclear [O'C11, YS12].

3.2.2 Contextual Inquiry

Theory and practice often differ a lot. This is why we conducted two contextual inquiries. First, we visited a 2999 GT general cargo ship, the *Orcana*, at the port of Antwerp on the 29th of September 2015. Second, we did observations of mariners in training during simulator maneuvering training at the Jade University of Applied Sciences in Elsfleth and consecutively participated in such training.

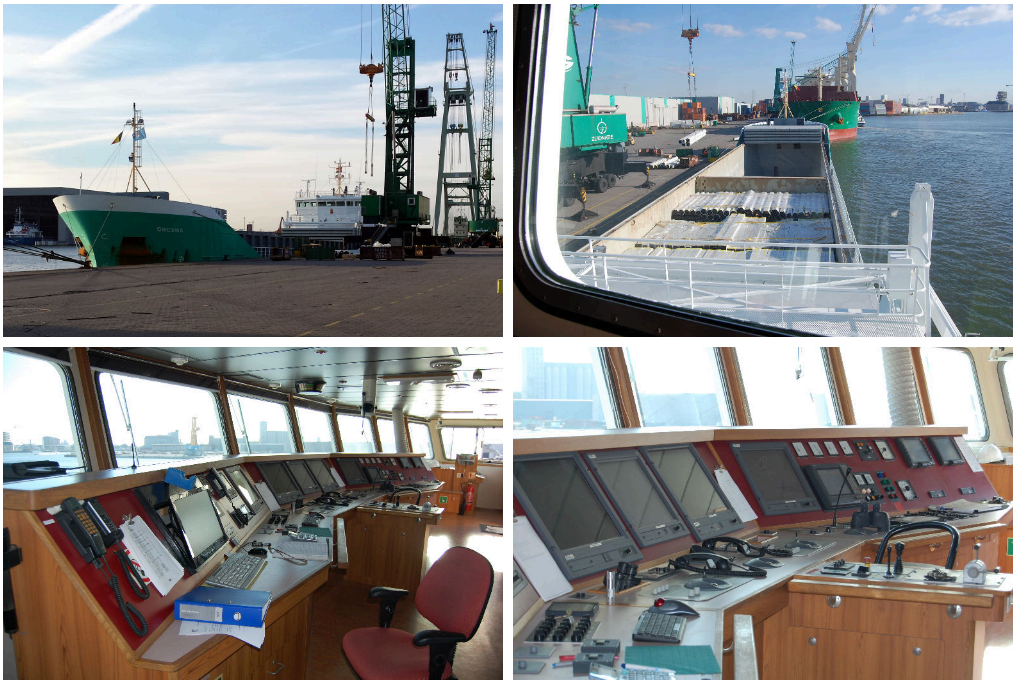


Figure 3.4: Photos of the Orcana in the port of Antwerp.

During our visit of the *Orcana*, we got a full tour of the ship and its systems, with a special focus on the ship's bridge. We took photos and sound recordings of the bridge alarm. One thing we noticed immediately when taking photos, was that the changing light conditions affected the salience of display content. After the tour, we conducted a semi-structured interview with the first mate of the ship. The structured part of the interview focused on state-of-the-art monitoring support systems and an activity analysis [ME03] for collision and grounding avoidance since these are the major accident types based on human error [Fed20] (see Problem Analysis). Figure 3.5 and Figure 3.6 show the results of our activity analysis for collision and grounding avoidance. In the unstructured part of the interview, the interviewee described two situations in which he had experienced potentially dangerous situations due to a lack in situation awareness.

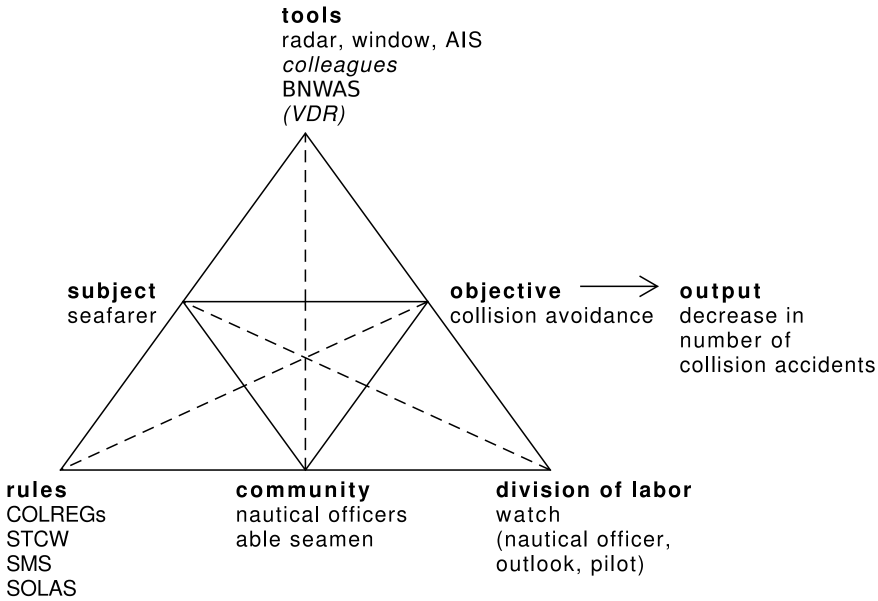


Figure 3.5: Activity diagram for the avoidance of collisions.

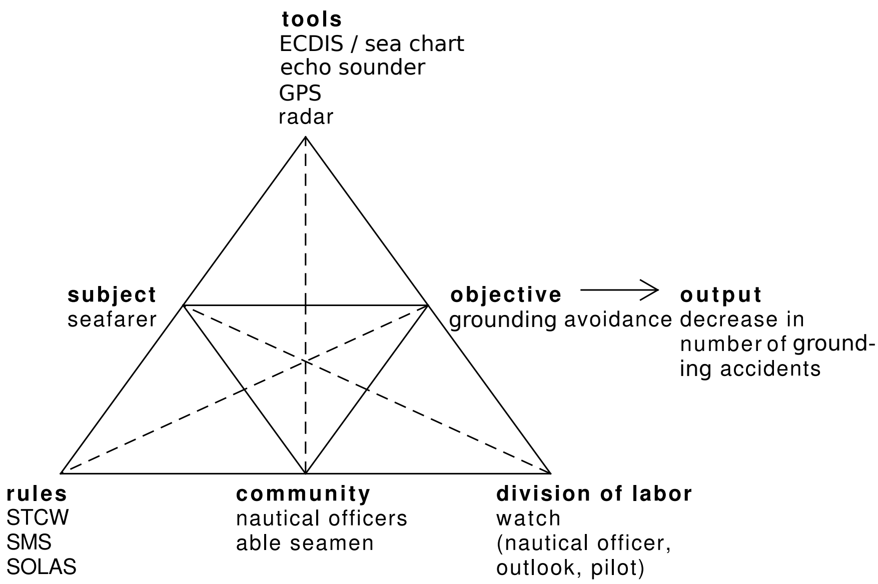


Figure 3.6: Activity diagrams for the avoidance of groundings.

3.2.3 Focus Group: Spatial Attention Shift

In a focus group with three maritime HCI experts and two human factors experts (mean working experience 5 years), we identified in which situations spatial attention guidance might be an effective approach. To come up with a list of situations, we used the 6-3-5 Brainwriting method [Rho69]. Afterwards, the situations were clustered by the participants, resulting in the following clusters: Occurrence of unexpected events, task resumption, the balance of task over- and underload, overwhelming situations (e.g. high workload), support of regular monitoring, upcoming or missed tasks, missing information, and distractions. Further, we found that it should be assured that human-to-human communication is always possible and that it might be counter-productive to shift the attention if the current task is almost finished.

3.3 Problem Analysis

From literature, we know that a lack of Situation Awareness is the most common cause for human error in maritime accidents [GHS02, BM05, Zia06]. Figure 3.7 shows the average amount of decision making and decision implementation time lost to obtaining Situation Awareness during near accidents as found by Psarros [Psa15].

He found that the time to implement a prevention action without creating mental stress amounted to about 5 minutes for near collisions and about 8.7 minutes for near groundings. The time slice to gain necessary Situation Awareness amounted to 2.3 minutes for collisions and 2.9 minutes for groundings. A monitoring support system could open the bottleneck of information perception (SA Level 1) by keeping the human in the loop and thereby minimizing the amount of time associated with gaining Situation Awareness. This would free more time for decision-making and decision implementation.

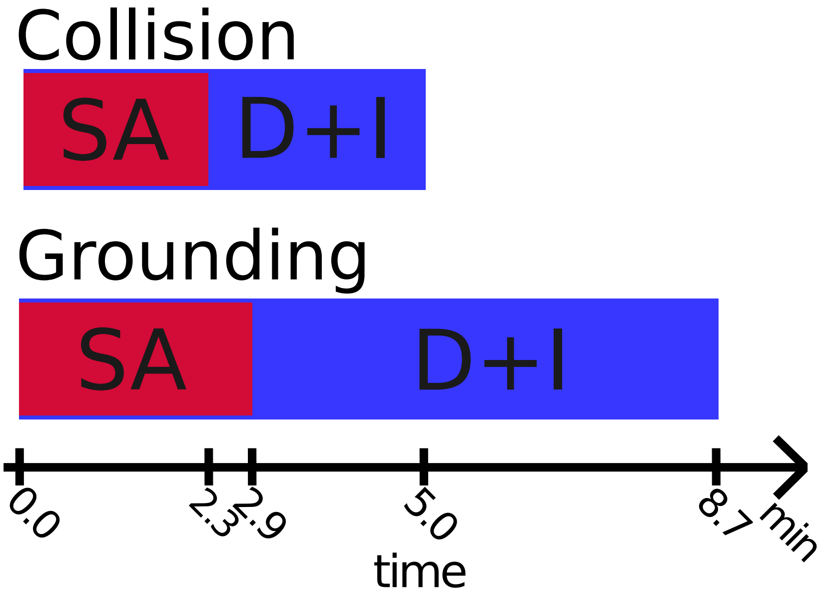


Figure 3.7: Average time for gaining situation awareness, making a decision, and implementing the decision for collision avoidance and avoidance of grounding [Psa15].

3.3.1 The Role of Endsley's Demons of Situation Awareness in Maritime Accidents

As mentioned before, human error is the cause of most maritime accidents and in a majority of the cases, the source of the human error is a lack of Situation Awareness. Endsley et al. have identified eight causes that corrupt the Situation Awareness of human operators, the so-called Demons of Situation Awareness (SA Demons). We analyzed over five-hundred maritime accident reports for each of the eight SA Demons to provide a ranking of the causes and to identify the most prominent ones. Addressing these SA Demons enables maritime system designers to enhance the Situation Awareness of maritime operators and thereby improves safety at sea. Moreover, we provide our corpus of 1376 maritime accident reports and perform our analysis on a subset of it. We investigate the occurrences and distribution of the eight SA Demons in a corpus of 535 maritime accident reports. Information about occurrences and distribution of the SA Demons enables maritime system designers to adjust their systems to the SA-related needs of the operator and to build assistance systems that focus on mitigating the specific cause of SA errors.

3.3.1.1 Related Work

Most scientific accident analyses in the maritime domain focus on the statistical classification of error causes, whereas the investigations of safety authorities focus on deriving guidelines to prevent the same accidents from happening again. Human error as the cause of maritime accidents is no new phenomenon. As long ago as 1987 Wagenaar et al. analyzed 100 maritime accidents, of which 96 were caused by human error [WG87].

In 2005 Baker et al. published their three-year enduring analysis of maritime accidents from the United States, Australia, Canada, Norway, and the United Kingdom. Their results show that the frequency of accidents is declining, but that human error continues to be the dominant factor in approximately 80 to 85% of maritime accidents [BS04, BM05]. According to their findings, failures in Situation Awareness are a causal factor in the majority of accidents attributed to human error. They identified some significant factors associated with Situation Awareness failures which include: Cognitive and decision errors, Knowledge-Skill-Ability errors, task omissions, and risk-taking. They expect most of them to be artifacts of fatigue.

Antão et al. used BNN models to analyse maritime accidents [AGSGT09]. Other work dealing with human error in maritime accidents is [dlCP05], [CLM+13], [Koe01] and [Rot00].

3.3.1.2 Corpus

Authority	MAIB	NTSB	USCG	ATSB	TSBC
# Reports	535	152	202	80	407
Period	1989-2015	1994-2015	2005-2015	1987-2015	1990-2015
Country	Great Britain	USA	USA	Australia	Canada

Table 3.2: This table gives an overview of the retrieved corpus. The table shows the total number of available full-text reports, the time period covered by the reports and the country of origin. *(last update: April 15, 2016)*

Performing an analysis on specific SA error causes requires a data source with a high level of detail. Therefore we retrieved full-text reports of maritime accident investigations. The full corpus consists of 1376 maritime accident reports from five transportation safety authorities between the years 1987 and 2015. The reports were gathered from the British Marine Accident Investigation Branch (MAIB)[1], the American National Transportation Safety Board (NTSB)[2],the United States

[1] https://www.gov.uk/government/organisations/marine-accident-investigation-branch

[2] http://www.ntsb.gov/investigations/accidentreports/pages/accidentreports.aspx

Coast Guard (USCG)[3], the Australian Transportation Safety Board (ATSB)[4] and the Transportation Safety Board of Canada (TSBC)[5].

We specifically chose authorities from these countries, because they have English as their first language and a high number of available full-text reports. We share our full corpus on request to support further research in this area. For our following analysis, we focused on the MAIB sub-corpus, but we intend to apply the same method of analysis to the whole corpus in the future.

3.3.1.3 Analysis

The MAIB corpus consists of over five hundred accident reports. To classify these accident reports we applied a request-oriented classification approach. We used boolean queries to perform a full-text search on all documents in the corpus. Beforehand the corpus had to be prepared and a list of keywords had to be created to build meaningful queries. The preparation of the corpus is described in the following. Thereafter we describe the generation of keywords and our classification method.

Preparation

To perform an analysis on the gathered corpus of accident reports some pre-processing of the corpus is necessary. We gathered full-text maritime accident reports in English and PDF-format from five transportation safety authorities. As preparation for the analysis, we extracted the plain-text from the reports in PDF-format and performed simple cleaning of the reports by removing the front page and fixing character encoding issues. Further, we converted the reports to lowercase to simplify the case-insensitive search. As some reports consisted of several files we merged these documents into one. After this preparation one document represents one accident.

For the exploration of the corpus, we created a document-term-matrix of the corpus and checked the most frequent terms. Furthermore, this enabled us to check term correlations in the corpus. We used R version 3.2.4 with several text-mining packages to perform this. The creation of the document-term-matrix requires some further pre-processing in R. The following pre-processing steps were conducted on the data-frame in R, only. We removed URLs, punctuation, numbers, standard English stop-words, and some custom stop-words from the corpus. From the pre-processed corpus we created a tf-idf-weighted document-term-matrix. Figure 2 shows a word cloud of the one hundred most frequent terms in the corpus.

[3] `http://www.uscg.mil/`
[4] `https://www.atsb.gov.au/marine/`
[5] `http://www.tsb.gc.ca/eng/rapports-reports/marine/index.asp`

Generation of Keywords

A list of keywords for each SA Demon was created. The selected keywords were derived from the description of the SA Demons and examples from [EJ11] and keywords identified during the exploration of the corpus. The keyword list was complemented with fitting synonyms of the keywords using wordnet [Mil95].

A meaningful choice of keywords and the proper construction of the boolean queries is critical to the success of the retrieval. Adjusting the query based on the exploration of the corpus always bears the danger of overfitting the queries to the specific corpus. Furthermore, the composition of the queries directly influences the precision and recall of the retrieval. Although we did not measure the recall, we tried to achieve a good balance between precision and recall.

The iterative exploration of the corpus showed unexpected usage of keywords, such as 'fatigue' in 'fatigue wear' of machine parts. The identification of these negative keyword combinations helped us to increase the precision of our search queries. We increased the recall of the query by reducing the keywords in the queries to their stems. The aim was to create a list of queries that can be applied to any set of maritime accident reports in English.

The generation of fitting keywords is a semi-automated process that highly relies on the judgment of a human analyst. In summary, the process consists of the following steps:

1. derive keywords from definitions and examples
2. find fitting synonyms for keywords using wordnet
3. explore corpus, find term-correlations for the keywords, and add new keywords
4. reduce some keywords to their stems to increase the recall based on human judgment

Furthermore, we added keywords for Situation Awareness and human error to be able to search on a meta-level if none of the keywords for a SA Demon returns any results. Table 3.3 shows the resulting list of generated keywords for each of the SA Demons.

SA Demon	*Keywords*
SAD1	preoccupied (him-/herself), pre-occupied (him-/herself), focus, not attent, no attent, fixate, concentrate, not note
SAD2	forget, forgot, not remember, no memory
SAD3	fatigue, workload, stress; *negative keyword combinations:* fatigue crack, fatigue wear, unlikely, distress, rope stress
SAD4	occupied, data overload
SAD5	caught attention, attracted attention, draw attention, distract, mislead attention
SAD6	misinterpret, not understand, complex
SAD7	misinterpret, misunderstand, misunderstood, not correct
SAD8	not aware, unaware
Human Error	human error, human element, human factor
Situation Awareness	situation, aware

Table 3.3: This table shows the generated keywords for each SA Demon. Some of them are reduced to their stem to increase their recall.

Retrieval Method

We classified the documents into the SA Demon categories by using boolean queries constructed from the SA Demon keywords. We performed test queries to identify the keyword combinations with the best balance of precision and recall. Table 3.4 shows the final queries we used to retrieve the accidents caused by the SA Demons.

For SAD2, SAD5, and SAD6 we could not find a fitting query that specifically retrieves them. Queries constructed from SAD6 keywords always delivered SAD7 problems, as the keywords are too similar. The keywords for SAD5 are often used by the authors of the accident reports to emphasize their findings and recommendations, e.g. ”[...] draw the attention of Owners, Skippers, Mates and crews to [...]”. We, therefore, used a more general query for these SA Demons.

We applied the *pipeline and filters* design pattern to implement the boolean queries as a UNIX pipeline combining the UNIX programs *find* and *grep*. The advantage of this approach over using an indexing search engine is the support of full-text search. To remove false positives, the query results were inspected manually in the context of the sentences containing the positive keywords. If we were unsure, the sentence before and after the finding was also inspected.

SA Demon	*Query*
SAD1	$(preoccupied \wedge (himself \vee herself)) \vee$ $(pre\text{-}occupied \wedge (himself \vee herself)) \vee (attent \wedge not) \vee focus$
SAD2	$(human \wedge error) \vee (human \wedge element) \vee (human \wedge factor)$ $\vee(situation \wedge aware)$
SAD3	$fatigue \wedge \neg crack \wedge \neg wear \wedge \neg not \wedge \neg unlikely \vee workload$
SAD4	$occupied$
SAD5	$(human \wedge error) \vee (human \wedge element) \vee (human \wedge factor)$ $\vee(situation \wedge aware)$
SAD6	$(human \wedge error) \vee (human \wedge element) \vee (human \wedge factor)$ $\vee(situation \wedge aware)$
SAD7	$misinterpret$
SAD8	$not \wedge aware$

Table 3.4: This table shows the composition of the boolean search queries for each SA Demon.

3.3.1.4 Results

The SA Demons with the highest proportion in the investigated sample were *WAFOS* with fatigue as main cause, *errant mental models*, and *attention tunneling.* We were not able to find accidents caused by *requisite memory trap*, *misplaced salience* or *complexity creep.* Not all Situation Awareness related accidents can be explained by the SA Demons. During analysis we found some accidents caused by a lack of Situation Awareness that could not be derived directly from a SA Demon, such as insufficient trip planning.

SA Demon	*Description*	*True Positives*	*Query Precision*
SAD1	attention tunneling	36 (7%)	0.14
SAD2	requisite memory trap	not found	-
SAD3	WAFOS	216 (40%)	0.87
SAD4	data overload	34 (6%)	0.17
SAD5	misplaced salience	not found	-
SAD6	complexity creep	not found	-
SAD7	errant mental models	40 (7%)	0.93
SAD8	out-of-the-loop syndrome	7 (1%)	0.02
Total		**333 (62%)**	
Expected		*300-321 (56-60%)*	

Table 3.5: Retrieved occurrences of SA Demons in MAIB Corpus. The Percentage behind the absolute counts indicates the count relative to the corpus size.

Table 3.5 shows the results of our request-oriented classification. The table lists the absolute count of retrieved accidents and the precision of the query for each SA Demon. The query precision is the positive predictive value of the query-request on the corpus. It is calculated as follows:

$$query\ precision = \frac{number\ of\ true\ positives}{number\ of\ true\ positives + number\ of\ false\ positives}$$

Moreover we calculated an estimate of the total number of results based on statistics from related work. This provides us with a weak sanity check of the total number of retrieved accidents related to SA problems. For the MAIB corpus this estimate amounts to 300-321 accidents. We based the estimate on the results of Baker et al. stating that in about 80-85% of maritime accidents human error is the dominant factor [BM05]. Further Grech et al. have stated that about 71% of maritime accidents caused by human error are caused by a lack of Situation Awareness [GHS02]. We combined these two statistics in the following calculations:

$$estimate_{lower} = 535 \times (71\% \times 80\%) = 535 \times 56\% = 300$$
$$estimate_{higher} = 535 \times (71\% \times 85\%) = 535 \times 60\% = 321$$

3.3.1.5 Discussion

The relationship between documents and SA Demons is a many-to-many relationship. That means more than one SA Demon could have lead to the accident. Our previously introduced weak sanity check suggests that our retrieval was quite successful. However, without knowing the number of false negatives and the recall of our retrieval this is just an educated guess.

We did not find any accidents caused by *requisite memory trap*, *misplaced salience* or *complexity creep*. However, the fact that we were not able to find them does not mean they do not exist. We expected these demons to be hard to find. Endsley has already stated in her definition of the SA Demons that ”complexity is a subtle SA Demon” [EJ11].*Requisite memory trap* is an internal processing problem that is hard to observe. The same applies to *misplaced salience*. As our source of data are accident reports, the completeness of the data regarding SA failures depends on the ability of the respective inspector conducting the investigation to identify human errors and their causes. The completeness, therefore, varies from inspector to inspector depending on their interpretation abilities and work experience.

The most frequent found SA Demons all affect Situation Awareness Level 1. This confirms prior work by Grech et al. identifying Situation Awareness Level 1 as the most prominent cause for a lack of Situation Awareness [GHS02].

3.3.1.6 Conclusion

Our results confirm that Situation Awareness Level 1 is the most prominent source of human error in maritime accidents. Likewise, it is the most prominent one of the three levels of Situation Awareness. All in all, the SA Demons with the highest proportion in the investigated sample were *WAFOS* with fatigue as the main cause, *errant mental models*, and *attention tunneling*. We were not able to find accidents caused by *requisite memory trap*, *misplaced salience* or *complexity creep*, however we still think that these exist. Unfortunately detecting these SA Demons in maritime accident investigation reports will remain difficult, unless it becomes part of the investigation itself. We advise taking special care of the SA Demons *WAFOS*, *errant mental models*, *data overload* and *attention tunneling* when designing new interfaces for ship bridges. Our findings might also be beneficial for the design of user interfaces for Vessel Traffic Management (VTM) centers.

3.4 Approach

In our accident analysis, we found that the SA Demons *WAFOS*, *errant mental models*, *data overload* and *attention tunneling* contribute the most to the lack of attention that led to missed perception of critical information for the current situation, resulting in accidents. Therefore, we reason that the perception of relevant information should be assisted through a monitoring assistance approach. To cope with errant mental models, this monitoring assistance should guide the attention of an operator on a regular basis to relevant information for the current situation. To avoid data overload, this should be realized through a context-aware model of the SA of the operator, see Chapter 6, so that cues are only triggered, if there is a demand for attention. This means an experienced OOW might get cues less often than an inexperienced or fatigued OOW.

To cope with attention tunneling, the guidance of attention should be realized by cues that are always perceivable by the operator. Further, we focus on cues that utilize exogenous orienting (cf. Section 2.4), as these cope better with human factors such as workload, fatigue, and other stressors. We intentionally do abstract from special ship bridge designs, so that the proposed spatial guidance method can be either deployed as assistant system complementary to existing bridge systems on currently active ships or integrated in future bridge designs.

This thesis aims to investigate the sufficient design of attention guidance cues and to propose a system that can apply these for spatial attention guidance on ship bridges through an experimental human centered approach. Our experimental approach considers the context of use, while controlling limiting factors that could interfere with the measurement of effects. We use laboratory studies, but simulate relevant components of the actual context of use, if necessary. We use eye tracking to objectively measure the effectiveness of our designs, see Section 4.4 for more details. Further, we chose realistic tasks and scenarios for our studies.

Individual Situation Awareness of the OOW

In this work, we focus on the Situation Awareness of the decision maker, the OOW.We agree that every person on the bridge contributes to an overall Situation Awareness and that every system on the ship's bridge might offer relevant information contributing to a distributed Situation Awareness. However, Kozlov et al. found that in situations, where the an external representation of the knowledge of an collaborator is available, it is faster to obtain the knowledge from it than through interaction with the collaborator [KEBH15]. As our goal is to ensure that the decision maker has all relevant information to form an adequate decision in the current situation, we focus on directly guiding his or her attention towards relevant information. Nevertheless, we are aware of the importance of communication and interaction between the members of the bridge crew. Therefore, we make sure that our cue designs do not hinder human-to-human communication in any way.

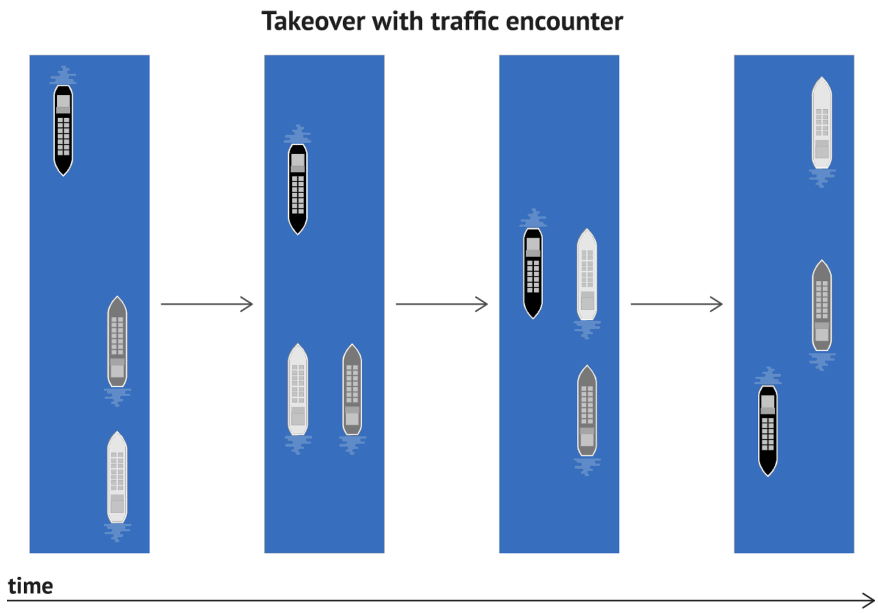


Figure 3.8: The simulator scenario: Takeover on a canal with traffic encounter. The white ship is the own ship, the gray ship has to be overtaken while a collision with the black ship has to be avoided.

Representative Scenario: Overtaking on a canal with traffic encounter

We interviewed two active and experienced mariners (male, age: 34, experience: 10 years; male, age: 35, experience: 8 years). The interview consisted of three parts and both experts were interviewed simultaneously. In the first part, we let the experts propose a suitable scenario. We decided for the scenario *overtaking with traffic encounter* as described in Figure 3.8. This scenario contains the danger of the two most common types of human error-induced accidents, collisions, and groundings.

After choosing the scenario, we performed a goal-directed task analysis (GDTA) [EBJ03] with the experts on the scenario. With the fulfillment of the scenario as the main goal, we identified the following three subgoals: keep a safe distance from other ships, regularly check course, and change course. *Regularly check course* and *change course* are both parts of the safe maneuvering on the planned path in the fairway. Furthermore, we identified the necessary decisions for each sub-goal, as well as the information needed for the respective decision. Figure 3.9 shows the resulting goal tree.

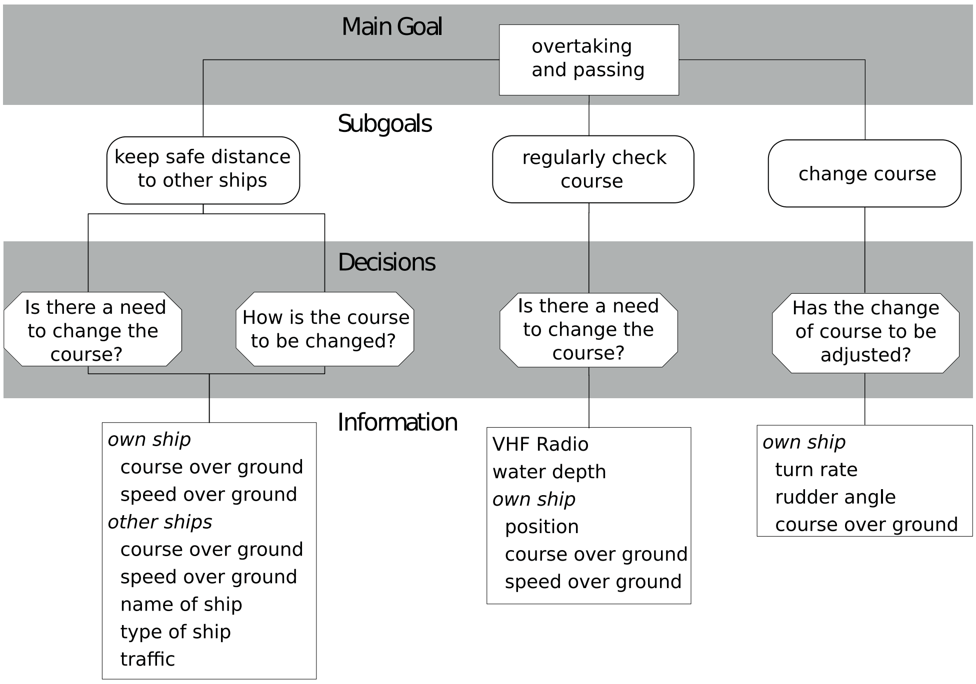


Figure 3.9: Goal tree of the analyzed scenario.

Towards Ecological Validity

As we described in Section 1.1 performing field studies on on-duty ships brings several challenges that make them impractical for the kind of experiments we are conducting. First, there is a logistical challenge, since they are underway most of the time (moving between different harbors), which narrows the reachable time frame. Second, the interference with active onboard systems is not allowed for safety reasons, limiting the study apparatus. Third, to reach the necessary sample size for statistically significant results in experiments, several sessions on different ships would be necessary stretching the time-frame of an experiment enormously, as the maximum number of deck officers onboard a vessel is three to four persons. But even the access to active maritime personal for on-shore experiments is limited. Typical experiments with users run in a time-frame of two weeks, while mariners are on-duty for different not necessary overlapping weeks or months-long time-frames, which makes the acquisition of study participants as well as the scheduling of sessions extremely challenging. This can partly be addressed by including nautical students after their first practical experience, retired mariners, pilots, and nautical researchers. Further, some experiments require no nautical background, therefore we fall back to including laymen for these. Therefore, we conducted two kinds of experiments, lab studies under highly controlled conditions with laymen to investigate fundamental cue designs, and contextual lab studies, where we simulated parts of the maritime environment and tasks with mariners or mariners in training. With the background knowledge from literature research, a contextual inquiry, and first-hand simulator experience we carefully designed each task in our contextual experiments to be representative of the characteristics of the domain. Further, we emulated workload by either utilizing well-founded workload tasks from psychology (e.g. n-back task) or through our representative scenario and the corresponding activities. Both methods allowed for different levels of workload, e.g. by altering the simulated weather conditions of the scenario.

As described in Subsection 2.3.2 eye trackers offer different measures for tracking a person's overt attention. Therefore, one of our key objective measurement tools for evaluating the effectiveness of cues and guidance strategies is a mobile eye tracker. Previous work by Hareide et al. applied eye tracking on on-duty ships and compared it to data recorded in a simulator [HO16, HOM16]. Their findings indicate the transferability of eye tracking results between simulators and reality, meaning that gaze paths and reactions of participants matched closely between simulator and reality.

Also, we took special care of confounding variables, such as visual, auditory, and tactile noise, as the cue designs we investigate for spatial attention guidance have to be effective under realistic sensory noise conditions. However, there are factors that we did not control.

For instance, we did neither directly measure the influence of fatigue nor did we control it. Although the workload of the tasks during the lab studies causes fatigue over time, due to the length of the sessions of maximal two one-hour-long blocks with a break in-between and the counterbalanced design of all studies, this small effect gets mitigated. This is a limitation on the ecological validity of our work.

But this early in the exploration of the design space, we argue that it does not make sense to limit the already small pool of possible study participants to people who are willing to voluntarily fatigue themselves, e.g. through 24-hour sleep deprivation. But rather evaluate more matured iterations of cue designs under actual conditions of fatigue. In Section 7.4 we described, how we would approach that.

3.5 Summary

In this chapter, we described our methodology and used methods, as well as the context of use, and explained our general approach. Further, we analyzed over five-hundred maritime accident reports for each of the eight SA Demons to provide a ranking of the causes and to identify the most prominent ones. Addressing these SA Demons enables maritime system designers to enhance the Situation Awareness of maritime operators and thereby improves safety at sea.

4 Apparatus

This chapter is partly based on the following publication:

- Stratmann, Tim Claudius, Gruenefeld, Uwe, Stratmann, Julia, Schweigert, Sören, Hahn, Axel, and Boll, Susanne. ”Mobile Bridge - A Portable Design Simulator for Ship Bridge Interfaces”. TransNav, the International Journal on Marine Navigation and Safety of Sea Transportation, 12(4), 763-768, 2018.

The efficacy of multi-modal displays highly depends on the environment and the context they are used in. Visual displays are affected by visual distractors such as bright daylight, auditory displays are affected by noise (e.g. engine noise), and tactile displays are affected by movements of the user or in the environment (e.g. vehicle vibration/movement). These distractors can mask the signals of the display and thereby hindering its perception by a user. Besides, there are also cross-modal confounders. For example, the McGurk effect [MM76] displays the interaction between hearing and vision in speech perception, where mismatching visual information from seeing a person speak changes the way you hear the sound of the speech. That is why multi-modal displays should be designed for the environment and context of their intended use.

As testing in the field is challenging in the maritime domain (see Section 1.1), there is a need for simulators as apparatuses in the design and early evaluation phases of multi-modal displays. These simulators specifically mimic realistic visual, acoustic, and tactile properties of a ship's bridge, ensuring a high ecological validity of results. We developed, implemented, and used three simulator systems, each targeting a different modality.

First, a transportable ship bridge simulator that enables the simulation of tasks and scenarios, and mocks visual systems and the view through windows on a ship bridge. Second, an artificial acoustic scene of a ship's bridge incorporating scenario-dependent machine noise, wind, wave, rain, and radio call sounds. Third, a vibration platform and signal that mimics the machine-induced environmental vibration on a ship bridge.

Further, we have implemented a measurement setup and software support for the Tobii Pro Glasses 2 eye tracking system that enables a nuanced investigation of gaze behavior triggered by spatial attention guidance cues. The aforementioned systems will be described below in more detail.

4.1 Transportable Ship Bridge Simulator

In recent years, various new software components for ship bridges have been proposed in research (e.g., for novel ways of interacting with ship bridge systems [CHM17]). However, while more and more technologies are presented in research the speed at which these technologies appear on real systems is rather slow. This is mainly due to limited access and high costs of testing these technologies on real ship bridges. However, for the development of new software components tests are essential. To solve this problem and to reduce the costs of the development, the process is divided into different stages. Thereby, the final test on a real ship bridge is only the last step of this process. By taking the approach of different development stages, the first steps can be done in a laboratory environment. This is beneficial because early-stage software requires shorter development cycles that support an uncomplicated execution which is simply not given on a real ship bridge.

However, due to the problems of testing software components on a real ship bridge, many researchers and developers used training simulators for their development in the past. These simulators support the fast development process in the early stages but generate a new problem when the components need to be transferred to a real ship bridge. To solve this problem a system is needed that can be used in all development stages that easily adapts to these stages. We propose Mobile Bridge, a mobile ship bridge that is easy to recreate and setup. It supports the early-stage development in short development cycles with an additional simulation environment as well as later-stage development as a parallel setup on a real ship without altering the live system. The Mobile Bridge is a configurable ship's bridge system in which new eNavigation technologies can be tested and demonstrated. In particular, new interaction concepts are within the focus of the development. This includes both, the providing of information to nautical personal as well as new control concepts. The portable structure of the system allows a straightforward demonstration and evaluation of these concepts in a variety of environments, such as fairs, research laboratories, and ultimately a real system environment. The final goal is to use it on real ship bridges as the system could be connected to a NaviBox [HN16] to get the necessary information and run in parallel with real systems. However, before field tests, new designs and concepts have to be evaluted and refined in a lab environment. Therefore, an additional vision system supports the design, development, evaluation, and demonstration of these interaction concepts within a virtual environment.

In our work, we took advantage of the high adaptability of Mobile Bridge in different configurations for lab studies, especially for studies in a anechoic chamber. The parallel setup of Mobile Bridge alongside the actual systems on a real ship bridge remains future work.

Related Work

In the beginning, maritime simulators have been mainly developed to allow mariners training under realistic circumstances without the potential risk of harm to a real environment or themselves. Its development evolved from rudimentary graphics and text-based simulation (e.g. port simulator from Hayuth et al. [HPR94]) to complex 3D virtual environments that assist in learning specific tasks (e.g. discharging operations [VS15]). A detailed overview of first maritime trainee simulators can be found in the paper from Hayuth et al. [HPR94]. The development towards 3D virtual environments was foreseeable since several papers proposed to use virtual reality for more immersive simulations already at the end of the nineties [XYYZ04], [Mag97]. But not only the visual possibilities increased also the purpose of maritime simulators extended fast to cover additional topics like research and development. Since the motivation of just having a virtual ship crash and not a real ship stays the same for these topics. Additionally, a simulation can simulate a specific part of reality and for that reason is more adaptive to new techniques.

Especially for the development of user interfaces, different concepts have been proposed based on maritime simulation. All these concepts focus on taking the human factor into account for the development process of new interfaces. Since accident investigation showed that human error is the most frequent reason for accidents [SB16]. Although, there is a connection between the design of user interfaces and the capability of nautical officers to understand their current situation and to decide correctly [HLS13]. As a first step, research focused on creating simulator environments to develop new user interfaces. Therefore, training simulators were adapted and combined with tools and techniques to set up an environment for user interface development (e.g. the design simulator for offshore ship bridges from Kristiansen and Nordby [KN13]). With respect to aspects of easy access and low price a simulator is a better choice over a real ship bridge, but cannot compensate for it (e.g. the important fieldwork). But the general idea of using a simulator as a valid strategy to conduct user studies got strengthened by the findings of Hareide and Ostnes [HO16]. They did a comparative study between a real ship bridge and a simulator for navigation training and found no differences in comparing the eye-tracking data of both environments. To use simulators for a redesign to create more user-centered solutions is only one goal of research. Another goal is the development of more unified interfaces that are consistent over different systems on one or more vessels. Therefore, Nordby and Komandur presented a laboratory for the design of advanced ship bridges [NK14].

But more than new environments for developing maritime user interfaces are also new design principles necessary since the given environment differs in many points from others. An approach for radical concept design is presented by Wahlström and Kaasinen [WKKM16]. For research not only the simulator environment is relevant also the operator is of high interest. For example, the effect of the spatially distributed space on a ship bridge on information demand and supply [Den14]. In the paper from Hontvedt and Arnseth, a ship bridge simulator has been used to investigate the social organization of nautical instructions [HA13]. Therefore, they looked into training sessions with nautical students and experienced mariners and observed their behavior. Such investigations can be used to create a model of the crew members' behavior and simulate it. These virtual nautical officers were for example created in the paper from Brüggemann et al. [BS09]. The Concept for our mobile ship bridge was first introduced by Hahn et al. as part of the eMIR Testbed [Hah14]. The idea of the eMIR Testbed is to set up a testing environment for simulation and physical real-world demonstrations. The focus is on how to validate and verify e-Navigation technologies. The related project HAGGIS [SGHB14] provides modeling and simulation tools. The physical testbed embedded in HAGGIS is called LABSKAUS [SBH14]. It is also mentioned that testbeds already exist in the automotive domain but are missing in the maritime domain.

Design of Mobile Bridge

In our approach, we designed a mobile bridge to fully support the development cycle of new software components. Key to our approach are flexible boxes called "BridgeElements". Our mobile bridge system consists of three equal segments that can be combined and connected. Each of these segments is build up of one information and one control element. Whereas the information element is realized as a multi-touch monitor. The control element could be either a multi-touch monitor or a set of bridge control elements like thrust levers or a steering "wheel". The multi-touch control element enables the testing of new concepts for virtual handles and controls. Every segment can be operated independently. This allows using more or less than three segments. The system is highly configurable, e.g. distance and position of displays and components can mimic a broad variety of real ship bridge configurations.

Requirements

To support the complete development cycle, our Mobile Ship Bridge needs to be transportable. Further, to fulfill the requirements of small and large ship bridges we need a modular design. This allows us to adapt the size of Mobile Bridge to the existing space on ship bridges. Our system consists of two main components: The Mobile Ship Bridge itself and the vision system. Our mobile ship bridge was implemented with regard to the following assumptions:

- The Mobile Bridge will be composed of multiple (1 to 3) Bridge Elements.
- A Bridge Element shall be transportable and easy to install.
- A Bridge Element that can be set up faster shall be preferred.
- A table to hold the Bridge Elements is not considered in this decision.

A Bridge Element is a hard coupled combination of a computer, a display monitor, and a control element (monitor or classical bridge controls). The flexibility for different kinds of experiments is ensured by the flexible combination of different Bridge Elements. A Bridge Element consists of a flight case containing the following components:

- An industrial computer (Intel i7 processor, 8 GB RAM, SSD hard disk) directly integrated into the flight case
- A power supply module
- A network switch
- Two 22” multi-touch monitors:
  - One monitor mounted on the bottom of the flight case, using an open frame case
  - One monitor mounted in the cover of the flight case, using an inclinable VESA mounter
  - A flexible cable duct for the monitor mounted in the flight case’s cover
- A faceplate for external power and network supply:
  - The faceplate is split into an input section for external power supply and network interface
  - A power - output element allows connecting different Bridge Elements in a row (daisy chain)
  - An additional network output element allows the network connection between two or more Bridge Elements

Figure 4.1 shows the hardware placement in the case, the case sketch with dimensions, and the wiring diagram. Detailed information on how to build a mobile bridge can be found in our Github repository[1]. By mounting the display monitor into the cover of the flight case, we can ensure an easy installation of Bridge Elements during experiments or demonstrations. Also, there is no need for another monitor holding facility. On the other hand, we do lose a little bit of flexibility to rotate the monitor, if mounted inside of the flight case cover. By integrating the computer into the flight case, no additional hardware needs to be carried. On the other hand, this will increase the cost for one Bridge Element by the means of 2/3 of the cost of one computer.

[1] `https://github.com/tcstratmann/MobileBridge`, last retrieved: July 5, 2021

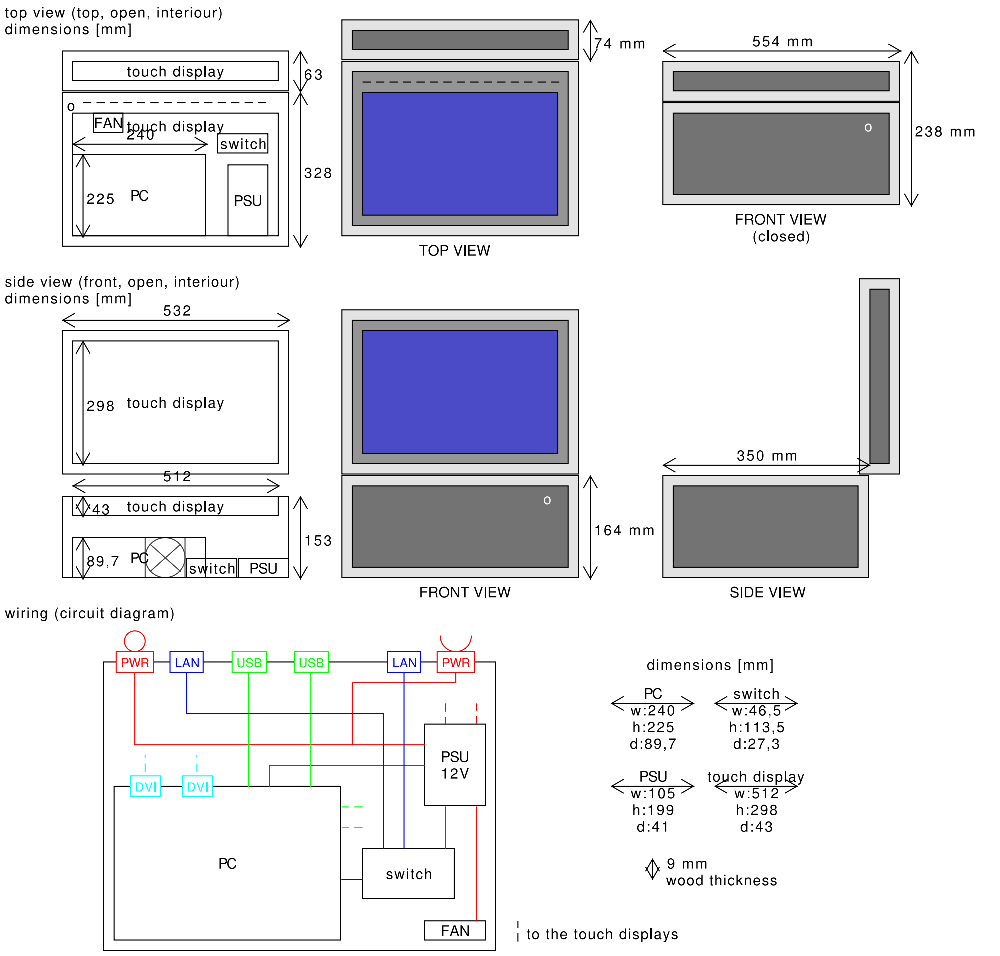


Figure 4.1: The Hardware placement in the case, the case sketch with dimensions and the wiring diagram.

In Addition to the Mobile Bridge Hardware, we created a huge set of virtual devices, such as GPS, VHF, light controls, machine telegraph, rudder, rudder angle indicator, etc. that can be connected to a simulation to populate Mobile bridge with information displays and controls. The full software toolkit is documented and hosted on Github as open-source software under the project name Virtual Handles[2]. Figure 4.2 shows an example screen with multiple devices. All virtual devices in the software toolkit were designed analog to existing maritime systems and controls with adjustments for ease of use through touch controls. However, the resulting touch-optimized virtual devices were not validated with experts.

[2] `https://github.com/tcstratmann/VirtualHandles`, last retrieved: July 5, 2021

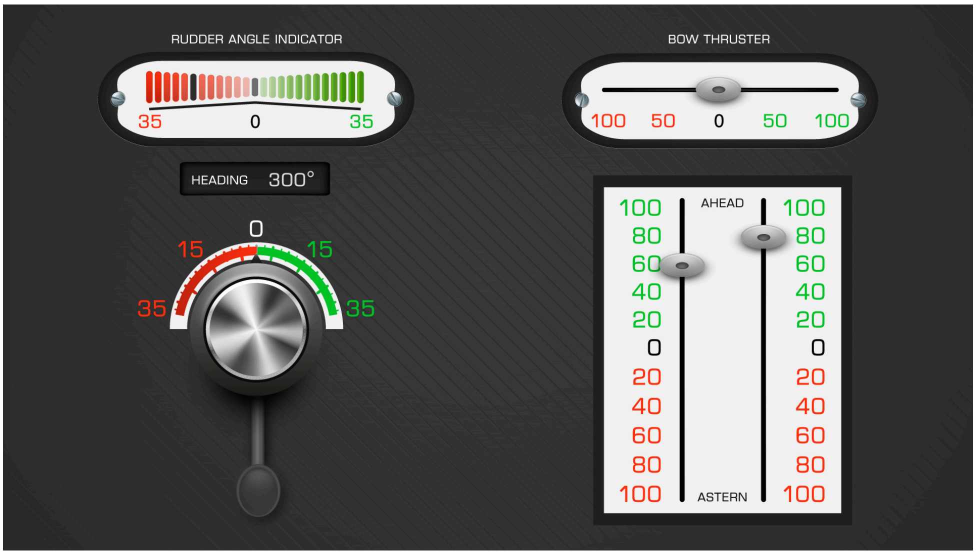


Figure 4.2: Example screen of Virtual Handles with rudder and machine telegraph.

Towards Virtual Environments

The second component, our vision system, is used to visualize a traffic simulation within a 3D environment. For this purpose, the vision system consists of three additional displays, which are realized by a high-definition curved television system but can be easily replaced by utilizing video projectors. To further ensure the portability of the bridge system, the hardware of the vision system is decoupled from that of the bridge system.

Combined, the two components form a fully functional Ship Bridge Simulator using the open source Simulator Software Bridge Command[3]. Further, the Mobile Ship Bridge supports commercial simulator software.

Towards Real Environments

The portable structure of the system allows a straightforward demonstration of these concepts in a real system environment, e.g. on real ship bridges. The system can be either connected to the sensors onboard the ship or to a NaviBox[4] to run on live data in parallel with the onboard systems. Figure 4.3 shows Mobile Bridge set up on the research vessel Zuse of the research institute OFFIS[5]. The goal of the parallel setup is to enable researchers and system designers to test their novel software and interaction concepts in the field.

[3] https://bridgecommand.co.uk/, last retrieved: July 5, 2021
[4] https://www.emaritime.de/services/labskaus/navibox/, last retrieved: July 5, 2021
[5] https://offis.de/, last retrieved: July 5, 2021

Figure 4.3: Mobile Bridge on research vessel Zuse (Source: OFFIS e.V.).

Use-cases and Applications

In combination with a vision system, it can be used for lab studies. The Mobile Bridge implements a full mission ship simulator. It is also possible to connect the Mobile Bridge to an existing full mission ship simulator. Other application scenarios are the use as a demonstrator on exhibitions and as a tangible interface for augmented reality solutions. The main use case of Mobile Bridge is to evaluate novel e-navigation software and prototypes. So far, we have successfully conducted three lab studies using the Mobile Bridge as a simulator.

Our system could also be used as a mobile ship bridge for in-situ studies on in-duty vessels. It is transportable in an aircraft and runs in parallel to the existing systems. It can be connected to the ship's sensors or get the navigational data from a NaviBox [Hah14].

We applied Mobile Bridge as a standalone full mission simulator in user studies (see Figure 4.4). It was used in combination with the Open Source Mission Simulator Bridge Command. The mobility of Mobile Bridge enables user studies in special laboratories such as anechoic chambers. We used such a setup to compare moving and static acoustical pointers in a simulated acoustic ship scene in the VR lab of the University of Oldenburg. Another potential usecase is the setup of Mobile Bridge in parallel to the existing bridge on in-duty vessels to test novel user interfaces in the field.

Figure 4.4: Mobile Bridge set up as Full Mission Simulator.

Limitations

The strong flexibility of the presented design simulator comes along with some compromises. There is a trade-off between the realism and mobility of Mobile Bridge. On the one hand, the choice of touchscreens as display and input units supplies us with an unlimited flat design space for visualizations, touch, and tangible input methods. On the other hand, we have to deal with the disadvantages of touchscreens in maritime environments, such as input problems with wet hands. As the standard configuration only consists of touchscreen surfaces, the system is more sensitive to bright environmental lightning conditions than native systems.

Summary

Mobile Bridge is a mobile modular platform for testing novel interaction concepts and software for ship bridges. The platform will enable system designers to implement and evaluate novel maritime HMI applications in the lab and the field. We tested Mobile Bridge in four different use-cases, which highly benefited from or were not even possible without the platform.

The Mobile Bridge is a very suitable and highly reconfigurable ship simulator environment for lab studies. It is especially suited for studies in special labs, such as an anechoic chamber.

4.2 Audio Lab and Acoustic Scene of a Ship Bridge

The virtual acoustical environment was created using the Toolbox for Acoustical Scene Creation And Rendering (TASCAR; [GH14]; [GLHH15]). Room acoustical modeling was based on the ship bridge of a 2999 GT general cargo vessel (see Figure 4.5). Early reflections of walls, windows, the console, and the table were rendered first order and supplemented by a diffuse reverb (feedback delay network). Stimuli were panned using vector-based amplitude panning ([Pul97]). Diffuse sounds (weather and engine, for details, see appendix) were directly mapped to 14 loudspeakers: 12 equally spaced loudspeakers in the horizontal plane (azimuth angles 0°, 30°, 60°, ...) and to the top and bottom loudspeakers (elevation angles 90°, -90°). Each speaker was playing the same sound loop, but they were delayed irregularly to minimize coherence and avoid comb filter effects at off-center positions.

We simulated the following environmental noises: Engine, rain, wind, and waves. Further, we triggered alarm sounds and radio calls at certain points in time. To be able to control them easily, the sound effects were single real-world recordings, which we combined analog to a full recording from a ship bridge. We adjusted the loudness of these effects according to present regulations. The noise level limits for the ship bridge on 1600 - 10000 GT merchant ships is 65 dB(A) according to Resolution MSC.337(91) [Mar12] an amendment to the International Convention for the Safety of Life at Sea (SOLAS) [Int74]. Table 4.1 gives an overview of the noise level limits for different navigation spaces. Further, we invited two experienced nautical officers to listen to our acoustic scene and get feedback on the realism of the scene.

Designation of rooms and spaces	Ship size 1,600 up to 10,000 GT	Ship size $\geq$ 10,000 GT
Navigating bridge and chart-rooms	65	65
Look-out posts, incl. navigating bridge wings and windows	70	70
Radio rooms (with radio equipment operating but not producing audio signals)	60	60
Radar rooms	65	65

Table 4.1: Noise level limits in dB(A) for navigation spaces according to IMO Resolution MSC.337(91).

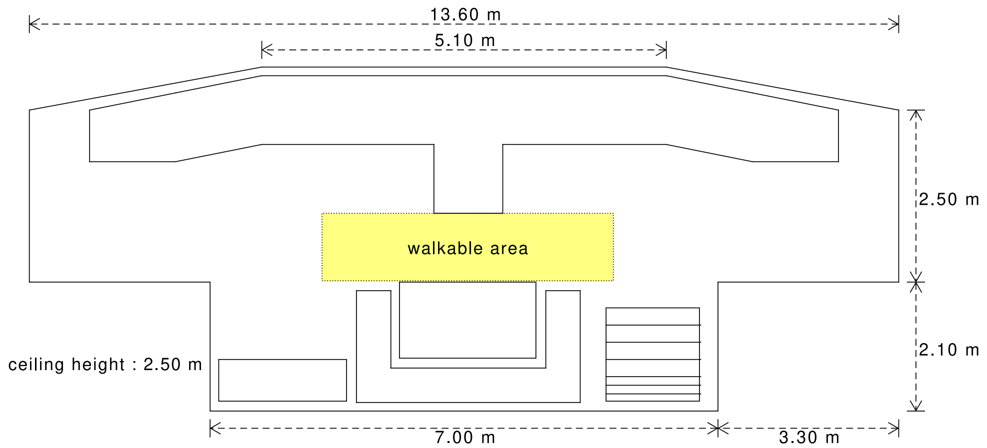


Figure 4.5: Dimensions of the simulated bridge room, taken from an existing 2999 GT general cargo ship.

For the rendering of the acoustical scene, we used the Virtual Reality Laboratory of the University of Oldenburg in Germany (see Figure 4.6). It is lab-based on an anechoic chamber with 7.4 m length, 4.6 m width, and 4.3 m height (absorbers excluded). The room is treated with foam wedge absorbers with a structural depth of 60 cm. For this experiment, a 7.7 m^2 grill floor was installed that allowed the participants to move between the console instruments. The lab is equipped with a curved video screen setup that covers 202.5° of the horizontal field of view. The screen has a height of 2 m and is mounted 68 cm above the grill floor. The projectors used were three Barco F50 and the video content was perspectively rectified using Barco WB2560 warping units. For sound reproduction, the lab contains 86 pre-installed Genelec 8030b studio monitors. These are set up in horizontal layers at elevation angles of 90° (1 loudspeaker), 60° (6 loudspeakers), 30° (12 loudspeakers), 0° (48 loudspeakers), -30° (12 loudspeakers), -60° (6 loudspeakers) and -90° (1 loudspeaker). Within the layers, loudspeakers are equally spaced starting from 0° azimuth. The center of the loudspeaker setup is matched with the center of the video screen.

Figure 4.6: Photo of the acoustic virtual reality laboratory.

4.3 Platform for Simulation of Environmental Vibration on a Ship

Ship bridges of in-duty cargo ships are a good example of working environments with constant vibrational noise. Which is why we designed and implemented a platform for the simulation of environmental vibration. Unfortunately, we could not use it for our experiments with tactile cues since these were already conducted as the idea of the platform design arose. However, we offer this detailed description to allow others to replicate and use it for future experiments. As in most working environments with vibrational noise, on ships, the vibration of the environment is caused by an engine or machine. In this case, it is the main engine of the ship. We choose a 2999 GT general cargo vessel with a variable pitch propeller as a reference for our simulation of vibrational noise, as it matches the ship that we visited during our contextual inquiry. This kind of ship has an engine running at a fixed speed (194.8 RPM), as the speed of the vessel is controlled by the pitch of the propeller, not the RPM of the engine. This creates an environment with uniform vibrational noise. Other examples of environments with vibrational noise are construction sites, production facilities, and motorized vehicles of all sorts. We do not consider the rolling of the ship in heavy seas to have any relevant masking effect on the perception of vibration, even for smaller ships that might pitch stronger. That is why we concentrate on the engine vibration and its uniform vibrational noise.

The Lloyd's Register assessed vibration levels on merchant ships [Fil06] based on ISO 6954:2000 Guidelines for the overall evaluation of vibration in merchant ships [ISO00]. According to their report, the recommended maximum acceptable values of frequency weighted r.m.s vibration velocity for vibration within the frequency of 1 to 80 Hz for working areas are 6 mm/s r.m.s under normal conditions and 8 mm/s r.m.s under excessive conditions.

Vibration as Audio Signal

From a physics perspective, there is not much difference in the mathematical description of vibrations and sounds. A vibration is a mechanical wave that creates a sound as a byproduct if the oscillation is within the hearable spectrum of humans. Both can be described using the parameters waveform, frequency, and amplitude. The latter has to be calibrated for the specific rendering hardware to match the intended strength in the real world.

Hardware

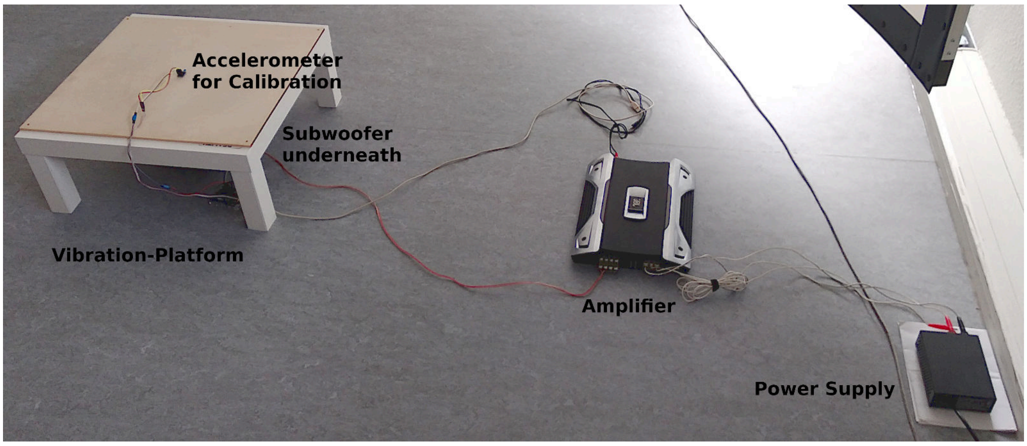


Figure 4.7: Photo of the vibration platform.

The vibration platform simulates environmental vibration. It is best suited for the simulation of environments, where the general direction of vibration is bottom-up. A subwoofer attached to the platform renders low-frequency audio signals (1-80 Hz). By design, the platform creates vibration and environmental noise at the same time. As Hardware, we used a JBL GTO-504 amplifier[6] and a JBL GT5-12 subwoofer loudspeaker[7].

Design of a Realistic Vibration Signal for a Ship's Bridge

The above-described hardware enables us to render audio signals as vibration. We derived such a signal from the technical properties of our reference ship, a 2999 GT general cargo ship with a variable pitch propeller. The main source of vibration on these ships is the main engine, with a constant RPM of 194.8, which equals 3.25 Hz. As it is a uniform vibration caused by the rotation of an axis, the basic waveform of the signal is a sinus wave. The ship's bridge is located 12 meters above the engine room. The vibration caused by the machine travels as a forced wave through the metal hull of the ship, adding a higher frequency wave of approximately 50 Hz with the same phase to the signal. We omitted to add extra white Gaussian noise to the signal, as the vibration platform itself will already add noise to the rendered result. Figure 4.8 shows the waveform and frequency spectrum of the final signal. The vibration velocity of the designed signal is 7.89 mm/s r.m.s., which is above normal but still below the maximum for excessive conditions as reported by the Lloyd's Register.

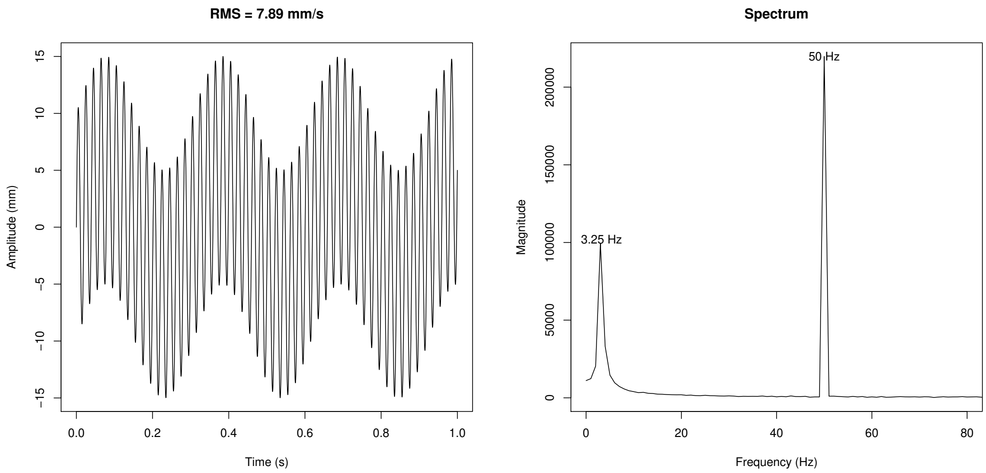


Figure 4.8: Waveform and frequency spectrum of the signal: The signal is the sum of two in-phase sine waves of 50 Hz and 3.25 Hz respectively.

For usage on the vibration platform, the amplitude (volume) of the signal was calibrated using an accelerometer mounted on the vibration platform. It was

[6] `https://www.manualslib.com/manual/1091116/Jbl-Gto504.html`, last retrieved: July 5, 2021

[7] `https://www.manualslib.com/manual/79144/Jbl-Gt5-12.html`, last retrieved: July 5, 2021

calibrated to match 6 mm/s r.m.s., which equals to the typical vibrational noise on merchant ships as measured by the Lloyd's Register.

We used an ADXL345 triple-axis accelerometer[8] mounted on the top-center of the platform for the calibration of the amplitude of vibration patterns. Figure 4.9 shows the measured vibration induced on the platform by rendering the signal at the targeted amplitude with and without a person standing on it. It reassembles the designed signal with additional noise from the physical movement of the platform.

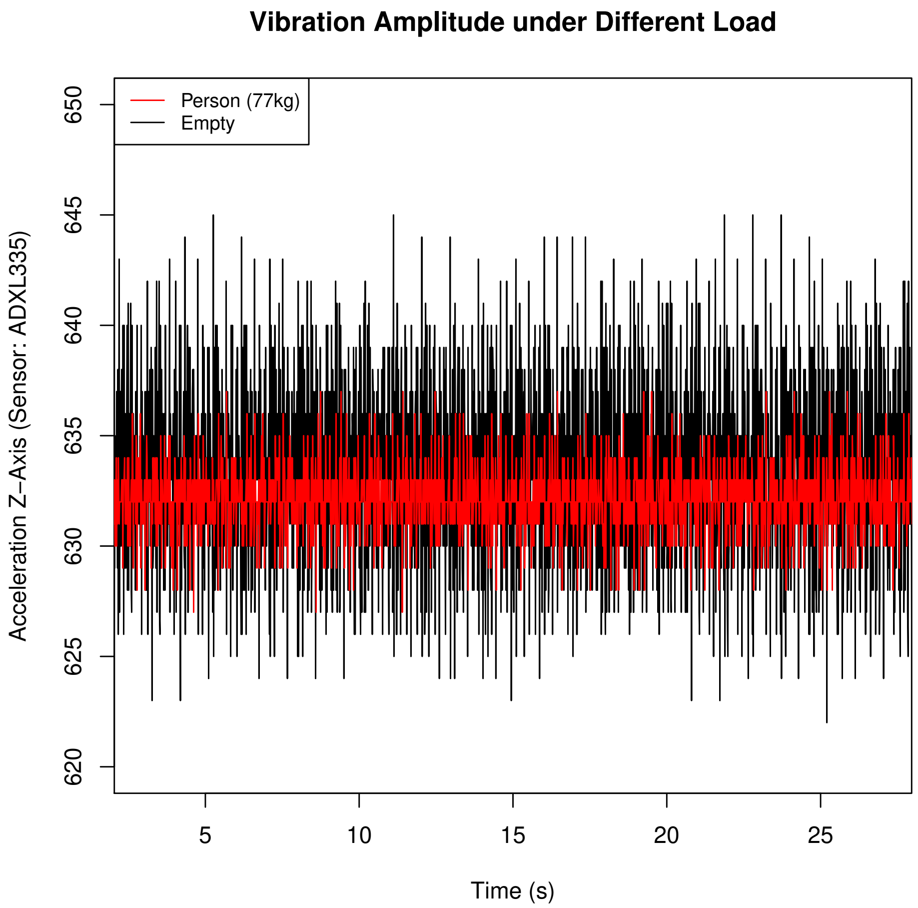


Figure 4.9: Measurement of vibration amplitude in test setup without load and with person standing on the platform. These values are needed for proper calibration of the platform.

[8] https://www.sparkfun.com/datasheets/Sensors/Accelerometer/ADXL345.pdf, last retrieved: July 5, 2021

4.4 Measurement Apparatus for Tracking of Overt Attention

Tracking the gaze of a user allows us to objectively measure if, in which order, and how fast something is perceived. Our gaze reveals our overt attention (cf. Subsection 2.3.1). Previous work by Hareide et al. applied eye tracking on on-duty ships and compared it to data recorded in a simulator [HO16, HOM16]. There findings indicate the transferability of eye tracking results between simulator and reality.

AOI-Support for Tobii Pro Glasses 2

The Tobii Pro Glasses 2[9] is a robust high quality mobile eye tracker. However, it lacks support for tracked AOIs. Therefore, we developed marker-based AOI support for the Tobii Pro Glasses 2 eye tracker based on the Tobii Pro SDK. We used the open-source library ArUco for marker detection [GJMSMCMC16, RRMSMC18]. Our python module is available at github.com[10]. It supports AOIs of rectangular and circular shape.

LED-AOI-Circle

The LED-AOI-Circle is an experimental setup for the evaluation of spatial attention shift cues. It consists of a circle with 12 RGB LED pillars with RGB LEDs of the type WS2812B[11]. The pillars can be positioned at individual heights covering the vertical and horizontal dimensions.

In a horizontal setup of equal height, the inter pillar distance can be calculated as follows:

$$\frac{2 \cdot \pi \cdot \text{radius}}{\text{number of pillars}} \tag{4.1}$$

[9] https://www.tobiipro.com/product-listing/tobii-pro-glasses-2/, last retrieved: July 5, 2021

[10] https://github.com/tcstratmann/tobii_glasses2_aoi_detector_aruco/, last retrieved: July 5, 2021

[11] https://cdn-shop.adafruit.com/datasheets/WS2812B.pdf, last retrieved: July 5, 2021

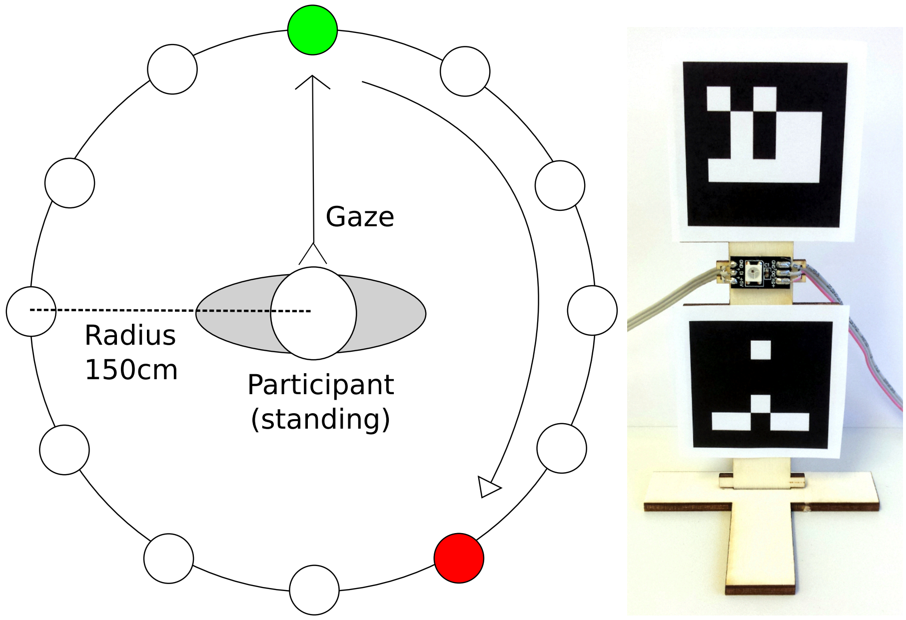


Figure 4.10: The setup consists of a 150 cm radius circle with 12 RGB LED pillars. Each Pillar consists of two optical markers from an ARuco dictionary and one RGB LED.

4.5 Summary

We proposed a mobile ship bridge system to fully support the development process from lab studies to tests in realistic environments. Our system allows developing new software components in the lab and setting them up on a ship bridge without interfering with the vessel's navigational systems. Further, combined with the open-source simulator software Bridgecommand, the system reassembles a full-mission simulator. Also, we set up an artificial acoustic scene of a ship's bridge incorporating scenario-dependent machine noise, wind, wave, rain, and radio call sounds. The acoustical scene can be rendered in the audio lab of the University of Oldenburg. Further, we set up a vibration platform and signal that mimics the machine induced environmental vibration on a ship bridge for a single standing person. As our apparatuses are based on real ship characteristics from our reference ship and were developed complying with the relevant standards (cf. Section 2.5), we find our apparatuses and the way we combine them in the upcoming chapters (Chapter 5 and Chapter 6) to be a valid answer to research question 1.2: *How can we simulate a ship bridge including its visual, auditory and tactile noise conditions in a lab environment?*.

5 Guidance Cues

This chapter is partly based on the following publications:

- Stratmann, Tim Claudius, Kempa, Felix, and Boll, Susanne. ”LAME - Light-controlled Attention Guidance in Multi-Monitor Environments”. Proceedings of the 8th ACM International Symposium on Pervasive Displays. ACM, 2019.
- Stratmann, Tim Claudius, Loecken, Andreas, Gruenefeld, Uwe, Heuten, Wilko, and Boll, Susanne. ”Exploring Vibrotactile and Peripheral Cues for Spatial Attention Guidance”. Proceedings of the 7th ACM International Symposium on Pervasive Displays. ACM, 2018.
- Stratmann, Tim Claudius, Sadeghian Borojeni, Shadan, Heuten, Wilko, and Boll, Susanne. ”ShoulderTap - Pneumatic On-body Cues to Encode Directions”. In Extended Abstracts of the 2018 CHI Conference on Human Factors in Computing Systems. ACM, 2018.
- Stratmann, Tim Claudius, Heeren, Jan, Hohmann, Volker, and Boll, Susanne. ”Attention Guidance on Nautical Ship Bridges: Comparison of Moved and Static Acoustical Pointers”. Submitted to: Journal of Human Factors. Sage, 2021 (under review).

Guiding a user’s attention successfully is highly dependent on the effectiveness of the utilized guidance cues. In this chapter, we describe the design space of cues for spatial attention guidance, which we then explore using example implementations and experiments that are presented ordered by modality. First, visual cues, then tactile cues, then auditory cues.

5.1 Design Space of Spatial Guidance Cues

Spatial Attention Guidance, is the spatial reorientation of overt attention (cf. Section 2.2) triggered and guided by cues. We focus on cues that utilize exogenous orienting (cf. Section 2.4), as these cope better with human factors such as fatigue. The design space of Spatial Guidance Cues is limited to the three modalities visual, tactile, and auditory, as they are the only cue modalities, that allow for spatial localization or mapping in 3D space. Concerning cue placement, we distinguish between cues placed onbody and cues placed in the environment. In the following, we will discuss our design considerations per modality. Table 5.1 provides an overview of the investigated modality - placement combinations, and where they were addressed in this thesis.

Design of Visual Cues

According to the Guidelines on Ergonomic Criteria for Bridge Equipment and Layout (MSC/Circ.982) by the International Maritime Organization (IMO), the preferred viewing area (+/-15° horizontally) and the immediate field of view (+/-35° horizontally) are reserved for information from displays and should not be occluded [Mar00]. Figure 2.3 in Section 2.5 visualizes these areas. Not blocking the foveal vision is also important in other domains. That is why we decided to investigate visual cues in the peripheral field of view. Peripheral vision comes with different characteristics than foveal vision. The color perception is more limited, there is no sharp vision, and the perception of changes and motions is stronger than the perception of details. Therefore we focused on investigating visual cues rendered by low resolution light displays. We controlled the brightness of the environment and the low resolution light displays in all our experiments to reflect the Guidelines on Ergonomic Criteria for Bridge Equipment and Layout [Mar00, 5.2.5 Illumination and Lighting]. We used a Voltcraft LX-1108 Luxmeter[1] (see Figure 5.1) for calibration.

Figure 5.1: Photo of Voltcraft LX-1108 Luxmeter.

Design of Tactile Cues

Tactile cues are widely used for conveying directions for navigation [TY04, MMUW15, HHBP08], which shows their high potential for successfully conveying spatial information. There are different ways to implement tactile cues, we focused on vibrotactile cues (vibration) and pneumatic cues (pressure). For the highest effectiveness, the placement of tactile cues should be limited to positions

[1] `https://produktinfo.conrad.com/datenblaetter/100000-124999/121885-an-01-ml-VOLTCRAFT_LX_1108_LICHT_MESS_de_en_fr_nl.pdf`, last retrieved: July 5, 2021

that allow for simple direction mapping. Further, close proximity to intimate body areas should be avoided, to avoid unpleasant user experiences. Also, the Guidelines on Ergonomic Criteria for Bridge Equipment and Layout [Mar00, 5.2.4 Vibration] state that "uncomfortable levels of vibration should be avoided on the bridge", which foremost refers to environmental vibration, however, it extends to onbody vibrotactile displays.

Design of Auditory Cues

Auditory cues are spatially locatable by humans, however, the quality of 3D audio is limited by hardware. There are two ways to render 3D audio, either through a surround-sound speaker setup or through headphones using a head-related transfer function (HRTF). Headphones have the disadvantage of physically limiting the perception of environmental sounds, such as face-to-face communications, VHF radio calls, and environmental sounds. Bone conduction speakers are alternative speaker hardware that allows for the simultaneous perception of environmental sounds. Unfortunately, they are not technically suitable for rendering 3D audio, as the sound does not travel through the outer ear but rather through a bone to the inner ear. That is why we decided to focus on auditory cues rendered in the environment through a surround-sound speaker setup, to ensure 3D localization of sounds while maintaining high speech intelligibility. Audio levels were calibrated to reflect the Noise Levels on Board Ships as defined by the IMO [Mar12].

	Visual	**Tactile**	**Auditory**
Onbody	√ Section 5.3	√ Section 5.3, Section 5.4	- not suitable
Environment	√ Section 5.2	- not suitable	√ Section 5.5

Table 5.1: Overview of the investigated modality - placement combinations, and where they were addressed in this thesis.

In the following sections, we present the research that we conducted to further investigate the proper design of spatial guidance cues for all suitable modality - placement combinations shown in Table 5.1.

5.2 Light-controlled Attention Guidance for Multi-Monitor Environments

Multi-monitor systems are a common setup for the monitoring of large safety-critical systems, such as control rooms of emergency centers, power plants or ship bridges, as they allow for the display of all relevant information in parallel. These systems offer a complete overview. However, human factors research tells us that humans cannot pay attention to all of the information at the same time. Typical problems are attention tunneling, data overload, and fatigue (c.f. [SB16]).

The central research question of this section is: *How can the attention of a user of multi-monitor systems, captured by eye-tracking, be directed to the target monitor by ambient LED light signals?* This question is based on the assumption that the attention of a person is at that point where the person's visual focus is.

We used a mobile eye-tracker to determine a user's attentional focus. The user's attention was then guided via LED light signals. By means of literature research and interviews with experts, we developed three guidance strategies and corresponding light patterns.

For the study, a ship bridge has been chosen as the scenario location, as this is a place where the attention of one person on several instruments is needed almost simultaneously. A mobile ship bridge simulator represents this environment. The scenario for the study was a trip with a ship along a river.

Our results show that a simple running light that moves from a source to a target monitor is the most efficient.

Attention guidance for multi-monitor systems is possible and useful by means of ambient light signals. The use of ambient light signals proved to be a suitable method for guidance, as did the use of an eye-tracker to capture attention.

5.2.1 Related Work

There are different approaches in related work for attention guidance through ambient light cues.

Tscharn et al. studied the influence of different ambient light conditions on gaze directions for attention guidance [TLTLH16]. They found that even though the participants did not notice the effect, their gaze was drawn towards the side that was more illuminated by the ambient light. Müller et al. used an ambient light display behind a monitor to unobtrusively remind users of an upcoming appointment in the periphery of their attention [MKHB16]. Booth et al. used projected visual cues on different parts of the environment to shift the user's attention to the position of the projected cue [BSM+13]. The results of their user study showed that they could effectively guide the user's gaze in a real-world environment using projected visual cues. Gutwin et al. studied visual popout effects in the human field of view and the accuracy of locating these manipulating different visual parameters. They used a three monitor setup to display their visual stimuli. As a result, they identified motion as a strong popout effect and found that the location accuracy for shape and color decreased rapidly across visual angles [GCC17]. Löcken et al. conducted an experiment comparing faded in or abruptly turned on LED-based stimuli in the periphery or in front of subjects to direct their attention [LBS+17]. Pomarjanschi et al. investigated LED arrays in a driving simulator to guide attention using gaze-contingent cues [PDBB13]. Alt et al. guided users in front of public displays using on-screen visual cues [ABGB15].

Fortmann et al. presented an assistance system that helped users to recover the mouse pointer in multi-display environments using visual on-screen cues [FNB+15].

5.2.2 Concept

In order to support the monitoring process, we propose to guide the attention of a user by incorporating the current user focus using an eye-tracker. A display is used to guide the attention of a user from one Area of Interest (AOI) to another. We propose and compare the following three guidance strategies:

Trace A trace from the currently focused monitor to the target monitor.

Pickup A signal at the currently focused monitor followed by a trace towards the target monitor.

Call A signal at the target monitor followed by a trace from the currently focused monitor to the target monitor.

These guidance strategies have been implemented by corresponding light patterns on a light display. The following two sections describe how we derived the design of each light pattern and how we implemented the light display rendering the patterns.

5.2.3 Light Pattern Design

Based on literature research, we created four different designs of light patterns. We conducted five expert interviews with HCI experts with 5 years of experience on average. The participants (2 females) were between 28 and 31 years old ($M = 29.00, SD = 1.30$). We presented our light pattern designs to the experts and discussed improvements and design recommendations. Further, we discussed with the experts where to place the light display rendering the pattern.

As a medium of communication in the interviews, we used an RGB LED strip controlled by an Arduino Uno to demonstrate our light pattern designs and a paper sketch of a multi-monitor setup, where the experts could draw in their placement recommendations.

There were two main results from the interviews. First, the light pattern should be implemented using a color that is unassigned in most multi-monitor environments, such as violet, to avoid misinterpretations, as many colors have certain semantics in many environments. Second, moving lights are to be preferred before pulsing or blinking lights.

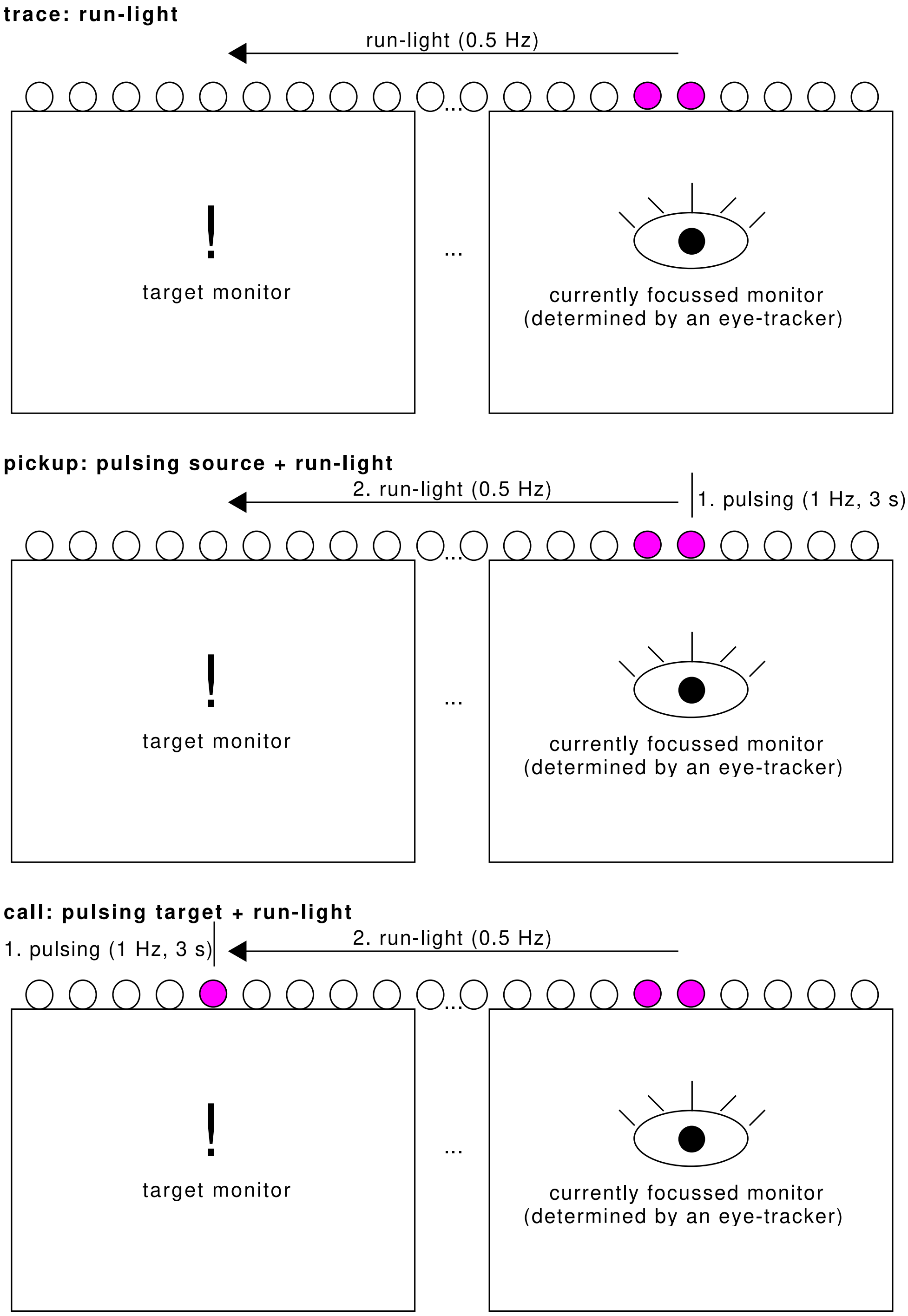


Figure 5.2: Guidance strategy implementations as light pattern on a horizontal LED light display. For each implementation, the run-light was running until the eye-tracker detected a fixation on the target monitor.

Further, the light pattern should not be dazzling, hence we decided to dim the led display adaptively using a light sensor to adjust the brightness of the display to the current environmental conditions. Concerning the placement of the light display, the experts agreed to put it on top of each multi-monitor row, extending horizontally. The final light pattern designs were:

Run-light (trace) A violet running light from the top-center of the currently focused monitor to the top-center of the target monitor.

Pulsing source (pickup) A violet light pulsing three times (1 Hz) on the top-center of the currently focused monitor, followed by a violet running light from the top-center of the currently focused monitor to the top-center of the target monitor.

Pulsing target (call) A violet light pulsing three times (1 Hz) on the top-center of the target monitor, followed by a violet running light from the top-center of the currently focused monitor to the top-center of the target monitor.

Figure 5.2 illustrates the three aforementioned strategy implementations for attention guidance in a multi-monitor environment.

5.2.4 Light Display Implementation

We used RGB LEDs of the type WS2812B[2] assembled in a strip of 144 LEDs per meter for the implementation of our light display. The light display consisted of aluminum bars which were mounted and connected with each other using 3D printed parts. Inside the aluminum bars, we put the RGB LED strips and frosted acrylic glass as a diffuser on top. We implemented an adaptive brightness control of the light display using an ambient light sensor of the type TEMT6000X01[3]. The display was controlled by an Arduino Uno that was connected to a computer for the communication with the eye-tracker.

[2] `https://cdn-shop.adafruit.com/datasheets/WS2812B.pdf`, last retrieved: July 5, 2021

[3] `http://www.vishay.com/docs/81579/temt6000.pdf`, last retrieved: July 5, 2021

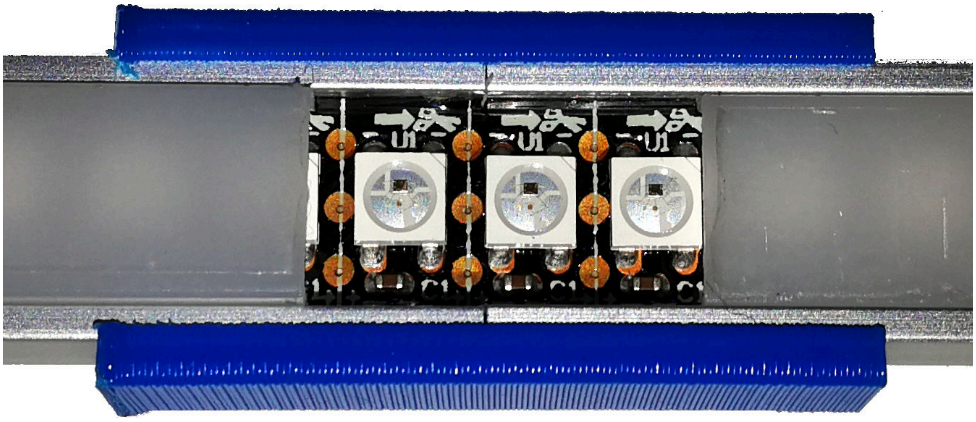


Figure 5.3: The light display consisted of aluminum bars which were mounted and connected with each other using 3D printed parts. Inside the aluminum bars, we put RGB LED strips and frosted acrylic glass as a diffuser on top.

5.2.5 Lab Study: Ship Handling

For our laboratory study, we chose the use case of ship handling as it involves the monitoring of spatially spread information on a one-dimensional multi-monitor system. As a ship bridge simulator, we used the Mobile Bridge multi-monitor system by Stratmann et al. [SGS+18] running the Bridge Command[4] ship simulator.

5.2.5.1 Study Design

We compared three light patterns, one for each strategy (run-light, pulsing at source, pulsing at target) in a counterbalanced manner. We measured the time to first fixation (TTFF), usability, obtrusiveness, annoyance, urgency, and collected qualitative feedback. The TTFF is a common measure in eye-tracking and is defined as the time between stimuli onset and the first fixation on an AOI. As a measure of usability, we used the standardized System Usability Scale (SUS) questionnaire [Bro96]. Obtrusiveness, annoyance, and urgency were rated via five-point Likert items. We hypothesize that the light pattern pulsing target (call) induces the shortest time to first fixation, as it implements a cue directly at the target position that is visible in the peripheral field of view of the user. Due to the shorter duration of the cue, we expect run-light (trace) to be the second fastest cue.

[4] `https://www.bridgecommand.co.uk/`, last retrieved: July 5, 2021

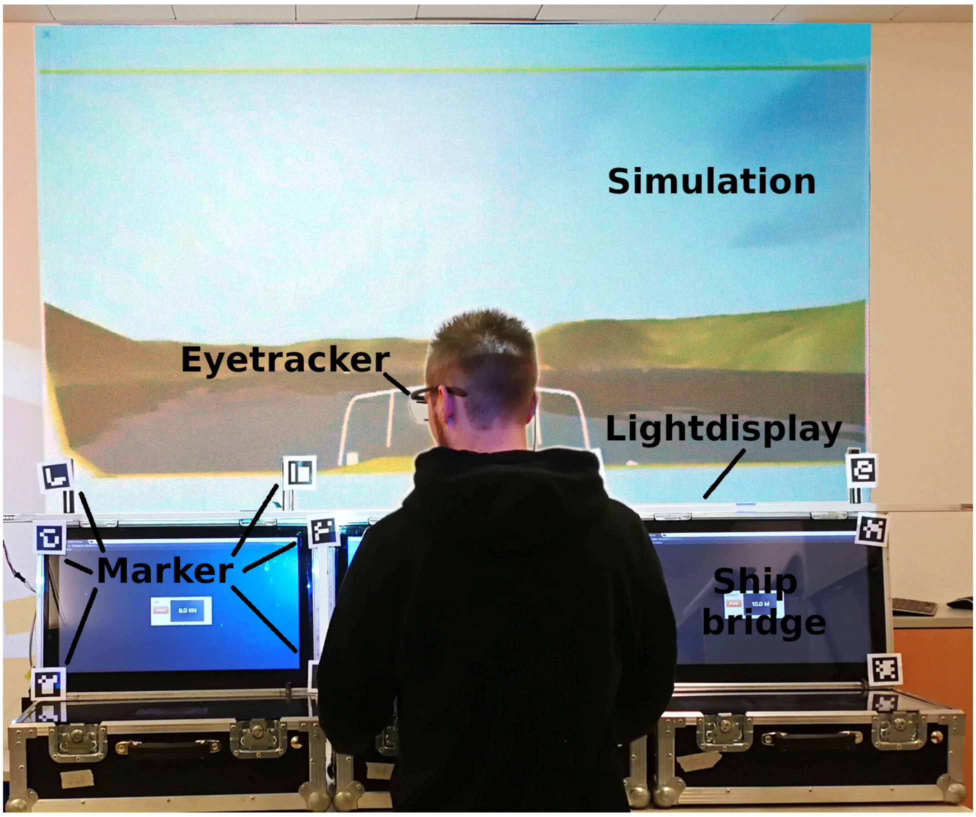


Figure 5.4: The study setup consisted of a projected environment simulation and three monitors assembling a ship bridge interface. The light display mounted on top of the monitors, as well as the monitors themselves, were marked as AOIs for the eye-tracker worn by the participant using ARuco markers.

5.2.5.2 Participants

We recruited 10 participants (5 females), aged between 20 and 28 years ($M = 24.30, SD = 2.16$). Only people without color blindness and normal or corrected to normal vision participated. As the goal of this study was to compare the response of human operators in multi-monitor environments to the different guidance strategies, there were no domain specific requirements concerning participants. Therefore the pool of participants was not limited to persons with maritime background. All participants were given detailed instructions about the procedure, task and control of the simulator paired with a 10 minute training session.

5.2.5.3 Apparatus

The laboratory study was conducted in a controlled environment. The ambient lighting was kept at constant daylight per participant. Figure 5.4 shows a sketch of the setup. It consisted of a projected environment simulation and six 22 inch LCD monitors in total, assembling a ship bridge interface. The top three monitors were used as source or target for the study. They were marked as AOIs for the eye-tracker worn by the participant using ARuco[5] markers. Also, the three parts of the light display above each monitor were marked as separate AOIs using this technique. The eye-tracker used in the study was a Tobii Pro Glasses 2[6]. The top-left displayed displayed the log with speed through water, the center display showed the radar, and the top-right display showed the echo sounder with depth in meters. The lower three displays were no AOIs and showed from left to right: NAVTEX weather receiver, ship controls (turn rate indicator, rudder, machine telegraph), and VHF radio.

5.2.5.4 Procedure

As scenario for the ship handling simulation, we chose the navigation on a narrow canal without traffic as an adaption of our representative scenario described in Section 3.4. Removing the incoming and overtaking traffic from the scenario allowed laymen to handle the virtual ship more easily. The task of the participants was to follow the fairway on the canal marked by buoys while keeping a speed between 5 and 7 nautical knots. Each participant started with a 10 minute training session to become used to the simulator. After training, the eye-tracker was calibrated followed by three blocks, one for each light pattern. In each block, the corresponding light pattern was presented ten times. After each block, the participants had to fill out a SUS and our own questionnaire rating obtrusiveness, annoyance, and urgency. The order of the blocks was counterbalanced between participants to mitigate its effect on the results. In the end, there was a short debriefing interview.

5.2.5.5 Results

Shapiro-Wilk tests showed that our data are not normally distributed ($p < .001$). Hence, we performed non-parametric tests to identify significant differences. We performed Friedman rank sum tests and posthoc Wilcoxon signed-rank tests with Holm-Bonferroni adjustments for pairwise comparisons.

Time to First Fixation

A Friedman test revealed significant differences in $TTFF$ between the light patterns ($\chi^2\,(2) = 8.88, p < .05$).

The pairwise comparisons showed that the $TTFF$ of run-light (trace) was significantly shorter than pulsing at target (call) ($W = 1867, Z = -2.26, r = .72, p < .05$), as well as it was significantly shorter than pulsing at source

[5] `https://www.uco.es/investiga/grupos/ava/node/26`, last retrieved: July 5, 2021
[6] `https://www.tobiipro.com/products/tobii-pro-glasses-2`, last retrieved: July 5, 2021

(pickup) ($W = 1701, Z = -2.83, r = .90, p < .05$). With an effect size of $r = .72$ and $r = .90$ respectively, both effects are large. However, there were no significant differences in $TTFF$ between pulsing at target (call) and pulsing at source (pickup) ($W = 2200.5, Z = -1.12, r = .35, p = .27$). With an effect size of $r = .35$, the observed effect is of medium size. Figure 5.5 shows a comparison of TTFFs between all three conditions.

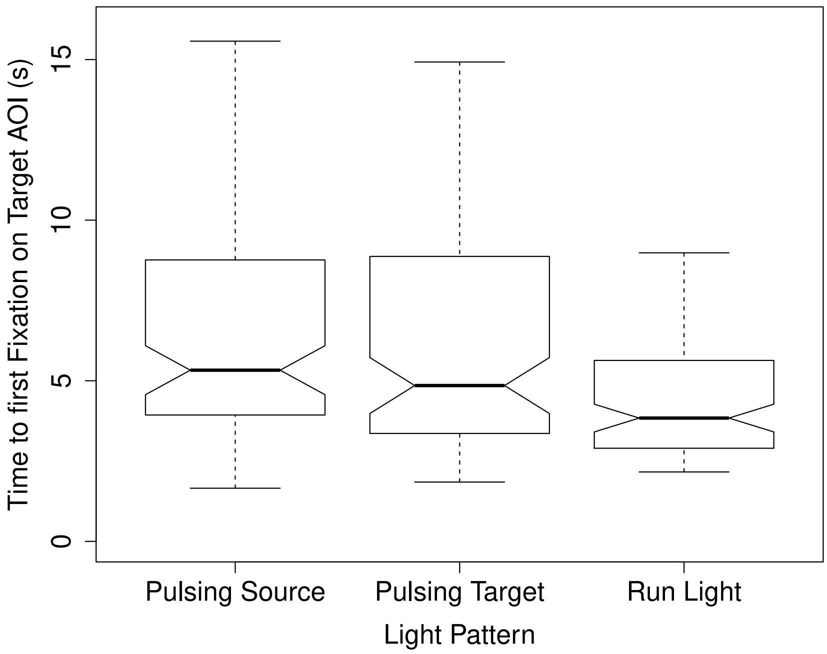


Figure 5.5: Comparison of the times to first fixation (TTFF) on the target monitors (AOI) between the light patterns.

Usability

A Friedman test revealed significant differences in *Usability* between the light patterns ($\chi^2(2) = 8.32, p < .05$). However, pairwise comparisons using Wilcoxon signed-rank tests with Holm-Bonferroni showed no significant differences. The light pattern run-light (trace) achieved a SUS score of 87.5 ($SD = 13.28$). The same score was reached by the pattern pulsing at target (call) with a SUS score of 87.5 ($SD = 13.69$). The light pattern pulsing at source (pickup) was rated with a lower usability, achieving a SUS score of 80.5 ($SD = 19.39$).

Obtrusiveness

A Friedman test revealed no significant differences in *Obtrusiveness* between the light patterns ($\chi^2(2) = 2.80, p = .25$). All three strategies have been rated as being unobtrusive, with call($Mdn = 1.50, IQR = 2.00$) being rated slightly more obtrusive than pickup ($Mdn = 1.00, IQR = .75$) and trace ($Mdn = 1.00, IQR =$

.75). However, this difference is not statistically significant.

Urgency

A Friedman test revealed no significant differences in *Urgency* between the light patterns ($\chi^2(2) = .40, p = .82$). The strategy pickup ($Mdn = 4.50, IQR = 1.00$) was rated as being slightly less urgent than call ($Mdn = 5.00, IQR = 1.75$) and trace ($Mdn = 5.00, IQR = 1.75$). However, this difference is not statistically significant.

Annoyance

A Friedman test revealed no significant differences in *Annoyance* between the light patterns ($\chi^2(2) = .42, p = .81$). All three strategies, trace ($Mdn = 1.00, IQR = .00$), pickup ($Mdn = 1.00, IQR = 1.00$), and call ($Mdn = 1.00, IQR = 1.00$), were rated as not annoying.

Qualitative Remarks

In the debriefing interviews, participants stated that the light pattern helped them monitor the instruments. However, some participants stated concerns of confusion when working with multiple persons in front of a multi-monitor system.

5.2.5.6 Discussion

Our hypothesis of pulsing target (call) being the fastest condition was not confirmed. Although the participants perceived the pulsing target (call) as slightly more obtrusive, it was significantly slower than run light (trace), but not significantly faster than pulsing source (pickup). Run light (trace) was the fastest condition, with no significant differences in usability, obtrusiveness, urgency or annoyance to the other conditions. This shows that a simple trace towards the target without prior attention arousal is sufficient for attention guidance in horizontal multi-monitor environments, such as ship bridges. However, we did not investigate cross-modal effects and domain-specific influences of environmental conditions, such as acoustical and vibrational noise as they could occur in reality on ship bridges. We further expect domain experts to experience less workload compared to laymen or novices during a task similar to the study task, potentially benefiting the arousal of attention.

5.2.6 Conclusion

We presented three different guidance strategies (trace, call, pickup) for spatial attention guidance in multi-monitor systems. We implemented and compared these strategies through the example of a ship bridge using a light display. Our findings indicate that ambient guidance cues that begin at the current focus of the user are faster in guiding the user to a target in the periphery than ambient guidance cues in the peripheral vision of the user. Although most multi-monitor systems have a larger extent on the horizontal plane, future work should also investigate how to translate between vertical planes. Further, the use of polarization filters like they are used in 3D glasses could enable multiple users to use our guidance system at the same time. We are planning to investigate the feasibility of such an approach for two users in parallel.

5.3 Exploring Peripheral and Vibrotactile On-body Cues

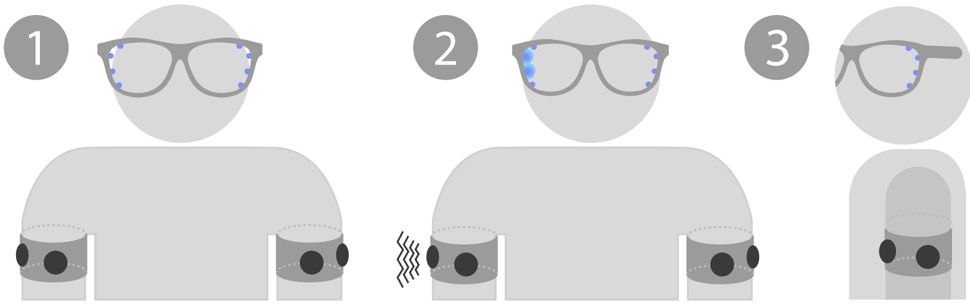


Figure 5.6: Person wearing a vibrotactile and a peripheral light display (1). Visual or vibrotactile cues arouse and direct the individual's spatial attention (2). The person follows the cue to find the information in demand of attention (3).

Cyber-physical systems can be described as systems of collaborating computational elements controlling physical entities such as automated cars, medical monitoring systems, autonomous ships, or process control systems [GB15]. As automation in these cyber-physical systems increases, we face the challenge of interacting with them in potentially complex physical environments. Instead of a single screen with a focused area of attention, we see multiple displays, devices, and interfaces loosely orchestrated into a larger, more complex, and potentially spacious cyber-physical system.

Receiving critical information currently often depends on perceiving primitive and unspecific alerts. This information can easily be missed in noisy and spacious environments. Even if it is perceived, it leaves the individual with the demanding task of identifying and localizing the problem, which usually increases cognitive load and alert fatigue. In these cases, the situation awareness is negatively affected because of a lacking perception of relevant information [End95]. In the past, many serious incidents happened due to a lack of situation awareness [SB16]. The complexity of cyber-physical systems or simple time pressure, demands more efficient human response to avoid further incidents. Humans interacting with the system should be able to perceive relevant information without using their cognitive resources on retrieving them.

We aim to shift attention by augmenting the user with on-body vibrotactile and peripheral displays. Instead of signaling the human with visual or auditory signals located at the information, we propose to shift the attention to the position of the information by cueing the user with on-body displays.

We designed two tactile displays placed on the upper arm and a visual display placed in the periphery. The vibrotactile displays consist of three vibration motors each. The visual display consists of a pair of safety glasses with eight integrated RGB LEDs. We conducted two user studies investigating four basic patterns on both displays.

We propose two research contributions:

1. We designed two on-body displays, a visual and a tactile display, for attention shift in spacious environments.

2. We evaluated the displays with four cue patterns in a 90° seated scenario and a 360° standing scenario.

5.3.1 Related Work

Shifting the visual attention includes spatially orienting it to the new target [Pos80]. Posner and Petersen describe three phases of attention shift: The Disengagement from the current target, the shift of attention from one stimulus to another and the focus of attention to a new target [PP90]. Several existing works apply the concept of attention shift for attention guidance. There are different approaches to design and place cues.

Visual Cues in the Environment

Booth et al. used projected visual cues on different parts of the environment to shift the user's attention to the position of the projected cue [BSM+13]. The results of their user study showed that they could effectively guide the user's gaze in a real-world environment using projected visual cues. Tscharn et al. studied the influence of different ambient light conditions on gaze directions for attention guidance [TLTLH16]. They found that even though the participants did not notice the effect, their gaze was drawn towards the side that was more illuminated by the ambient light. Gutwin et al. studied visual popout effects in the human field of view and the accuracy of locating these manipulating different visual parameters. They used a three monitor setup to display their visual stimuli. As a result, they identified motion as a strong popout effect and found that the location accuracy for shape and color decreased rapidly across visual angles [GCC17].

On-body Visual Cues

Renner and Pfeiffer investigated different peripheral and in-view Attention Guidance techniques for augmented reality applications [RP17]. Danieau et al. designed four different virtual effects to guide the attention of a user in a virtual reality scene and investigated two of them in a user study [DGD17].

Apart from augmented and virtual reality applications, on-body visual cues are used in wearable peripheral displays. Poppinga et al. studied a pair of glasses with 12 LEDs placed in the periphery of the user's field of view [PHF+12]. They found that the user could identify the rough position of LEDs with 92% accuracy and that their technique is suitable to encode directions. Other examples for peripheral displays in glasses are the works of Costanza et al. [CIP+06] and Lucero et al. [LV14].

On-body visual cues have also been explored for other body locations than the head. Harrison et al. investigated wearable visual cues on seven different body locations between the shoulders and feet and measured the respective reaction times [HLSH09a]. They measured average reaction times over 15 seconds for all investigated body locations. However, they found that the response times were faster when a user observed the state change of the light. Lyons investigated different visual parameters to draw the users attention to information on a wrist-worn smartwatch [Lyo16]. Ashbrook et al. measured device access times for three on-body locations [ACL+08].

On-body Tactile Cues

Vibrotactile feedback has been explored on various body locations to encode directions in navigation tasks. Tsukada et al. and Heuten et al. used wearable vibration integrated into a belt to encode directions [TY04, HHBP08]. Dobbelstein et al. investigated vibrotactile cues on a wristband for navigation [DHR16]. Kaul and Rohs created HapticHead, a system for haptic spatial guidance. It consists of multiple vibrotactile actuators distributed around the head. They compared it to auditory cues (generic head-related transfer function) and visual cues as a baseline. While their system did not perform better than the visual baseline, it was faster and more accurate than the auditory cues [KR17].

Complementing related work, we designed four light patterns inside a pair of glasses and four vibrotactile patterns which are located on both upper arms. We tested how effective these patterns can direct attention without annoying the wearer.

5.3.2 Directional Cue Design

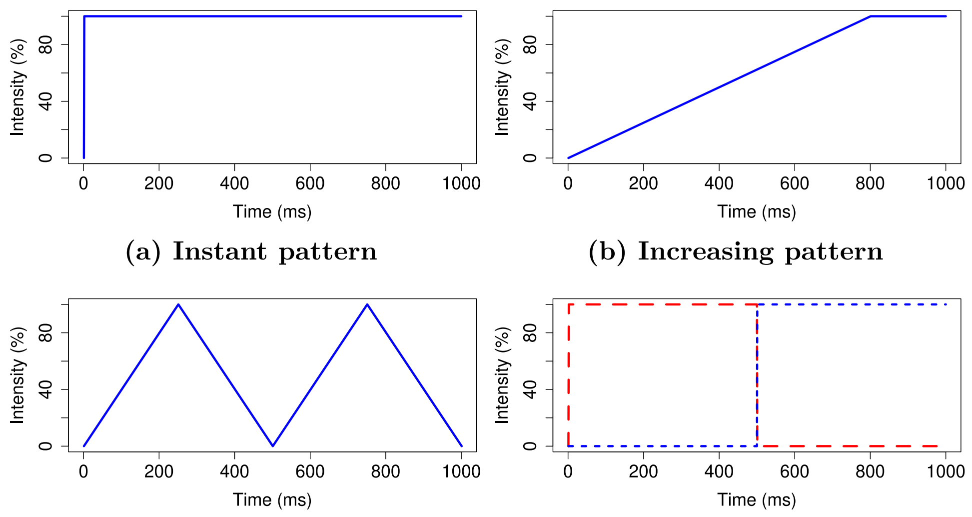
Based on the findings of Harrison et al., we decided to use visual stimuli using light in the peripheral field of view to ensure the immediate perception of the cues [HLSH09a]. Further, we were interested in the differences between the modalities for similar cues in different body worn positions. In the following, we describe the four patterns that were used in our experiments. All of them use intensity as a parameter that changes over time, as sketched in Figure 5.7.

The simplest patterns are *InstaLight* and *InstaVibe*. As soon as the cue is triggered, the intensity of the outer actuators is instantly increased to the maximum defined level as depicted in Figure 5.7a). This cue is commonly used as status indicator.

IncLight and *IncVibe* use an increasing intensity for the first 800 ms and stay at the maximum level (see Figure 5.7b). The duration is based on findings by Löcken et al. [LBS+17]. We expect this smoother activation to be perceived as less annoying than *InstaLight* and *InstaVibe*.

PulseLight and *PulseVibe* use triangular functions with a peak at 250 ms and 750 ms (see Figure 5.7c). We expect pulsing cues to be perceived as more annoying but to result in faster response times.

MovLight and *MovVibe* first activate the inner actuators for 500 ms and then activate the outer ones at full intensity. The sequence for both actuator groups is shown in Figure 5.7d. We designed this kind of cue to explore how using the spatial dimension affects reaction times and perceived annoyance.



(a) Instant pattern

(b) Increasing pattern

(c) Pulsing pattern

(d) Moving pattern

Figure 5.7: Intensity of vibration or blue light channel, respectively, over time for all four cues. The solid or short dashed lines represent the outer actuators and the long dashed line the inner actuators, which were only used in the *Moving* cue pattern.

We used flat 3V cellphone vibration motors of the type C0834B011F[7] to implement our tactile patterns and RGB LEDs of the type WS2812B[8] on pre-assembled stripes to implement our light patterns. As the vibration of the motors is created by an eccentric rotating mass, they have a latency range from 40-60 ms. The patterns on the armband used at least one vibrotactile motor, while the cues in the glasses used at least two LEDs with blue lights. We decided to use blue light as it is the best perceivable color in the periphery of human perception [BD80]. Apart from one cue design, all designs use the two most left or right LEDs in the glasses or the vibrotactile motors pointing away from the participant, as sketched in Figure 5.6. The inner actuators are one LED closer to the participant on the glasses or the vibrotactile motors that are pointing towards the participant, respectively.

As the related work shows, position and intensity of the cue are appropriate parameters for orientation and notification purposes when using light displays [RMC+15]. Hence, we used these parameters. We did not change the color of the light or the frequency of the vibrotactile display. The intensities for the vibrotactile cues ranged from 17.6% to 100% and the brightness of the blue channel of the LEDs from 0% to 19.6%. However, these borders are specific to our hardware and were chosen to range from “just noticeable” to “still bearable” by two participants in a pretest.

5.3.3 Lab Study: Seated 90°

We performed a lab study in order to assess the effect of our attention shift cues on reaction time in a multitasking environment with induced workload. We simulated a monitoring workplace environment with two displays. We equipped participants with our LED-glasses and our vibrotactile armbands.

5.3.3.1 Design

Our lab study compared nine conditions. All conditions were counterbalanced using a balanced Latin Square. They were presented in three slots, one slot with four visual cues, one slot with four vibrotactile cues and one slot without any cue support. The dependent variables were button response time, perceived annoyance, perceived urgency, perceived alarmingness, and perceived pleasantness.

5.3.3.2 Participants

We recruited 20 participants (6 females), aged between 21 and 65 years ($M = 28.4, SD = 8.92$). Only people without color blindness and normal or corrected to normal vision participated. The goal of this study was to compare the response

[7] https://www.mpja.com/download/19229md.pdf, last retrieved: July 5, 2021
[8] https://cdn-shop.adafruit.com/datasheets/WS2812B.pdf, last retrieved: July 5, 2021

of human operators to the different cue designs utilizing exogenous orienting. To achieve a high internal validity in this exploratory study, we strongly controlled the study setup and refrained from using a maritime scenario, as this would have introduced too many confounding variables in this exploratory experiment. Therefore, the task in this experiment is a widely used task in psychological experiments that requires no nautical experience, which is why the pool of participants was not limited to persons with maritime background.

5.3.3.3 Apparatus

The laboratory study was conducted in a controlled environment. The ambient lighting was kept constant per participant. Figure 5.8 shows a sketch of the setup. It consisted of two spatially separated 19” LCD screens on a table. The distance between them was about 130 cm. The participant was sitting in front of the screens at a distance of 90 cm to each screen. A 10" Android tablet was placed in front of the participant.

A laptop controlled the two LCD screens displaying a large random number within the range of one to three in white font on a black screen. The tablet PC was used to display a visual 1-position-back task [Kir58] and a questionnaire between the conditions. We further equipped the participants with the glasses or armbands, depending on the task. A remote control was handed to the participants to respond to the response task as described in the next section. The remote control was wireless and consisted of three buttons.

5.3.3.4 Procedure

The participant was asked for demographic data. Each participant started either with the glasses, the armbands or without any support.

Each of the four cues was tested for 5 minutes, followed by a short questionnaire. In the questionnaire, the participants had to rate four statements on Likert items from one to six (*strongly disagree* to *strongly agree*). The statements were: ”I perceived the cue as annoying.”, ”I perceived the cue as urgent.”, ”I perceived the cue as alarming.”, ”I perceived the cue as pleasant.”

Within these 5 minutes slots, each cue was shown twice directing to the left and twice directing to the right in a counterbalanced manner. A cue is triggered randomly every 55 to 65 seconds. At the same time, a random number appears on the corresponding screen left or right to the participant. The participant is instructed to react as quickly as possible to a cue via pushing the correct button on the remote control. If the user does not respond within 5 seconds, the missing response is logged, and the system continues with the next cue. To increase the participant’s workload and ensure that his or her attention does not stay at the screens, participants are also instructed to perform a visual 1-position-back task on the tablet PC as good as possible during each trial.

In a debriefing interview, the participants had to vote for the condition with the highest experienced workload. Any qualitative remarks by the participants were recorded. Overall, the experiment took about 60 minutes per participant.

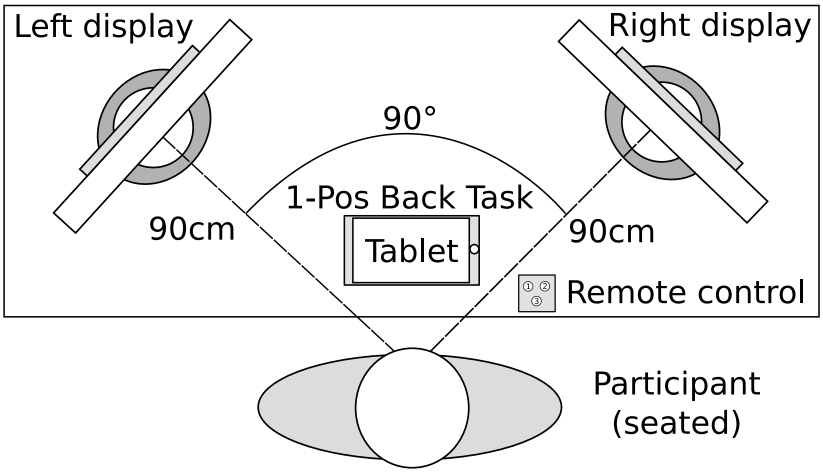


Figure 5.8: Sketch of the study setup. The participant sat in front of a tablet PC and two 19" screens to the left and right.

5.3.3.5 Results

Shapiro-Wilk tests showed that our data is not normally distributed ($p < .001$). Hence, we performed non-parametric tests to identify significant differences. We performed Friedman rank sum tests and posthoc Wilcoxon signed rank tests with Holm-Bonferroni adjustments for pairwise comparisons.

Error rate

We measured the error rate of the shift in attention by counting the number of wrong button presses. Overall, the participants did not respond to 10 out of a total of 720 stimuli (1.4%). Nine of these misses occurred in the condition *without* cues and one miss in the *InstaLight* condition. Therefore, the error rate was 0% for all conditions except *without* (11.25%) and *InstaLight* (1.25%).

Response times

A Friedman test revealed significant differences in response time between conditions ($\chi^2(6) = 20.30, p < .01$). Post-hoc Wilcoxon tests showed significant differences between *InstaVibe* and *IncLight* ($p < .01, r = .80$), *InstaVibe* and *MovLight* ($p < .01, r = .89$), and *InstaVibe* and *PulseLight* ($p < .01, r = .79$). The median response times are shown in Figure 5.9. Without cues, the mean response time was 2.48s ($SD = .89$). The mean reaction times for most other cues were slower. Only using *InstaVibe* resulted in a slightly faster button response time with a mean value of 2.41s ($SD = .71$). Comparing modalities, reaction times with cues using light are slightly slower than reaction times with vibrotactile cues.

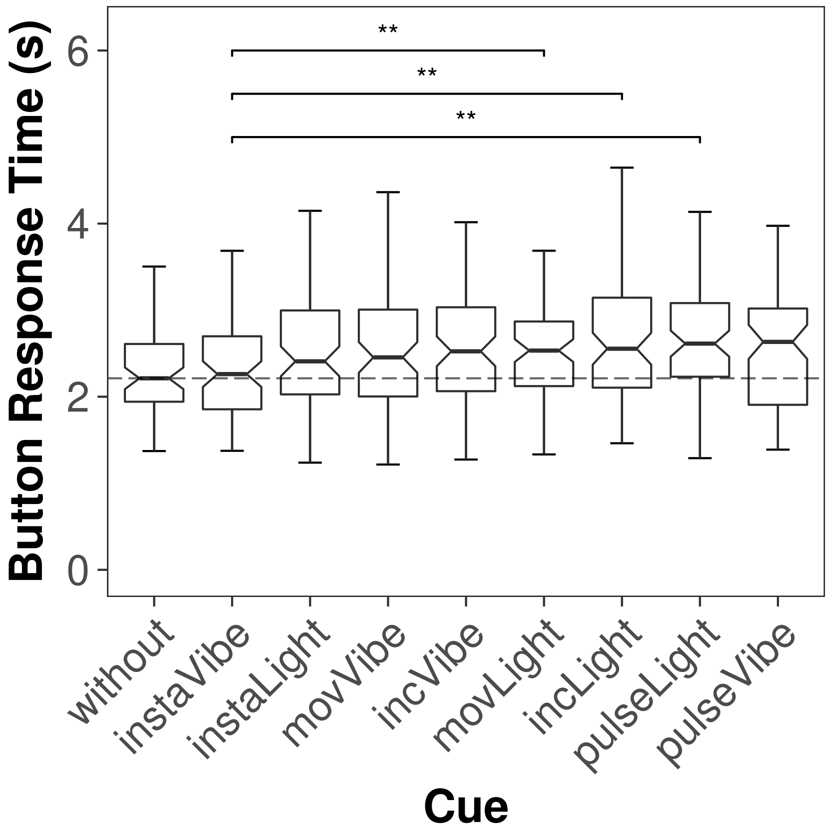


Figure 5.9: Response times for button press. The dashed line marks the median for the *without* condition ($p < .01$).**

Subjective measures

Looking into *Annoyance*, all cues were rated below three on average, indicating that most participants did not perceive the cues as annoying. The most annoying cue is *movVibe* ($M = 2.8, SD = 1.4$), while the least annoying cue is *instaVibe* ($M = 1.75, SD = .91$). A Friedman test indicated that there was a significant effect of the *cue* on *perceived annoyance* ($\chi^2(7) = 20.41, p < .01$). However, a pairwise comparison using Wilcoxon tests did not reveal any significant differences between individual cues.

With an average above four for most cues, most participants seem to perceive the cues as *urgent*. The least urgent cue is *IncLight*. With a mean rating of 3.6 ($SD = 1.19$), more participants agreed with it being urgent than not. The most urgent cue is *MovVibe* ($M = 5, SD = .79$). The Friedman test indicated significant differences in *perceived urgency* between the cues ($\chi^2(7) = 20.65, p < .01$). However, pairwise comparisons using Wilcoxon tests did not show significant differences.

All cues were rated to be less *alarming* than *urgent*. *MovVibe* ($M = 4.25, SD = 1.37$) is the most alarming cue, while *IncLight* ($M = 2.75, SD = 1.48$) was rated to be the least alarming cue. Looking into the distributions, most cues seem to be neither alarming nor not alarming, which is reflected in the mean values between three and four for most cues. However, we were able to observe a significant difference between the cues for *perceived alarmingness* ($\chi^2(7) = 20.47, p < .01$). A Wilcoxon test showed significant differences between *IncLight* and *MovVibe* ($p < .05, r = .77$).

With averages above four, all cues were perceived as *pleasant* to some extent. The most pleasant cue is *IncVibe* ($M = 5.2, SD = .77$). The least pleasant cue is *MovVibe* ($M = 4.25, SD = 1.33$). There was a significant effect of the *cue* on *perceived pleasantness* ($\chi^2(7) = 20.48, p < .01$). Pairwise comparisons showed no significant differences.

All Participants stated that they experienced the highest workload in the condition without any supporting cues.

5.3.3.6 Discussion

Our results show that all investigated cues were on average rated as urgent but not annoying. The annoyance level depends on the individual cue. Also, as our participants remarked, the brightness of the visual display and the intensity of the tactile stimuli should dynamically adjust to the environment. The cues have to be obtrusive enough to build up the trust of the user, the user will not rely on cues he or she fears to miss. With only one miss for the visual display, the placement of the visual and tactile display ensured a high perception rate of the presented stimuli. The low error rates for conditions with cue support compared to no support suggest that cue support results in a performance improvement of the user. Interestingly, we can observe a clear difference in *perceived urgency* between increasing and constant patterns as well as pulsing and moving patterns for visual and tactile stimuli.

5.3.4 Lab Study - Standing 360°

We performed a second lab study to test our patterns for targets in 360°. This included targets in the field of view of the user as well as targets outside of it, e.g. behind the user. In this study, we again equipped our participants with our LED-glasses and our vibrotactile armbands.

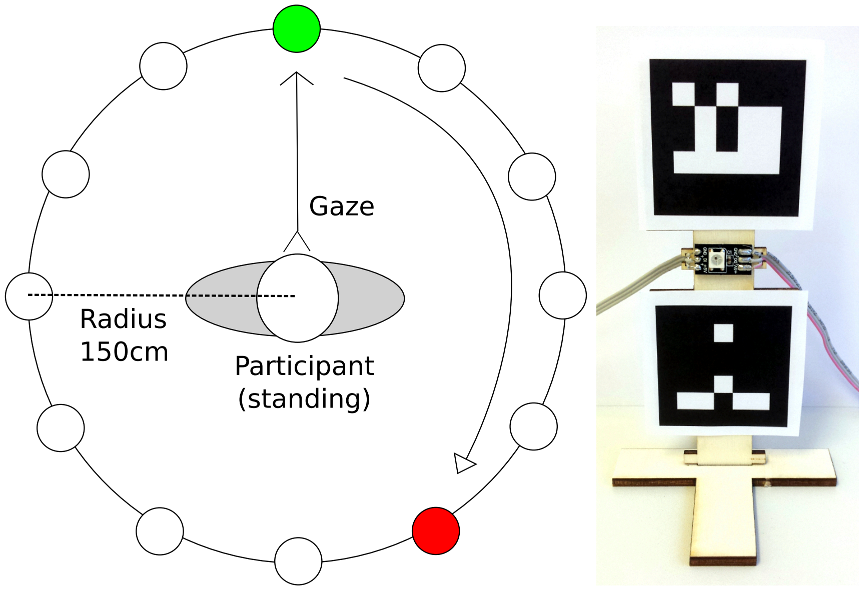


Figure 5.10: Sketch of the second study setup. The participant is placed in the center of a 150 cm radius circle with 12 RGB LED pillars. Each Pillar consists of two optical markers from an ARuco dictionary and one RGB LED.

5.3.4.1 Design

The experiment was a 2 x 3 within-subjects design. All conditions were counterbalanced using a balanced Latin Square. The patterns for this study are *increasing* and *pulsing*. The pattern *increasing* derived from *incVibe* and *incLight* as the most effective patterns with low urgency ratings for each modality. The pattern *pulsing* derived from *pulseVibe* and *pulseLight* as the highest urgency patterns with low annoyance ratings for each modality. The two independent variables were pattern (*increasing*, *pulsing*) and modality (*light*, *vibration*, *light + vibration*). The dependent variables were time to target acquisition, gaze response time, usability and perceived workload. Each condition was repeated 12 times in slots, resulting in a total of 72 measurements per participant.

5.3.4.2 Participants

We recruited 20 participants (8 females), aged between 20 and 65 years ($M = 28.85, SD = 9.06$) without color blindness and normal or corrected to normal vision. The goal of this study was to compare the response of human operators to the different cue designs utilizing exogenous orienting. To achieve a high internal validity in this exploratory study, we strongly controlled the study setup and refrained from using a maritime scenario, as this would have introduced too many confounding variables in this exploratory experiment. Therefore, the task in this experiment is a widely used task in psychological experiments that requires no nautical experience, which is why the pool of participants was not limited to persons with maritime background.

5.3.4.3 Apparatus

The laboratory study was conducted in a controlled environment. The ambient lighting was kept constant per participant. Figure 5.10 shows a sketch of the setup, which consisted of 12 circular equidistantly placed pillars. Each pillar consists of two optical markers from an ARuco dictionary[9] and one WS2812B RGB LED (Figure 5.10). The radius of the resulting circle was 150 cm. During the experiment, the participant was located in the center of the circle. The participant was wearing eye-tracking glasses to interact with the pillars through his or her gaze. We defined the interaction area of each LED as a circle with the LED as the center and a radius of the distance between the centers of the upper and lower marker of the pillar.

5.3.4.4 Procedure

Each participant was asked for demographic data. Afterward, the head-worn eye-tracker, a Tobii Pro Glasses 2[10], was calibrated. The modality was counterbalanced, hence, a participant started either with the glasses, the armbands or both. The pattern was counterbalanced as well.

The task of the participant was to focus on the currently highlighted green LED and shift his or her focus to the next highlighted LED, when he or she perceived a cue from the current prototype(s). The cue lasted until the target was acquired. It always gave the direction to the target LED and the target LED was highlighted in red. When the participant's gaze reached the area of the target LED it turned green and the previously focused LED was turned off. This was repeated 12 times per slot with five seconds delay between the end of a shift and the start of the next shift. The start LED changed per slot in a counterbalanced manner. After each slot, the participants were asked to complete two questionnaires, a System Usability Scale [Bro96] and a RAW-TLX form [Har06].

In a debriefing interview, the participants had to pick a favorite. Any qualitative remarks by the participants were recorded. Overall, the experiment took about 60 minutes per participant.

[9] `https://www.uco.es/investiga/grupos/ava/node/26`, last retrieved: July 5, 2021
[10] `https://www.tobiipro.com/product-listing/tobii-pro-glasses-2/`, last retrieved: July 5, 2021

5.3.4.5 Results

Shapiro-Wilk tests showed that our data are not normally distributed ($p < .001$). Hence, we performed non-parametric tests to identify significant differences. We performed Friedman rank sum tests and posthoc Wilcoxon signed rank tests with Holm-Bonferroni adjustments for pairwise comparisons.

Speed to Target

As the distance between targets varied between one to six pillars, it was necessary to normalize the time until the target was acquired by the individual distance. The result is the *speed to target*. There were no significant differences in *speed to target* between cues, modalities, and patterns.

Further, we looked for differences in *speed to target* for targets within and without the field of view. We defined targets with a distance greater than three pillars ($> 180°$) as outside the participant's field of view. A Wilcoxon test revealed significant differences in *speed to target* between targets within and targets without the field of view ($W = 241220, Z = 19.96, r = 4.46, p < .001$). The *speed to target* was higher for targets without the field of view.

We split the time to acquire the target into *arousal time* and *shift speed*. The *arousal time* was the time between triggering the cue and the gaze leaving the interaction area of the LED. The *shift speed* was the time between the gaze leaving the interaction area of the LED and the gaze entering the interaction area of the target LED normalized over the distance like *speed to target*. Figure 5.11 shows the differences in *arousal time* and *shift speed* between the different investigated cues.

Arousal Time

A Friedman test revealed significant differences in arousal time between conditions ($\chi^2(5) = 30.49, p < .001$). A pairwise Wilcoxon test revealed that *incLight* was slower than *incVibe* ($p < .05, r = .67$) and *pulseVibe* ($p < .001, r = .99$). Also, *pulseBoth* was slower than *pulseVibe* ($p < .01, r = .84$). Further, *pulseLight* was slower than *pulseVibe* ($p < .05, r = .70$). All in all, tactile patterns corresponded to shorter median *arousal times* than visual pattern. There were no significant differences in *arousal time* between modalities or patterns.

Shift Speed

A Friedman test revealed significant differences in arousal time between conditions ($\chi^2(5) = 17.34, p < .01$). A pairwise Wilcoxon test showed, the shift speed of *incVibe* was significantly lower than *incLight* ($p < .001, r = 1.00$), *pulseBoth* ($p < .01, r = .77$) and *pulseLight* ($p < .001, r = .99$). The shift speed of *pulseLight* was significantly faster than *pulseVibe* ($p < .01, r = .78$). Overall, the visual cues were faster than tactile cues regarding the median shift speed. Figure 5.11 shows a boxplot of *shift speed* for all cues.

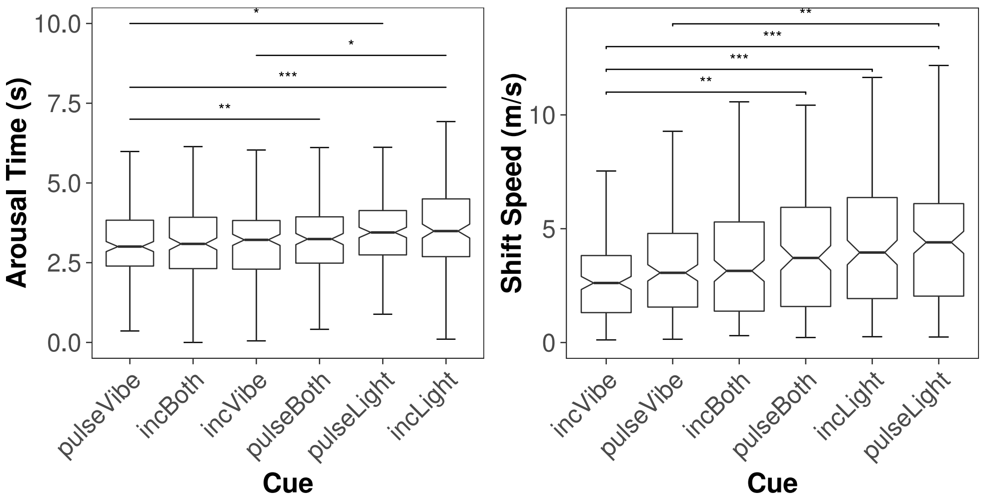


Figure 5.11: Arousal time and shift speed per cue.

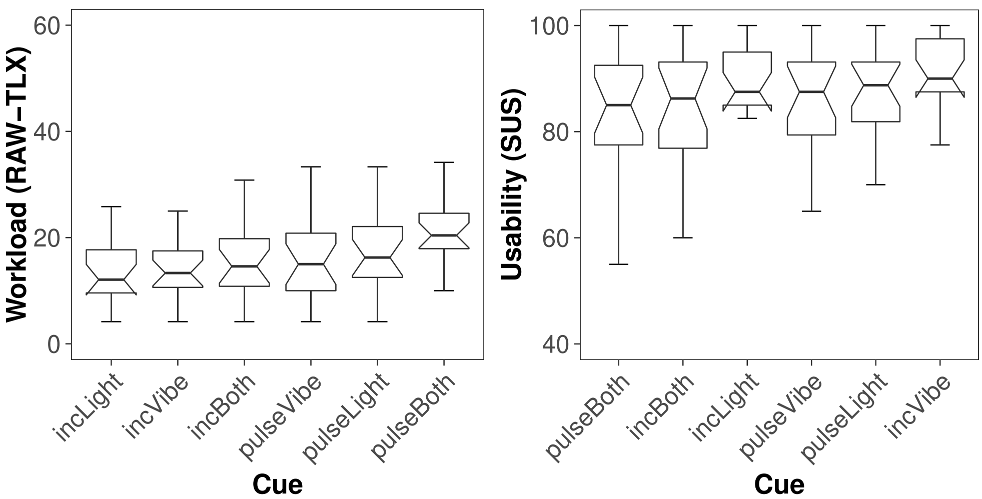


Figure 5.12: Perceived workload and usability of the cues.

Workload

Friedman tests indicated significant differences in *perceived workload* between *cues* ($\chi^2(5) = 25.52, p < .001$) and *modalities* ($\chi^2(2) = 15.11, p < .001$). The *perceived workload* for *incVibe* and *incLight* was clearly lower than for *pulseBoth* (see Figure 5.12). However, pairwise comparisons showed no significant differences. The *perceived workload* for the modality combination *light + vibration* was significantly higher than for the modalities *light* ($p < .05, r = .51$) and *vibration* ($p < .05, r = .64$) alone. The perceived workload for the pattern *pulsing* was significantly higher than for the pattern *increasing* ($W = 1133, Z = 3.32, r = .74, p < .001$).

Usability

The *usability* of the cue *incVibe* ($M = 90.88, SD = 7.75$) was rated greater than all other cues. There were no significant differences in *usability* between modalities or patterns.

In the debriefing interview, eight out of 20 participants liked *incVibe* the most. Six participants liked *incLight* the most. Two participants liked *incBoth* the most and four were undecided.

5.3.4.6 Discussion

In our experiment, tactile cues led to faster *arousal times* than visual cues, whereas the *shift speed* for visual cues was faster than tactile cues. However, the total response time from cue trigger to target acquisition was shorter for tactile cues than visual cues. As there is no significant difference in arousal time and shift speed between *increasing* and *pulsing*, the decision which pattern to use should also incorporate the subjective measures *perceived workload* and *usability*. The combination of modalities led to significantly increased *perceived workload* compared to single modalities. Therefore, the combination of tactile and visual cues should be avoided for low urgency attention shifts and only be considered for high urgency attention shifts. We recommend *incVibe* for low urgency attention shifts and *pulseBoth* for high urgency attention shifts.

5.3.5 Conclusion

We implemented and tested four cue pattern on a visual and a tactile on-body display, as well as the combination of two of them. Except for *instaLight* (one missed cue), all cues successfully shifted the attention of the user in 100% of the cases. We found that tactile cues led to faster *arousal times* than visual cues, whereas the *shift speed* for visual cues was faster than tactile cues. The combination of visual and tactile cues led to increased workload and should be avoided in situations and environments, where the workload is already high. Instead of the concurrent combination of modalities, we propose to combine modalities consecutively and use vibration for attention arousal and peripheral light for the shift. As for the use of single modalities, tactile cues tend to have a faster total response time than visual cues.

As the cues are located on-person and on positions that allow an easy integration into clothing, they are applicable in various cyber-physical system environments.

Our current results are transferable to seated and standing workplaces.

5.4 Use of Pneumatic On-body Cues to Encode Directions

In recent years body-worn tactile displays have been used widely to convey navigational information to users [PHB09, JMW11]. The individual wears an on-body display that presents cues to the somatosensory system (touch, thermal, pain) in a laminar display on the body – for arousal and embodied directional cues. Using these displays is beneficial from several aspects:

a) They are mobile and unlike traditional computers do not require users to be in a stationary setup, and thus, they support spontaneous interactions [HLSH09b].

b) In some domains, such as ship bridges or intensive care units, users are required to move constantly and the visual demand is high. In this case, when the performance time is limited, according to Wicken's multiple resource theory [Wic02], using visual cues can create a bottleneck in sharing the visual information processing resources. Therefore, the tactile channel is a potential way of conveying information.

As a prominent modality for on-body displays, vibrotactile displays in mobile and wearable user interfaces have been proposed [BB04, VE02]. vibrotactile displays have been widely applied for conveying information to users in wearables such as smart watches. Despite advantages such as acceptability and effectiveness, vibrotactile displays have some drawbacks when used in specific use cases such as working environments with environmental vibrations. Examples for such working environments are vehicles with strong engine vibrations (e.g. ships, cars, construction machines). Further, if integrated into clothing, the tactile cue might get fuzzy, through inconstant contact to the body.

In this work, we propose a pressure-based form of tactile cue to be integrated into clothing to convey navigational information. The proposed display is a shape-changing interface located on the users' shoulders. Shape-changing interfaces have several affordances such as representation of information through haptic channel to convey computational states to users [YNO+13]. We pursue to investigate whether using a shape-changing interface can be an alternative for vibrotactile displays for conveying navigational information to the users; and if there is a preference between these two types of displays.

5.4.1 Related Work

Kettner et al. and Pohl et al. both compared vibrotactile and pressure-based cues for notifications on wrist-worn devices [KBK+17, PBNQR17]. They both used a blood pressure gauge for the implementation of their pressure-based tactile notifications. Kettner et al. found that vibrotactile cues increase the stress level of the user more than pressure-based cues. Pohl et al. further looked into how to give reactive cues using deflation patterns.

Schönauer et al. used visual, vibrotactile and pneumatic actuation to guide human motion [SFO+12]. Kim et al. created an inflatable mouse that extended the capabilities of a normal mouse with pressure-based input and tactile feedback [KKL+08]. The mouse could be completely deflated for easy storing. Enriquez et al. implemented pneumatic cues into a steering wheel to display alerts while driving [EAYM01]. The pneumatic cue was controlled by an electrical pump. They used the pump to create vibrotactile cues by inflating and deflating their pneumatic pockets with frequencies up to 10 Hz.

Instead of vibration or pressure-based cues, Pfeiffer et al. used electrical muscle stimulation to control walking directions [PDS+15]. Their approach sucessfully influenced the walking direction of participants by 16°/m. However, this kind of direct muscle feedback is not suited for the integration into clothing, as the system needs to be exactly located on the respective muscles and depends on direct skin contact in order to function.

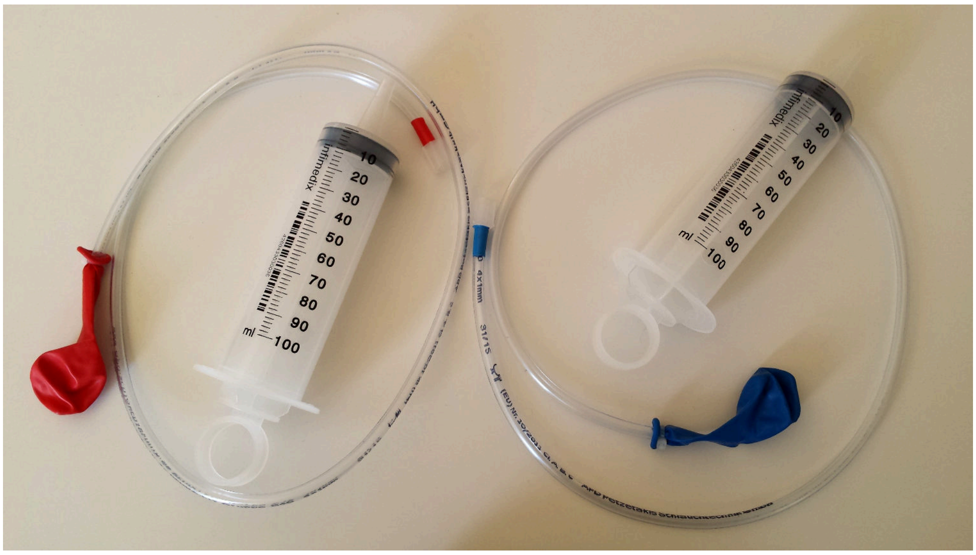


Figure 5.13: The pneumatic system of the prototype.

5.4.2 Design

As we intended to mimic a guiding touch by a person, we positioned the cue on the upper back at each shoulder based on the topography of social touching by Suvilehto et al. [SGD+15]. To avoid possible analogies with blood pressure gauges we excluded the upper arm and wrist positions for pneumatic cues. The first question to answer regarding the requirements of this artifact's direction mapping of the cue was: Would the cue be interpreted as a shoulder tap mapping the direction directly to the shoulder side or shoulder push mapping the direction opposite to the shoulder side?

Therefore we performed a user study with 6 participants (1 female), aged between 25 and 37 years ($M = 30.0, SD = 4.7$). We positioned a cloth with two airbags, made from balloons, at the upper back of the seated participant. We controlled the airbags with two hand pumps (medical syringes) as Wizard of Oz prototype, see Figure 5.13.

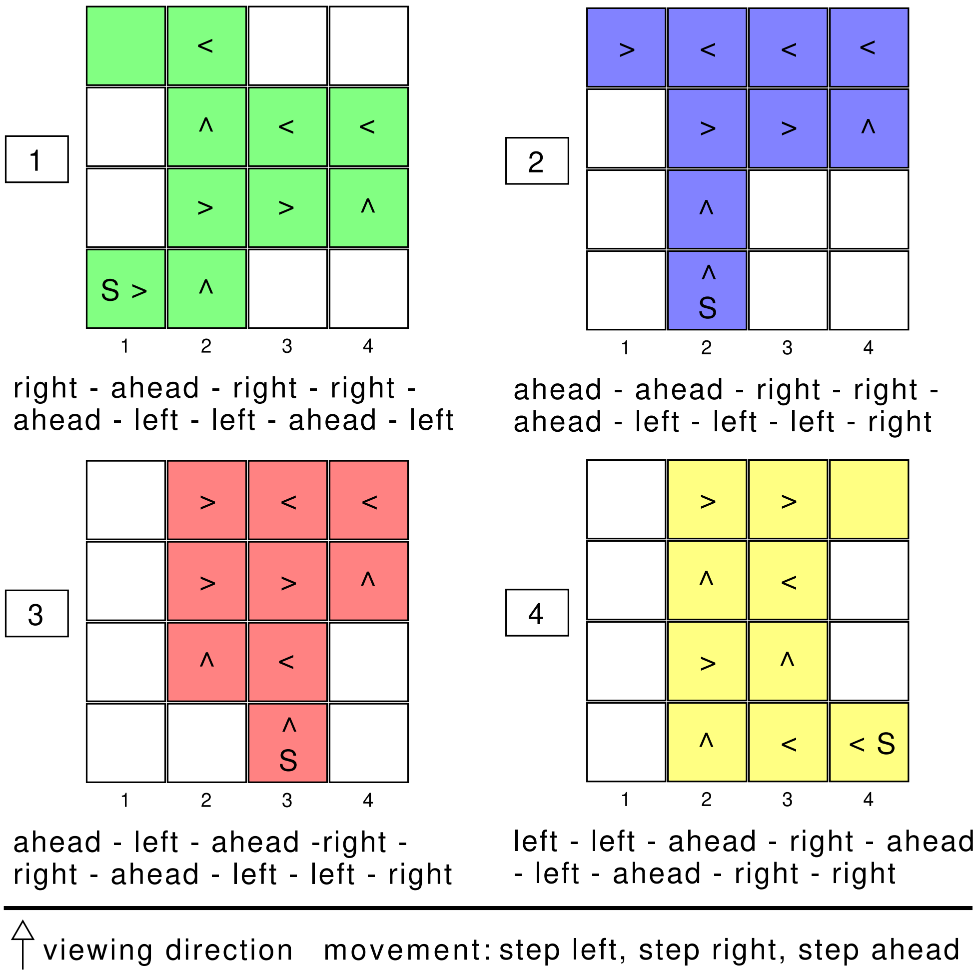


Figure 5.14: Path directives for the lab study.

Each participant was presented with the following cues in a counterbalanced manner: 2 x left, 2 x right, 1 x both. After each cue they had to give the position where they felt it. After that the participants were presented again with the following counterbalanced cues: 1 x left and 1 x right. After each cue we asked them which direction they would go.

Our results show that all participants identified the position of all presented cues correctly. Further, all participants mapped the pressure on the left shoulder to the left direction and the pressure on the right shoulder to the right direction. This corresponds to the shoulder tap metaphor. One participant stated that the back is a quite personal position and that he did not like it much. The remaining five participants liked the cue. Two participants stated, they could imagine having this kind of cue integrated into a jacket or wearing it under their clothes.

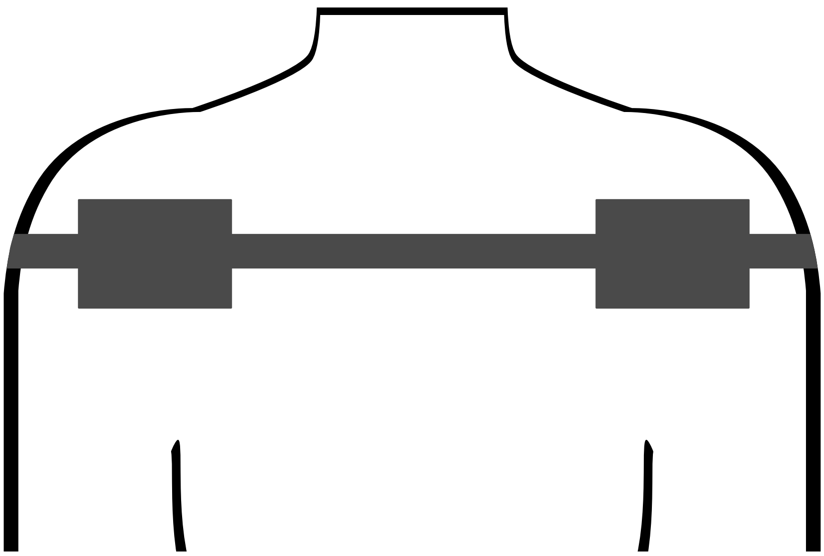


Figure 5.15: Placement of the prototype on the back.

Based on our results, we implemented an improved wearable prototype shown in Figure 5.16. It is worn like illustrated in Figure 5.15, Figure 5.13 shows the pneumatic system of the prototype.

5.4.3 Lab Study

We performed a lab study (Wizard of Oz) to compare our pneumatic prototype to a comparable prototype using vibration. The participants got the task to navigate four counterbalanced paths under two different conditions, using vibrotactile cues on the shoulders, and ShoulderTap.

5.4.3.1 Participants

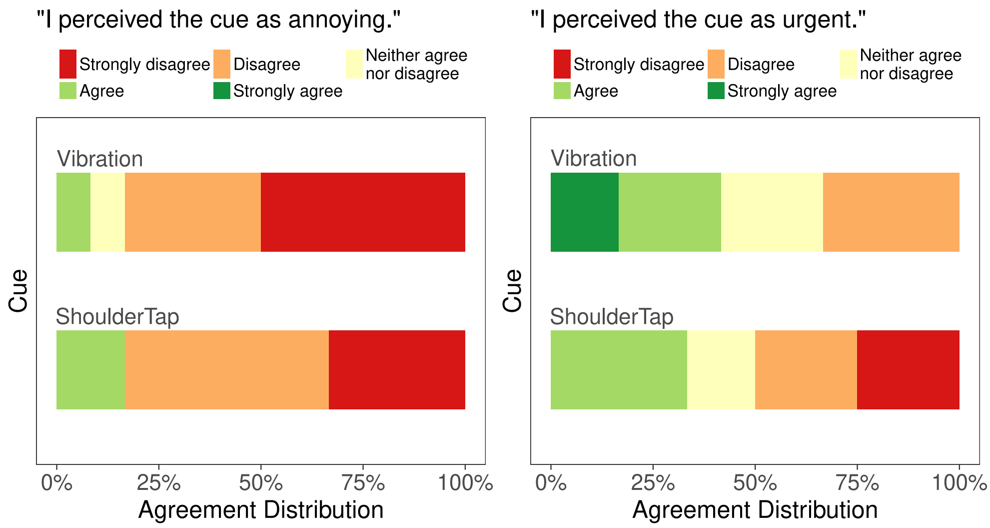
We recruited 12 participants (3 females), aged between 26 and 37 years ($M = 29.8, SD = 3.7$). The goal of this study was to investigate the feasibility of pneumatic onbody cues to convey directions and compare their effectiveness to vibrotactile cues. Participants need no experience in the maritime domain, as this experiment is designed to measure the human response in general.

Figure 5.16: Participant wearing prototype, headphones and an input button (left); close up photo of prototype (right).

5.4.3.2 Apparatus

The laboratory study was conducted in a controlled environment. We prepared a four-square meter field divided into 16 squares of equal size (Figure 5.14). Additionally, we marked one row of squares around the field to give participants the illusion of a full set of possible directions while navigating on the field. The operator of the air pumps for the Wizard of Oz prototype had an extensive training session before the actual study to ensure correct and homogeneous triggering of the cues for all participants. We used two Eccentric Rotating Mass (ERM) vibration motors of type C0834B011F[11] for the vibrotactile cue. Each ERM motor was fixated with Velcro between either of the airbags and the shoulder of the participants. We used the same duration of one second for both cue types. The ERM motor was powered via a PWM signal with maximum power. The air pumps pumped 100 ml air into an airbag. In order to allow the participants maximum mobility, we used extra long tubing for the pneumatic system of ShoulderTap. Figure 5.16 illustrates the study setup using a mock participant. We encoded three directions typical for pedestrian navigation: ahead, left and right. The direction *ahead* was encoded by activating both airbags at the same time. The directions *left* and *right* were encoded by the left and right airbag respectively, as identified for the shoulder tap metaphor in our design study.

[11] `https://www.mpja.com/download/19229md.pdf`, last retrieved: July 5, 2021



(a) Annoyance Rating. **(b) Urgency Rating.**

Figure 5.17: Rating distribution for perceived annoyance and perceived urgency (1 = strongly disagree, 5 = strongly agree).

5.4.3.3 Procedure

In the beginning, we presented each participant all three cues for each prototype in a short training session. The participants had the task to navigate on the prepared field based on directions cued under each condition. During all trials, the participant had to wear headphones, that played a distraction noise in form of loud music, so they could neither hear the sound of the pumps filling the airbags nor the vibration sound of the ERM motors.

Each Participant navigated all four paths once for each condition, resulting in a total number of eight runs per participant. After each condition the participants where asked to answer a specially designed questionnaire consisting of 5 point Likert items. On the questionnaire, the participants rated their agreement to the following six statements: ”The cue was intuitive.”, ”The cue was helpful.”, ”I perceived the cue as annoying.”, ”I perceived the cue as urgent.”, ”I felt confident using the system.”, ”I can imagine having the cue integrated into clothing.” Further, the System Usability Scale (SUS) was used to measure the usability of the system.

We measured perceived annoyance, perceived urgency, confidence for the interpretation, intuitiveness, helpfulness, error rate and usability (SUS) [Bro96].

5.4.3.4 Results

The Participants performed 97.45% (10/432 errors) of all triggered movements correctly using ShoulderTap. The success rate for vibration was 97.69% (11/432 errors).

With our questionnaire, we collected subjective ratings of the two different tactile cues. The rating distributions for perceived annoyance and perceived urgency are shown in Figure 5.17. Table 5.2 shows the median ratings for all Likert items of our questionnaire.

A Wilcoxon Rank Sum test revealed a significant difference in perceived urgency between ShoulderTap and vibration ($W = 0, Z = -2.23, r = .64, p < .05$). The perceived urgency of ShoulderTap ($Mdn = 2.50, IQR = 2.25$) was rated lower than the perceived urgency of vibration ($Mdn = 3.00, IQR = 2.00$).

The usability of ShoulderTap was rated higher than vibration with an average score of 89.17 ($SD = 10.02$). The usability of vibration was 86.04 on average ($SD = 11$).

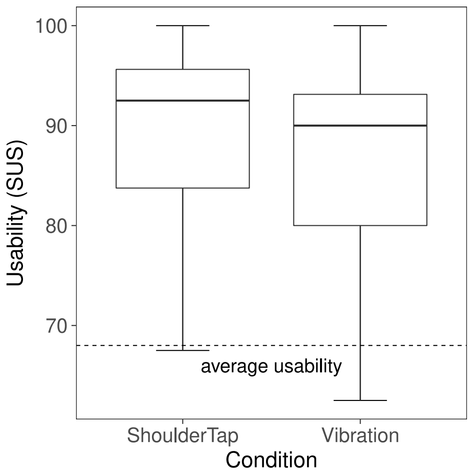
Ten out of twelve participants could imagine having the ShoulderTap cue integrated into their clothing, the same for vibration. They gave various reasons for and against an integration. Reasons against integrating vibration into clothing were ghost vibrations experienced, when the vibration was on top of a bone (e.g. bladebone). Reasons against ShoulderTap were related to comfort and aesthetics. As one participant stated: ”It could look silly.”

In comparison 7 out of 12 participants preferred ShoulderTap over vibration (58.33%).

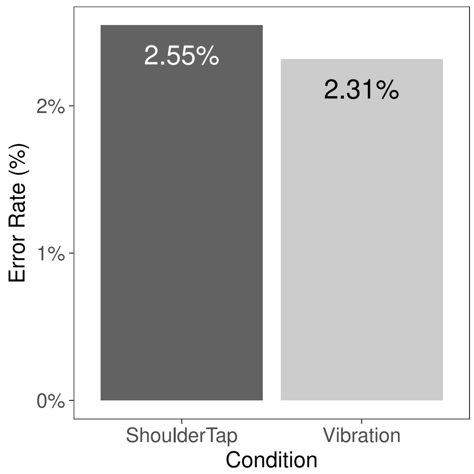
Table 5.2: Subjective Ratings: Median (IQR).

	ShoulderTap	**Vibration**
Urgency	2.50 (2.25)	3.00 (2.00)
Annoyance	2.00 (1.00)	1.50 (1.00)
Confidence	4.00 (1.00)	3.50 (2.00)
Helpfulness	3.00 (.25)	3.00 (.25)
Intuitiveness	3.00 (1.00)	3.00 (1.00)

During the study we collected all qualitative remarks the participant gave us. One participant remarked, that the use of ShoulderTap in combination with a backpack might be problematic. Further, a participant stated to experience a second, softer cue, when the air-bags deflated. Another comment was, that the pressure should be adjustable, depending on what clothing is worn underneath the prototype, e.g. in winter time. Concerning vibration cues, a participant noted that it feels more artifical and is therefore more clearly distinguishable. Another participant stated, that vibration was more easy to process, but also felt much more urgent. One participant remarked, that vibration felt more time critical than ShoulderTap.



(a) **Comparison of Usability.**



(b) **Comparison of navigation errors.**

Figure 5.18: Usability as measured by the System Usability Scale and error rate for ShoulderTap and vibration.

5.4.3.5 Discussion

Although there was one error more for ShoulderTap, the participants felt more confident interpreting directions conveyed by the ShoulderTap prototype than vibration. Moreover, vibration was rated as significantly more urgent than ShoulderTap. There were no significant differences in annoyance, helpfulness, intuitiveness and usability. This suggests that pneumatic cues are an eligible alternative to vibrotactile cues for conveying directional cues on the shoulders.

5.4.4 Conclusion

We compared vibrotactile and pressure-based tactile cues on the shoulders to convey direction information for left, right and ahead. All in all, we found that ShoulderTap is a valid alternative to vibrotactile cues, as the differences between both conditions were minor. In contrast to vibration, the pressure-based cue was perceived as less urgent and less artificial. Both tactile cues performed similar in all other measured variables.

We plan to update our Wizard-of-Oz prototype to be controlled with an electrical pump. This will allow for a fair comparison of reaction times between vibration and pressure-based cues. Further, we plan to compare both forms of tactile cues on an vibrating platform, to evaluate the interpretability of cues under environmental vibration, as we find it in a number of working environments.

This experiment was highly exploratory and the results are not directly transferable to a ship bridge environment. The takeaway message of this study is that pneumatic cues are an eligible alternative to vibrotactile cues for conveying spatial directions and that human-computer interface designers of monitoring assistance systems could consider these as a more calm and less artificial implementation of directional tactile cues.

5.5 Comparison of Moved and Static Acoustical Pointers

Attention guidance to task-relevant information in large physical workspaces such as ship bridges, emergency rooms or production lines demands the guidance of an operators attention to an object that may be out of sight and also a few meters away from the current position. To date, these systems solve the need for attention mostly by an allocentric solution in which a machine, device or display aims to get attention by multimodal stimuli, often simple visual and auditory alarms. However, complexity of such cyber-physical systems, noisy and hectic environments, or simple time pressure, demands more efficient human guidance.

The intention in applying warning sounds in safety-critical environments is to help to avoid accidents, but the opposite may happen if a warning sound of low urgency distracts the attention of an operator from more important operations. Warning sounds should be intuitively recognizable and meet the associated urgency. [ES95] introduced a standardized design and evaluation approach for auditory warning signals, that particularly takes the recognition accuracy and urgency ranking of end-users into account. Requirements to the pointer are:

- It should be identified as a warning/notification sound of low urgency.
- It must be locatable in reverberating environments.
- It should not disturb steering processes or conversations.

Criteria for the design of a low-urgency warning sound were evaluated by e.g. [HED93], [HC95]. Accordingly, the lowest perceived urgency was observed for sequentially played tonal sounds without frequency modulations. Furthermore, mid sound pressure levels (65 dBC) are perceived as less urgent than higher levels (79 dBC). Secondly, a tonal component is needed to give the cue an intuitive machine notification sound character. The first requirement implies the need for a broadband component because tonal sounds are not properly locatable in reverberant rooms ([Bla97]). Three factors led to the choice of a sequence of very short sounds: first, continuous sounds lead to masking and would disturb more than short sounds. Second, continuous sounds lead to a higher perceived urgency ([HC95]). Third, the localization performance is best on onsets ([Per69]).

We present a comparative study of how to guide an operator's attention in the spatiotemporal domain. The experiments were run in a ship bridge simulator in an anechoic chamber. In our experiments, we were able to clearly identify the effects of static and moving acoustical pointers while creating a realistic setup in which we simulated environmental noise such as engine, wind and water waves.

We propose the following research contributions:

- an easily locatable acoustical pointer for spatial attention guidance
- a manipulate-able realistic acoustic scene of a ship's bridge
- a comparison of the feasibility of moving and static cues for spatial attention guidance

5.5.1 Stimulus (Cue Design)

In our pretesting, we compared Higher Order Ambisonics (HOA) and Vector Base Amplitude Panning (VBAP) for the spatial rendering of our audio cues. We compared the accuracy of sound localization at different positions. The positions were in the center of the sweet spot, at the leftmost target and at the rightmost target. We extended the sweet spot of Ambisonics to be comparable. However, we decided to use VBAP, as the sweet spot for HOA, even with the extension, is to small for a moving operator.

Besides acoustical pointers consisting of ton-complexes, we also considered earcons or auditory icons as possible designs. A fitting voice cue could be the "PAN PAN" urgency call used in radiotelephone communications. For a fair comparison with the other non-semantic audio cues, voice cues that encode the identity of the target, such as "RADAR", should be excluded. However, speech is already used for radio and human to human communication, which is why we decided to use non-speech exogenous cues.

Our final acoustical pointer was a sequence of five complex tone pulses with noise burst featured onsets. Each pulse had a duration of 30 ms. Complex tones contained the first and the second harmonic (pink weighted) for the fundamental frequency of 800 Hz. Von-Hann ramps of 10 ms were applied. Onsets of the pulses were featured with a 2 ms von-Hann window of white noise. Noise and complex tone had equal RMS values. In the sequence, the inter-pulse intervals were 570 ms.

5.5.1.1 Pretesting

In a pretesting session with two participants, we compared the localization accuracy of five different cue designs per cue dynamic (static, dynamic). Also, for moving cues, we compared linear to circular movement. The Experiment was conducted in a clean room (no noise, no reverberation). However, all cue designs were pretested in our acoustic scene with noise beforehand.

We decided to use the same audio cue for both conditions. The cue had the same duration of 5 repetitions for both conditions.

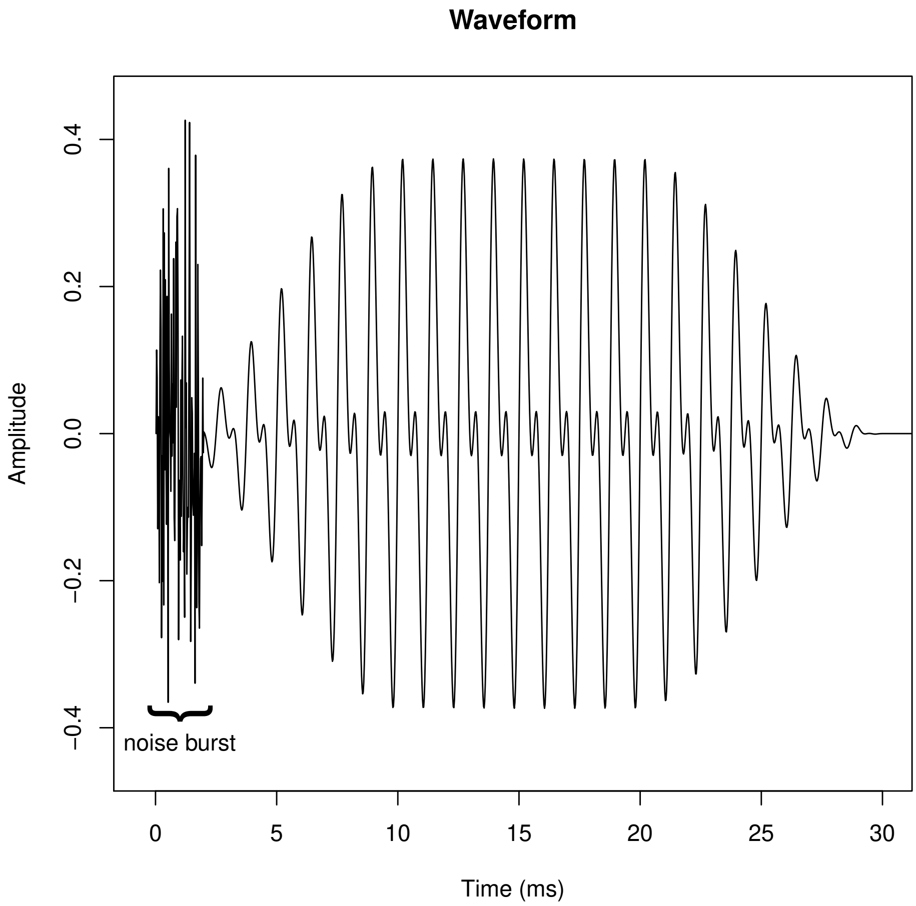


Figure 5.19: Audio cue consisting of complex tone pulse with noise burst featured onset.

5.5.2 VR Lab

Measurements were conducted in the Virtual Reality Laboratory of the University of Oldenburg, Germany. It is a lab based on an anechoic chamber with 7.4 m length, 4.6 m width and 4.3 m height (absorbers excluded). The room is treated with foam wedge absorbers with a structure depth of 60 cm. For this experiment, a 7.7 m^2 grill floor was installed that allowed the participants to move between the console instruments. The lab is equipped with a curved video screen setup that covers 202.5° of the horizontal field of view. The screen has a height of 2 m and is mounted 68 cm above the grill floor. Projectors used were three Barco F50 and the video content was perspectively rectified using Barco WB2560 warping units. For sound reproduction, the lab contains 86 pre-installed Genelec 8030b studio monitors. These are set up in horizontal layers at elevation angles of 90° (1 loudspeaker), 60° (6 loudspeakers), 30° (12 loudspeakers), 0° (48 loudspeakers), -30° (12 loudspeakers), -60° (6 loudspeakers) and -90° (1 loudspeaker). Within the layers, loudspeakers are equally spaced starting from 0° azimuth. The center of the loudspeaker setup is matched with the center of the video screen.

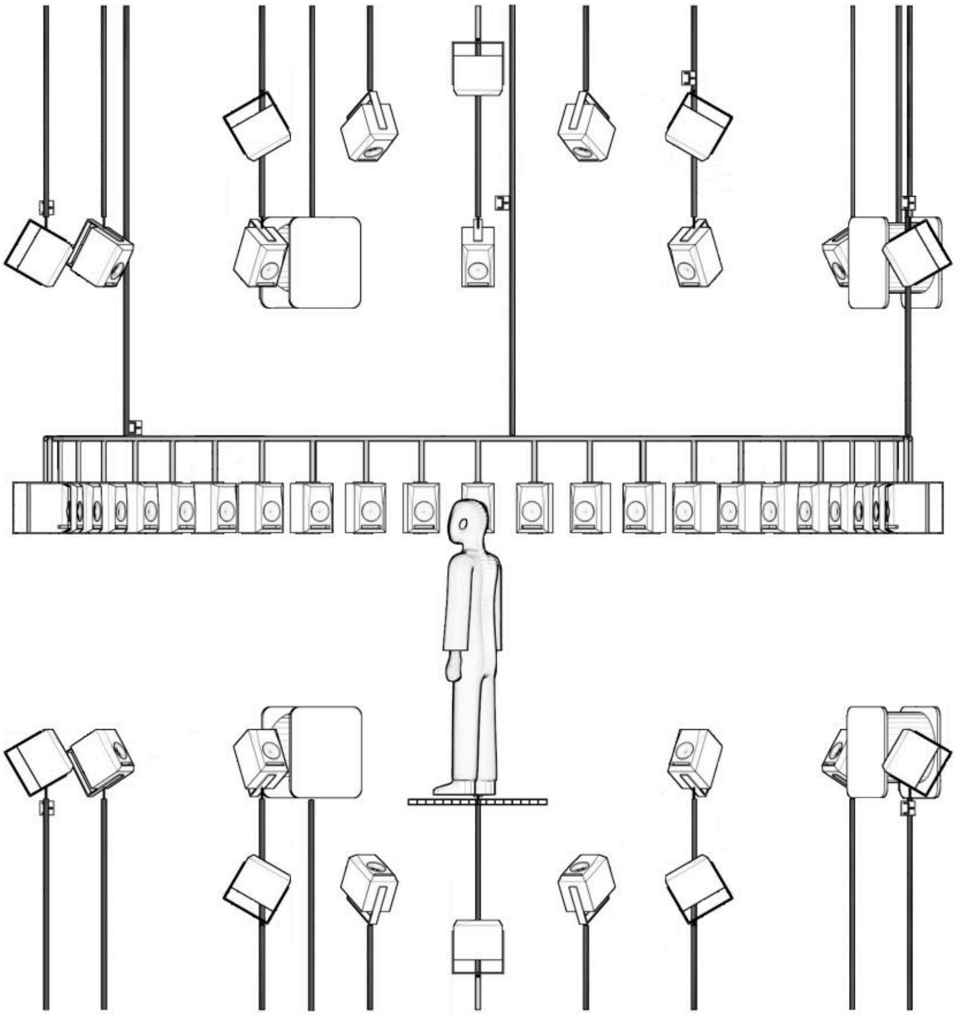


Figure 5.20: Speaker setup in the anechoic chamber: 48 speakers on the horizontal plane, 12 above and 12 below the user.

5.5.3 Ship Simulator

For our apparatus, we used our transportable ship bridge simulator (cf. Section 4.1)with a wide projector viewing system and three units with ship control systems in an anechoic chamber. The ship simulator consists of three components, a visual scene, an acoustical scene and the user interface. The full apparatus is shown in Figure 5.21. Figure 5.20 shows the speaker setup in the anechoic chamber.

Figure 5.21: The apparatus consists of a mobile ship bridge simulator with a 202.5° viewing system and three units with ship control systems, nautical instruments, and devices in an anechoic chamber. The anechoic chamber incorporated a full surround sound speaker array, with 48 speakers on the horizontal plane.

5.5.3.1 Visual Scene

The visual scene was rendered on a 202.5° viewing system. The simulator used the open source interactive 3D ship simulator Bridge Command 5.0[12] to render an overtaking scenario on a canal. In the scenario, there was one ship on counter-course and one slower ship in front of the participant's ship, that had to be overtaken. We prepared the scenario with two different weather conditions in order to induce different levels of workload. We choose a sunny weather scenario with clear sight, little wind and calm sea for low workload and a stormy weather scenario with limited sight, strong wind, high waves and rain for a high workload, which required radar-based navigation.

[12] `https://www.bridgecommand.co.uk/`, last retrieved: July 5, 2021

5.5.3.2 Acoustical Scene

The virtual acoustical environment was created using the Toolbox for Acoustical Scene Creation And Rendering (TASCAR; [GH14]; [GLHH15]). Room acoustical modeling was based on the ship bridge of a 2999 GT general cargo vessel (cf. Figure 5.22). Early reflections of walls, windows, console, and table were rendered first order and supplemented by a diffuse reverb (feedback delay network). Stimuli were panned using vector based amplitude panning ([Pul97]). Diffuse sounds (weather and engine, for details, see appendix) were directly mapped to 14 loudspeakers: 12 equally spaced loudspeakers in the horizontal plane (azimuth angles 0°, 30°, 60°, ...) and to the top and bottom loudspeakers (elevation angles 90°, -90°). Each speaker was playing the same sound loop, but they were delayed irregularly to minimize coherence and avoid comb filter effects at off-center positions.

We simulated the following environmental noises: Engine, rain, wind, and waves. Further, we triggered alarm sounds and radio calls at certain points in time. To be able to control them easily, the sound effects were single real-world recordings, which we combined analog to a full recording from a ship bridge. We adjusted the loudness of these effects according to present regulations. The noise level limits for the ship bridge on 1600 - 10000 GT merchant ships is 65 dB(A) according to Resolution MSC.337(91) [Mar12] an amendment to the International Convention for the Safety of Life at Sea (SOLAS) [Int74]. Table 5.3 gives an overview of the noise level limits for different navigation spaces. Further, we invited two experienced nautical officers to listen to our acoustic scene and get feedback on the realism of the scene.

5.5.3.3 Instruments (UI)

For our apparatus we used a mobile ship bridge simulator with three units of ship control systems, nautical instruments and devices (cf. Section 4.1). The upper center screen rendered a radar display and the lower center screen the controls for rudder and engine. The upper left and upper right displays rendered devices displaying the current speed of the vessel. These two displays were used as AOI (area of interest) targets in the study. The lower left and lower right displays showed light controls and a map of the scenario. All displays were fitted with visual ARuco [13] markers, to be detectable as AOIs be an eye-tracking system.

[13] `https://www.uco.es/investiga/grupos/ava/node/26`, last retrieved: July 5, 2021

Designation of rooms and spaces	Ship size 1,600 up to 10,000 GT	Ship size $\geq$ 10,000 GT
Navigating bridge and chart-rooms	65	65
Look-out posts, incl. navigating bridge wings and windows	70	70
Radio rooms (with radio equipment operating but not producing audio signals)	60	60
Radar rooms	65	65

Table 5.3: Noise level limits in dB(A) for navigation spaces according to IMO Resolution MSC.337(91).

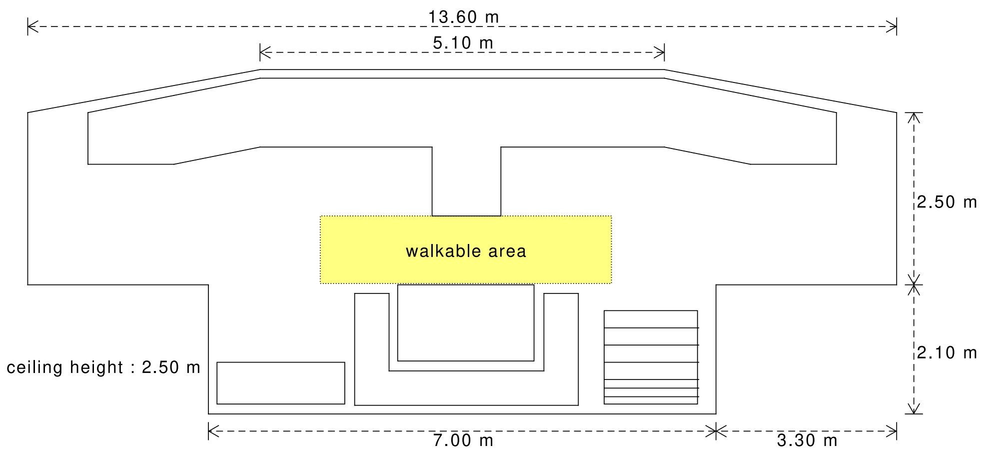


Figure 5.22: Dimensions of the simulated bridge room, taken from an existing 2999 GT general cargo ship.

5.5.4 Lab Study: Audio Cues for Attention Guidance

In this lab study, we investigate the accuracy and feasibility of audio cues for spatial attention guidance. Hypothesis 1: Moving cues achieve a higher localization accuracy than static cues. Hypothesis 2: Moving cues are slower than static cues.

5.5.4.1 Design

We compare the two factors *workload* (regular, high) and *cue dynamic* (none, static, moving towards speech, moving away from speech), resulting in a 2 x 4 within-subjects factorial design (8 conditions). All conditions were counterbalanced using a balanced Latin Square. For conditions none and static, the speech was rendered at 0° azimuth. We measured reaction time, and speech intelligibility. Further, we assessed situation awareness (SART) and usability (SUS) via standardized questionnaires. With a custom questionnaire, we assessed the perceived intuitiveness, perceived pleasantness, perceived annoyance, perceived urgency and perceived alarmingness of the cues using Likert items.

Attention guidance response (time to first fixation) through moved and static acoustical pointers was tested against the intelligibility of pseudo radio-calls, realized by a speech perception test. The pointer destinations were speed indicators located at +-60° azimuth. Moving pointers started at 0° azimuth and moved towards the target directions with a velocity of 25 °/s (signal duration: 2.4 s). Pointers and speech were presented simultaneously. For moving pointers, speech was either presented from 0° azimuth or from the current target direction resulting in spreading (condition moving away from speech) or merging (condition moving towards speech) signal directions. Static pointers were tested against speech at 0° (condition STAT). Additionally, a reference speech condition was measured at 0° azimuth without acoustical pointers (condition none). These four conditions were tested for two (virtual) weather conditions: sunny vs. rainy and windy, reflecting the workload levels regular and high.

5.5.4.2 Participants

We recruited 20 participants (4 females), aged between 24 and 66 years ($M = 32.45, SD = 9.32$). The Participants were either trained mariners or mariners in training, who successfully completed a maneuvering course. Together, they had 50.5 years of maritime working experience ($M = 2.52, SD = 3.01$). Each participant signed an informed consent before the start of the experiment.

5.5.4.3 Procedure

The participant was asked for demographic data. Afterward, the eye-tracker was calibrated. Before the first run, each participant practiced in a 12-minute training session to get familiar with the task and the simulator environment. Each participant started the scenario either with moving or static cues. The order of the cues was altered between the participants in order to avoid carryover effects. The scenario was run two times, each run took 45 minutes. The workload of the scenario is increased through higher task complexity by means of harsher environmental conditions (rain, fog, stronger wind/waves, day-time (morning/evening). We had a good weather scenario for regular workload and a bad weather scenario for high workload. All Participants started with the good weather scenario. After each run the participant had to fill out a SART and rate both cue conditions. After the last run, the participant had to rate the usability of both cue conditions. Speech perception was measured using the Oldenburg Sentence Test OLSA [WBK99].

The OLSA is a matrix sentence test with the sentence structure name-verb-numeral-adjective-object, e.g. "Peter has four nice forks". Sentences are arranged in lists of 20 leading to equal intelligibility thresholds. In total, 80 sentences were presented during a trial (4 conditions, 20 sentences per condition). For each of the four conditions, 20 sentences were presented. German native speakers (16 subjects) were tested using the original OLSA (male german speech material). Other participants (4 subjects) were tested using the American english OLSA (research and development edition, female American english speech material). The speech was initially presented at 0 dB signal-to-noise ratio and adaptively adjusted towards the 50% perception threshold.

5.5.4.4 Results

Time to first fixation (TTFF)

A Friedman test revealed significant differences in TTFF between the conditions ($\chi^2(6) = 20.30, p < .01$). The TTFF for *moved away* ($W = 11158, Z = 3.50, p < .001, r = .78$) and *moved towards* ($W = 12370, Z = 5.17, p < .001, r = 1.16$) were both significantly lower (faster) than for *static*.

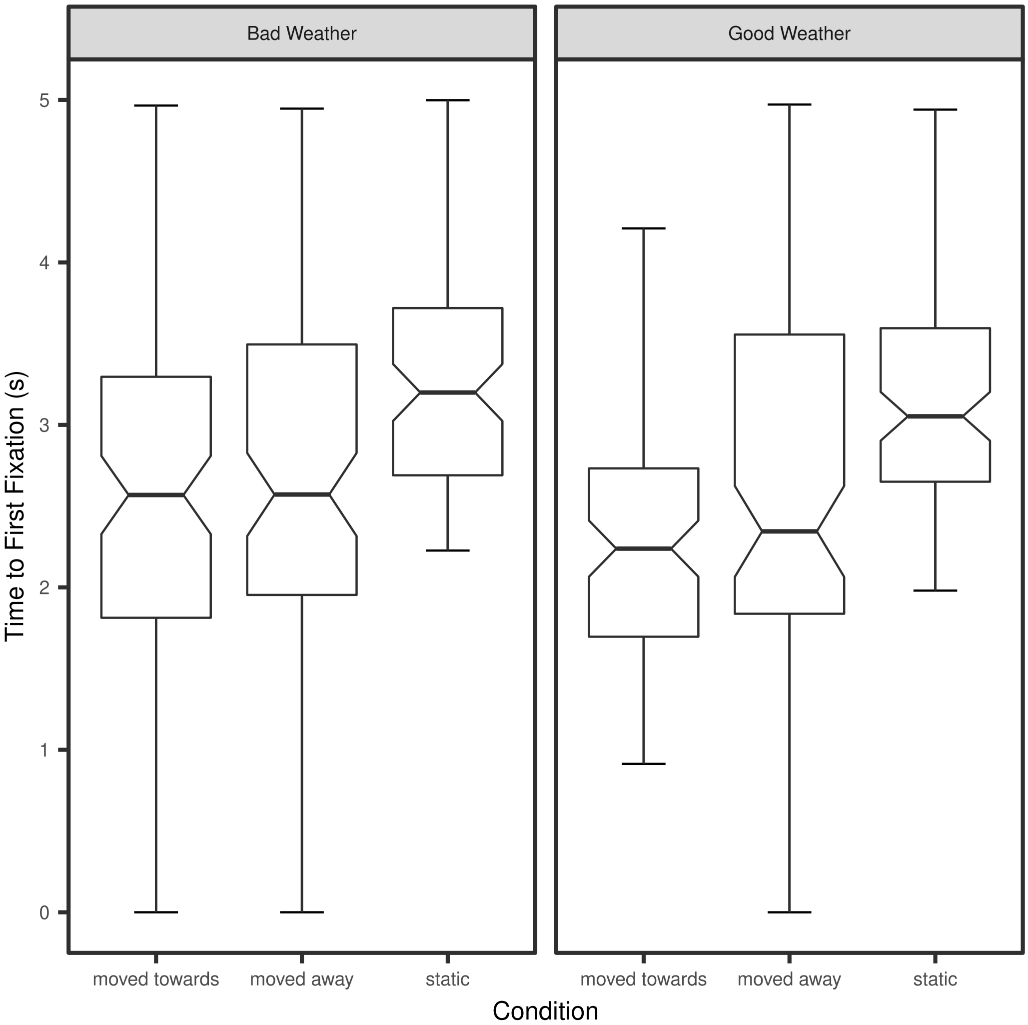


Figure 5.23: TTFFs for each cue condition for high (bad weather) and regular (good weather) workload.

Speech Intelligibility

The speech recognition threshold (SRT) is defined as the sound pressure level at which 50% of the speech is identified correctly. Median speech reception thresholds for all movement conditions range from -4.7 dB to -5.4 dB (weather condition ”sunny”) and from -5.0 dB to -6.0 dB (weather condition ”rainy and windy”), not showing any statistically significant differences.

Subjective Measures

There were no significant differences in annoyance and pleasantness. Moving pointers was perceived as significantly less intuitive ($W = 26, Z = 2.66, p <$

$.05, r = .60$) than *static*. Moving pointers were perceived as significantly less urgent than static pointers ($W = 26.5, Z = 2.30, p < .05, r = .52$).

Both cues were rated with a high usability score of over 83. However, static pointers ($M = 92.25, SD = 8.69$) were rated significantly more usable than moving pointers ($M = 83.63, SD = 13.29$) ($W = 4.5, Z = 3.45, p < .01, r = .77$).

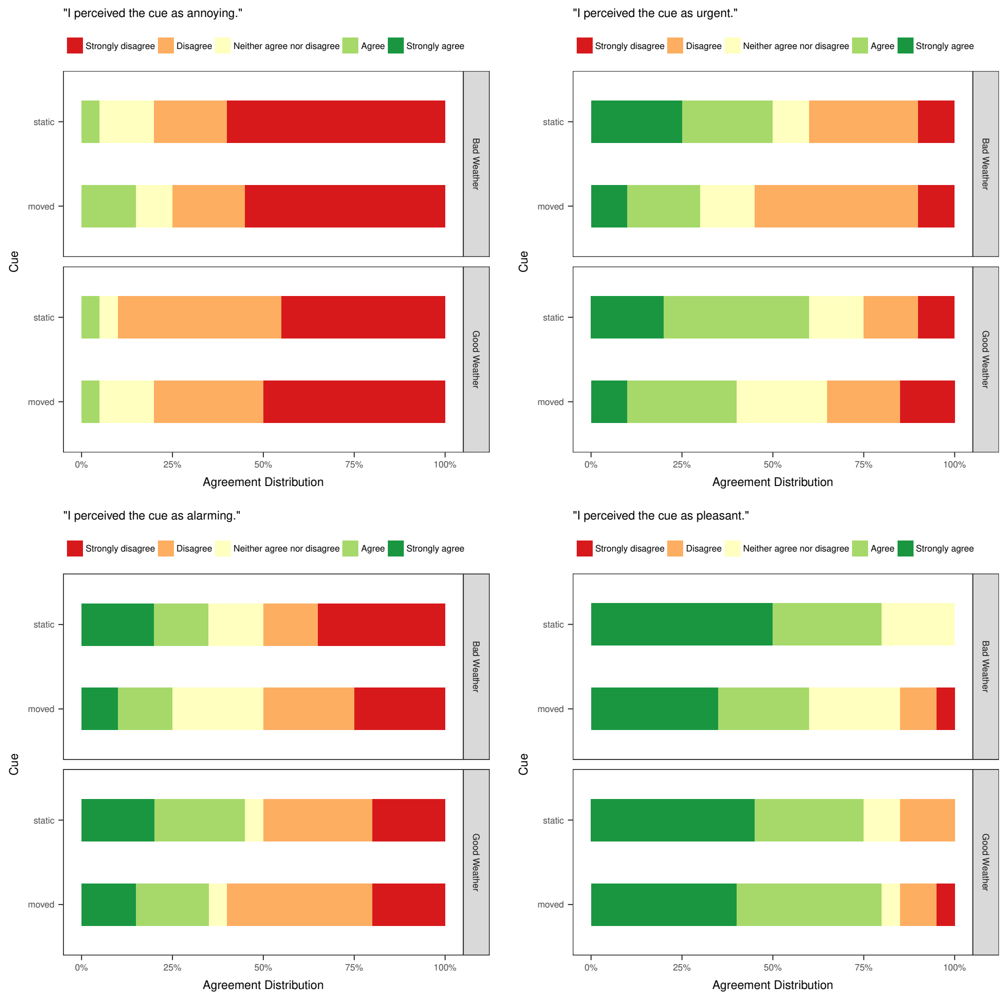


Figure 5.24: Rating distribution for perceived annoyance, urgency, alarmingness, and pleasantness (1 = strongly disagree, 6 = strongly agree).

5.5.4.5 Discussion

The quantitative results are in favor of moved pointers, while qualitative results are in favor of the static pointers. While the intuitiveness of static acoustical pointers was rated significantly higher than for moved acoustical pointers, the response time and error rate were both significantly lower for moved acoustic pointers. We assume this is due to static acoustical pointers being the current state-of-the-art for acoustical alarms on ship bridges. However, response times and error rates are more critical factors for safe cueing.

We observed that static and moving conditions triggered different behavior in our participants. Static acoustical pointers led to a more chaotic gaze pattern and head movements searching for the source of the signal, whereas moving pattern led to a more stable and smooth head and gaze movement towards the target. This difference in head and gaze movements had an influence on the measurement of TTFFs as the target AOI was detected averagely 1.7 ms faster by the system for static acoustical pointers. However, this measurement error even emphasizes the observed effect in our results that moving acoustical pointers lead to faster TTFFs.

5.5.5 Conclusion

We presented an acoustical pointer specifically designed for spatial localization in ship bridge environments. Further, we compared the performance of the designed pointer with a static position to the pointer moving towards the target. Our results show that moved acoustical pointers are faster and more effective in guiding the attention. As it is safety critical, that the acoustical pointer does not mask or negatively affect the perception of speech on the ship's bridge, we measured speech intelligibility. There were no significant differences in speech recognition thresholds, therefore we conclude that the usage of our acoustical pointers does not negatively affect verbal communication on the ship bridge. Concerning the transferability of our results to a real ship bridge environment, we simulated acoustic as well as light conditions for two different weather conditions (sunny vs. rainy and windy) and changing day light (twilight), and chose realistic scenarios with different induced workload (navigation by sight/radar-based navigation) to foster the ecological validity of our results. We did not simulate environmental vibration.

5.6 Summary

In this chapter, we introduced the design space of spatial attention guidance cues considering the limitations and special requirements of maritime ship bridges. We then presented the research that we conducted to further investigate the proper design of spatial guidance cues for all modality - placement combinations that we previously identified as suitable.

In our work, we developed a light display for a horizontal multi-monitor setup, as commonly found on ship bridges, that is controlled by eye-tracker input to guide the attention of a user from the currently focused display to another display, that is in demand of attention. Together with HCI experts for light displays we designed, implemented, and evaluated three different strategies for attention guidance with our light display in a user study. We found that ambient guidance cues that begin at the current focus of the user are faster in guiding the user to a target in the periphery than ambient guidance cues in the peripheral vision of the user.

We explored shifting attention towards the location of relevant entities in large cyber-physical systems. Therefore, we used pervasive displays: tactile displays on both upper arms and a peripheral display. With these displays, we investigated shifting the attention in a seated and standing scenario. In a first user study, we evaluated four distinct cue patterns for each on-body display. We tested seated monitoring limited to 90° in front of the user. In a second study, we continued with the two patterns from the first study for lowest and highest urgency perceived. Here, we investigated standing monitoring in a 360° environment. We found that tactile cues led to faster arousal times than visual cues, whereas the attention shift speed for visual cues was faster than tactile cues.

We explored a novel method based on pneumatic cues to provide a more natural tactile output. We use two airbags positioned at the back of the user, at shoulder height to give navigational cues. We utilize the shoulder tap metaphor to give directions to the left, right, or ahead. We compare the pneumatic cue to the vibrotactile cue at the same position. Our results show, that the pneumatic cue was rated as significantly less urgent than the vibrotactile cue. As there were no significant differences in error rate, annoyance, and usability, we rate ShoulderTap as an eligible alternative to vibrotactile cues.

On a virtual ship bridge, moved and static acoustical pointers were applied to announce the need to check an instrument. Participants with nautical experience steered a virtual freight ship through a fjord with some traffic. Two weather conditions were performed with respect to different stress levels: sunny vs. rainy and windy. During this, they had to answer radio calls and check the pointed instruments. Radio calls were realized by a speech perception test with adaptive speech levels. Acoustical pointers were sequences of a synthesized xylophone sound that pointed to an instrument that was located at either +60° or -60° azimuth. The background noise was a realistic ship noise. Pointers and speech were presented simultaneously. Moving pointers always started at 0° azimuth. Speech was either presented from 0° or the current target direction (+-60° az). The time to first fixation on target area after a pointer was measured by eye tracking. Results indicate that moving pointers lead to reduced times to first fixation. At the same time, participants judge the urgency lower than for static pointers. Movements of the pointers did not influence the intelligibility of the radio calls.

6 Context-aware Guidance Control

This chapter is partly based on the following publication:

- Stratmann, Tim Claudius, Brauer, Dierk, and Boll, Susanne. "Supporting the Perception of Spatially Distributed Information on Ship Bridges". Proceedings of Mensch und Computer 2019. ACM, 2019.

This Chapter is structured the following: First, we propose an implementation of an assistance system that can utilize attention guidance cues as described in Chapter 5. Further, we propose model adaptations to an existing attention demand model for the ship bridge environment and propose a model for context-aware cue selection.

6.1 Spatially Distributed Information of Heterogeneous Complexity

Ship bridges are spacious areas. Instead of a single screen with a focused area of attention, we see multiple displays and interfaces forming a larger, more complex workspace. The operators have to move between these systems, interacting both with automated processes and with other individuals.

Situation Awareness (cf. Section 2.1) consists of three parts: The perception of the elements of the current situation, the comprehension of the current situation, and the projection of its future status. To support nautical officers, more precisely deck officers, within the process of operating a vessel, we use an attention guiding system, to support the perception of information in demand of attention on the ship's bridge. For this, it has to be evaluated which information has a high *demand for attention* and therefore should be highlighted.

We propose a system, which rates the situational perception of a nautical officer based on eye tracking data. For that purpose, we translated the so-called monitoring assistant system (MAS) [FM14], which utilizes the *Demand for Attention Score* (DfA-Score) by Fortmann [For15], so it can be applied on a ship bridge. Further, we identified model parameters from an interview with two experts and tested our system in a short evaluation with experts and novice users.

We propose the following research contributions:

- An advanced monitoring assistant system for spatial user interfaces consisting of multiple displays with different levels of information complexity.

- Parameters and preliminary results for the ship maneuvering scenario *overtaking with traffic encounter* as required for the DfA-Score.

6.1.1 Monitoring Assistant System

In the following, we will shortly introduce the DfA-Score on which the MAS operates. Moreover, we present our extensions to the original MAS and explain, why they were necessary.

6.1.1.1 DfA-Score by Fortmann et al.

Fortmann et al. defined the *demand for attention* (DfA) [FM14] based on Wickens' SEEV-Model of selective attention [WM07], which has been validated with empirical human-in-the-loop data [WMA$^+$08, GHS$^+$06] and was less error-prone compared to probabilistic models [GHWSN09]. They further presented a tool called MAS, that calculates and ranks the *demand for attention* of multiple areas of interest (AOIs) online based on live eye tracking data. *Information objects*, e.g. an unmanned aerial vehicle (UAV), are associated with multiple *information elements*, such as fuel level, height, and speed. The calculated *demand for attention* for each *Information object* depends on the DfA of the associated *information elements*. As the goal is to support regular monitoring, the neglect time, the time since the last check of the information, is taken into account for the calculation of the DfA score. Therefore, the DfA of an *information element* is calculated based on the task-relevance of the *information element*, a value between zero and one, the maximal neglect time (*Maximum Neglect Time*) for the monitoring interval of the *information element* and the actual neglect time, as measured by eye tracking (Equation 6.1). For further details on the calculation, see Fortmann and Mengeringhausens paper [FM14].

$$\text{DfA} = \text{Relevance} \cdot \left(1 - \min\left(1, \frac{\text{Actual Neglect Time}}{\text{Maximum Neglect Time}}\right)\right) \tag{6.1}$$

6.1.1.2 MAS Extensions

The transfer of the original MAS from a 2D to a 3D domain requires extra information. In the use case of Fortmann et al., all information was displayed on a single 2D display. While the overall complexity of the information presented on that display was considerately high, due to the number of *information objects*, the complexity of information per *information object* was considerately low.

In the case of a ship bridge, each display represents an *information object* containing multiple *information elements*. As the complexity of information varies drastically between displays (e.g. radar or turn rate indicator), we introduce two new parameters: The *fixation quotient*, which reflects the number of fixations on the display, and the *fixation duration quotient*, which reflects the duration of the visual inspection of the display by the operator. Both parameters were introduced to cope with the complexity of the displays, as van de Merwe et al. found, that the fixation rate and dwell time are good indicators for Situation

Awareness [vdMvDZ12]. Depending on the complexity of a display, there are more areas of interest AOIs on it, and the time to comprehend the information on it might be longer. The *Fixation Quotient* (FQ) is calculated as shown in Equation 6.2, where *Number of Fixations* is the number of measured fixations and *Number of AOIs* is the number of AOIs on the display.

$$\text{FQ} = \min\left(1, \frac{\text{Number of Fixations}}{\text{Number of AOIs}}\right) \tag{6.2}$$

The *Fixation Duration Quotient* (FDQ) is calculated as shown in Equation 6.3, where *Current Fixation Duration* is the measured time the gaze rested on the display and *Minimum Fixation Duration* is the minimal time it takes to comprehend the information.

$$\text{FDQ} = \min\left(1, \frac{\text{Current Fixation Duration}}{\text{Minimum Fixation Duration}}\right) \tag{6.3}$$

Both parameters, *Number of AOIs* and *Minimum Fixation Duration* have to be determined per information display through interviews and test runs with experts. The information of an information display is recognized as 'perceived' by the system if either the *fixation quotient* or the *fixation duration quotient* reaches a value of one. This is to cope with measurement errors of the eye tracker and to avoid unnecessary cues.

Table 6.1: This table shows task-relevant information, its relevance to the task and its maximal neglect time respectively the time interval, in which the information has to be checked. TCPA stands for Time to Closest Point of Approach.

Task	Information	Relevance	Maximum Neglect Time
keep safe distance to other ships	course over ground (own ship)	1.0	depends on TCPA
	speed over ground (own ship)	1.0	depends on TCPA
	course over ground (other ship)	1.0	depends on TCPA
	speed over ground (other ship)	1.0	depends on TCPA
	name of ship (other ship)	0.5	once
	type of ship (other ship)	0.7	once
	traffic	0.7	once
regularly check course	VHF radio	0.6	passive
	water depth	0.5	10 minutes
	position	1.0	0.5 minutes
	course over ground (own ship)	1.0	0.5 minutes
	speed over ground (own ship)	1.0	0.5 minutes
change course (maneuvering)	turn rate	0.6	10 seconds
	rudder angle	0.8	10 seconds
	course over ground (own ship)	0.8	10 seconds

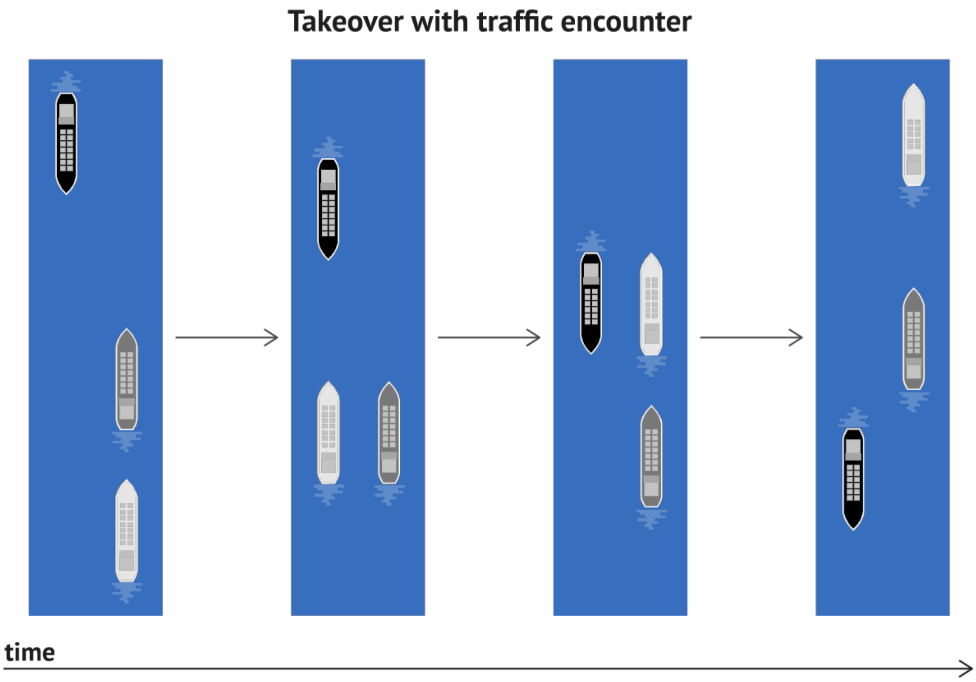


Figure 6.1: The simulator scenario: Takeover on a canal with traffic encounter. The white ship is the own ship, the gray ship has to be overtaken while a collision with the black ship has to be avoided.

6.1.2 Interview: Assess Parameters

To determine the necessary parameters for the calculation of DfA-Scores, we interviewed two active and experienced mariners (male, age: 34, experience: 10 years; male, age: 35, experience: 8 years). The interview consisted of three parts and both experts were interviewed simultaneously. In the first part, we let the experts propose a suitable scenario. We decided for the scenario *overtaking with traffic encounter* as described in Figure 6.1.1.2.

Table 6.2: TCPA to *Maximum Neglect Time* conversion for TCPA-dependant relevance, e.g. information on other ships.

TCPA	Max Neglect Time
$<$ 30 minutes	10.0 minutes
$<$ 15 minutes	5.0 minutes
$<$ 10 minutes	3.0 minutes
$<$ 5 minutes	0.5 minutes

After choosing the scenario, we performed a goal-directed task analysis (GDTA) [EBJ03] with the experts on the scenario. With the fulfillment of the scenario as the main goal, we identified the following three subgoals: keep a safe distance to other ships, regularly check course, and change course. *Regularly check course* and *change course* are both parts of the safe maneuvering on the planned path in the fairway. Furthermore, we identified the necessary decisions for each sub-goal, as well as the information needed for the respective decision. Figure 6.2 shows the resulting goal tree.

In the last part of the interview, we determined the necessary parameters for the MAS. For each information, we let the experts assign a *Relevance-Value* and the *Maximum Neglect Time*. We found that some information has to be perceived once, some has to be checked in a fixed interval and for some information, it depends on the situation (e.g. distance to other ships), how frequently it demands attention (see Table 6.1). Therefore, we decided together with the experts, to base the frequency for the latter on the Time to Closest Point of Approach (TCPA), a common time distance measure from the maritime domain. Table 6.1 shows the identified parameters for all scenario relevant information. Table 6.2 shows our conversion from TCPA to *Maximum Neglect Time*.

6.1.3 Lab Study: Ship Bridge Simulator

To test the performance and functionality of the extended MAS for maritime scenarios, we conducted a lab study with a ship bridge simulator.

6.1.3.1 Study Design

Our within-subjects lab study compared two conditions in a counterbalanced manner. In the condition *intelligent*, the attention guidance system was controlled by the extended MAS. In the condition *periodic*, the attention guidance system was controlled by fixed interval timers. This approach was inspired by Bridge Navigational Watch Alarm Systems (BNWAS) [Mar02], which represent the current state of the art. The dependent variables were Situation Awareness, perceived workload, and usability.

6.1.3.2 Participants

We recruited 9 participants (3 females), aged between 23 and 46 years ($M = 28.50, SD = 6.64$). Three participants were trained mariners (experts) and six participants were mariners in training (novices), who successfully completed a maneuvering course. Each participant signed an informed consent form before the start of the experiment.

6.1.3.3 Apparatus

The study apparatus was a Mobile Bridge [SGS+18] simulator configuration, consisting of a two display viewing system and six information displays, that were fitted with fiducial markers from an ARuco dictionary[1] to mark them as AOIs for a head-worn eye tracker. The eye tracker used was a Tobii Pro Glasses 2[2]. Figure 6.3 shows a photo of the study apparatus. We modeled our scenario, *overtaking with traffic encounter*, for the interactive 3D ship simulator Bridge Command[3], which rendered the simulation. Further, we implemented an interface to get the current values of all relevant *information elements* from Bridge Command into the extended MAS and our information displays. For a full list of rendered information elements see Figure 6.2.

6.1.3.4 Procedure

First, the participant was introduced to the ship bridge simulator. In a training session, the participant could familiarize himself with the simulator. After the training session, the participant got an overview of the task.

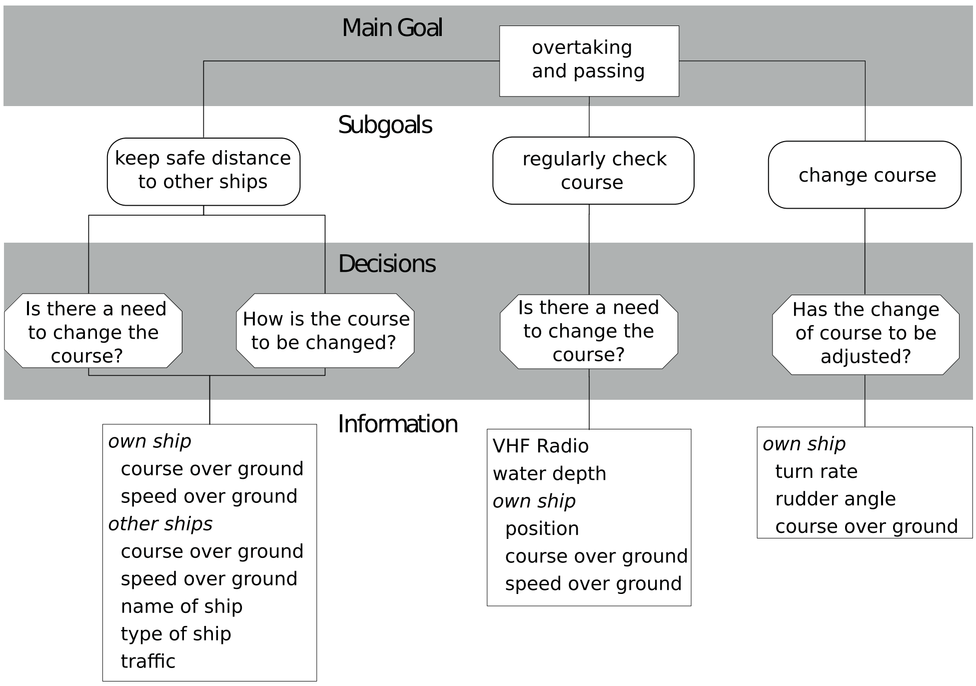


Figure 6.2: Goal tree of the analyzed scenario.

[1] `https://www.uco.es/investiga/grupos/ava/node/26`, last retrieved: July 5, 2021
[2] `https://www.tobiipro.com/product-listing/tobii-pro-glasses-2/`, last retrieved: July 5, 2021
[3] `https://bridgecommand.co.uk/`, last retrieved: July 5, 2021

Then, the first run of the scenario started. As the starting condition was alternated between participants, the participant started either with condition *intelligent* or *periodic*. The counterbalancing of start conditions between participants mediates learning effects. The participant had to take the duties of the officer of the watch, who had the authority of the bridge. A provided steersman steered the ship according to the participant's command.

The participant was instructed to maneuver through the scenario and perform regular watch-keeping. Visual cues were used to guide the attention of the participant to information displays in demand of attention, by flashing the whole screen of the respective display in red. For the condition *intelligent*, the cue was triggered for a display, when DfA ≥ 0.7 for an *information element* on that display. For the condition *periodic* the cue was triggered every 90 seconds. For both conditions, only one display was highlighted per time. When the participant had inspected the display, detected by gaze activity on the display, the DfA-Score respectively the timer was reset.

After each run, questionnaires were handed to the participant, to assess the perceived workload, usability, and situational awareness during the scenario. We used the standardized questionnaires Situational Awareness Rating Technique (SART) [Tay90], System Usability Scale (SUS) [Bro96] and NASA Task Load Index (NASA-TLX) [HS88]. Each run took 30 minutes. The second run was analogous to the first run, except for the changed condition (*periodic*/*intelligent*).

6.1.3.5 Results

There were no significant differences in workload, usability, and Situation Awareness. However, we can already depict some light tendencies.

The mean Situation Awareness rating for condition *intelligent* ($M = 18.00, SD = 5.27$) was slightly lower than for *periodic* ($M = 18.22, SD = 6.00$). However, the median rating for Situation Awareness for condition *intelligent* ($Mdn = 18, MD = 7.41$) was higher than for *periodic* ($Mdn = 16, MD = 1.48$). The mean workload rating for condition *intelligent* ($M = 30.56, SD = 15.51$) was lower than for *periodic* ($M = 34.96, SD = 15.51$). This correlates with the median ratings. The mean usability rating for condition *intelligent* ($M = 86.11, SD = 8.11$) was higher than for *periodic* ($M = 81.67, SD = 12.37$). This correlates with the median ratings.

In the debriefing interview, participants had the opportunity to give individual feedback. One participant stated that he had the feeling that sometimes the intelligent system was signaling even though he was aware of every system status. Another participant pointed out, that the chosen cue, highlighting a display by flashing the whole screen in red, was not always sufficient, even though the simulator bridge was rather small.

All participants experienced the periodic cueing as annoying. Meanwhile, the intelligent system was experienced as more pleasant by all participants. Further, two participants suggested to make the intelligent system even more context-aware, e.g. reacting also to the distance to buoys, not only to other ships.

Figure 6.3: The study apparatus: A ship bridge simulator, consisting of a two display viewing system and six information displays, that were fitted with fiducial markers to mark them as AOIs for the eye tracker.

6.1.3.6 Discussion

In our preliminary study, we were able to get some interesting insights. Our evaluation in the ship bridge simulator showed, that the combination of the MAS with our extensions and visual cueing was functional. Also, we were able to observe tendencies that indicate that our adaptive approach was more usable, with a lower workload than a fixed interval reminder per information display.

Still, the difference in Situation Awareness between the two conditions is not clear. The mean is slightly larger for *periodic*, but the standard deviation is as well. Further, the medians suggest, that *intelligent* was rated with a higher Situation Awareness. Given the small sample size, we would assume, the medians display the more accurate tendencies. However, the median absolute deviation of Situation Awareness for *intelligent* (MD = 7.41) is too large to make any clear statements concerning differences in Situation Awareness.

6.1.4 Conclusion and Outlook

As our work shows, the MAS is transferable to spatial interaction domains, such as the maritime domain. Moreover, with our extensions, it is capable of dealing with *information objects* of varying information complexity. In our evaluation, our system was perceived as less annoying than a fixed interval reminder per information display. Furthermore, it was rated as being more usable and having a lower workload.

In the future, we plan to refine the parameters for our scenario through an interview with further experts. The refined version of the system will then be evaluated with more participants against a ground truth condition using improved guidance cues.

6.2 Concept for Context-aware Guidance Cue Selection

In Chapter 5, we investigated visual, tactile, and auditory guidance cues that were located on-body or in the environment. We found, that these cues differ in their perceived urgency, as well as their response times and perceived workload. Further, depending on the current situation, modal channels can be under different load, e.g. noise masking the cue or an incoming VHF call occupying auditory resources (cf. Wickens' multiple resource theory [Wic91]). Therefore, we propose to implement multiple guidance cues addressing different modalities for monitoring assistance systems on ship bridges. This enables the monitoring assistance system to choose the best-fitting cue for the current context, considering urgency and noise masking.

This section describes a simplistic approach for the live selection of guidance cues based on the current context. The approach is based on decision matrices and sensor input. Useful sensor input includes photo-sensors to get the current environmental light conditions and microphones backed with a voice activation detection (VAD) algorithm to detect human communication. The concept of decision matrices was first introduced by Stuart Pugh [Pug91]. The weighted decision matrix was derived from the initial Pugh Matrix. We propose to use a dynamic weighted decision matrix (cf. Figure 6.4). The dynamic weighted decision matrix is constructed and used following these steps:

1. Find static weights (relative importance) with paired comparison analysis.

2. Get total importance from live data (dynamically).

3. Make a decision based on the decision matrix.

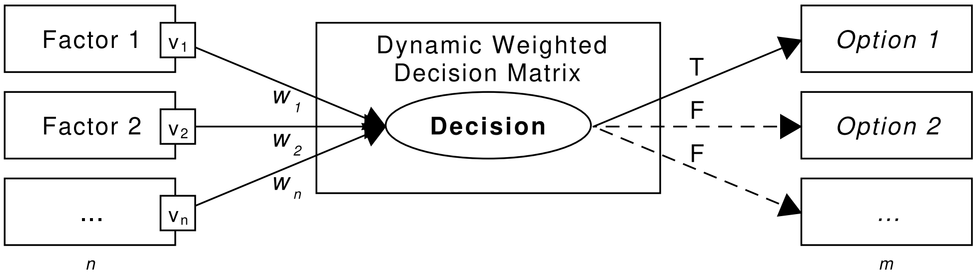


Figure 6.4: Dynamic Weighted Decision Matrix.

Decision Matrices have the advantage of easy readability and comprehensibility, as the decision space can be visualized as a table or plotted. Considering the traditionally conservative attitude in the maritime domain, this is an important factor.

There are two approaches: Either we use a large decision matrix for all cue combinations or we organize multiple decision matrices in a tree structure, taking consecutive decisions, e.g. choose a modality first, then the best pattern for the selected modality.

Weights (w_1 - w_n) are constants, assigned based on a priori paired comparison analysis. Each weight is a vector of length m, providing one weight per option. Each factor provides a dynamically changing value (v_1 - v_n) as input. Based on the input one or more options are selected (true/false).

Figure 6.5 shows examples of relevant factors grouped into environmental and situational factors. Ongoing communication, which can be detected via voice activity detection (VAD) is another interesting factor to be considered. The implementation and testing of such a context-aware cue selection system is out of the scope of this thesis and is left for future work. However, it should be easy to implement the presented concept, which is why we decided to share our concept as a starting point.

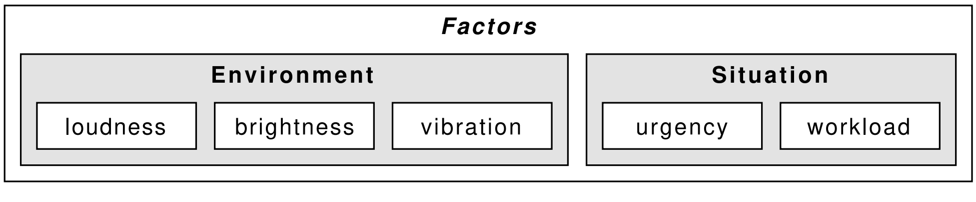


Figure 6.5: Factors for cue selection.

6.3 Summary

We adapted an existing monitoring assistant system to cope with information displays of varying information complexity and used it to rate the situational perception of a nautical officer on the basis of eye tracking data. Based on this we supported nautical officers with a simple attention guidance system during a maneuvering scenario in a ship bridge simulator. In this work, we present our adaptation of the monitoring assistant system, parameters to use it in the maritime scenario ”takeover with traffic encounter” and the results of a preliminary user study in a ship bridge simulator. This work addresses research question 1.2.

Finally, we described a simplistic approach for the live selection of guidance cues based on the current context. The approach is based on decision matrices and sensor input. The implementation and testing of the proposed context-aware cue selection system is out of the scope of this thesis and is left for future work.

7 Conclusion

Concluding our work, we give a summary of the thesis, present our contributions to the investigated research questions, discuss the reliability and validity of our results, and give suggestions for future work.

7.1 Summary

In Chapter 1, we motivated our work by illustrating the addressed problem and stating the challenges of the presented research. The chapter introduced our research objectives as well as summarizes our contributions.

In Chapter 2, we introduced concepts and related work on which this work is based on. Starting with a definition of Situation Awareness, followed by models of attention, and how attention can be tracked, the chapter closed with related work about attention guidance and relevant regimentations in the maritime domain.

Chapter 3 describes the general approach of this thesis. Starting with a brief description of the applied methodologies, we follow up with a description of the context of use, problem analysis and end with a structured description of our approach. For the problem analysis, we analyzed over five-hundred maritime accident reports for each of the eight SA Demons to provide a ranking of the causes and to identify the most prominent ones. Addressing these SA Demons enables maritime system designers to enhance the Situation Awareness of maritime operators and thereby improves safety at sea.

In Chapter 4, we proposed a mobile ship bridge system to fully support the development process from lab studies to tests in realistic environments. Our system allows developing new software components in the lab and setting them up on a ship bridge without interfering with the vessel's navigational systems. Further, combined with the open-source simulator software Bridgecommand, the system reassembles a full-mission simulator. Also, we set up an artificial acoustic scene of a ship's bridge incorporating scenario-dependent machine noise, wind, wave, rain, and radio call sounds. The acoustical scene can be rendered in the audio lab of the University of Oldenburg. Further, we set up a vibration platform and signal that mimics the machine-induced environmental vibration on a ship bridge for a single standing person.

In Chapter 5, we explored shifting attention towards the location of relevant entities in large cyber-physical systems. Therefore, we used pervasive displays: tactile displays on both upper arms and a peripheral display. With these displays, we investigated shifting the attention in a seated and standing scenario. In a first user study, we evaluated four distinct cue patterns for each on-body display. We tested seated monitoring limited to 90° in front of the user. In a second study, we continued with the two patterns from the first study for lowest and highest urgency perceived. Here, we investigated standing monitoring in a 360° environment. We found that tactile cues led to faster arousal times than visual cues, whereas the attention shift speed for visual cues was faster than tactile cues.

We explored a novel method based on pneumatic cues to provide a more natural tactile output. We use two airbags positioned at the back of the user, at shoulder height to give navigational cues. We utilize the shoulder tap metaphor to give directions to the left, right, or ahead. We compare the pneumatic cue to vibro-tactile cue at the same position. Our results show, that the pneumatic cue was rated as significantly less urgent than vibro-tactile cue. As there were no significant differences in error rate, annoyance, and usability, we rate ShoulderTap as an eligible alternative to vibro-tactile cues.

We developed a light display for such a multi-monitor setup, that is controlled by eye-tracker input to guide the attention of a user from the currently focused display to another display, that is in demand of attention. Together with HCI experts for light displays we designed, implemented, and evaluated three different strategies for attention guidance with our light display in a user study. We found that ambient guidance cues that begin at the current focus of the user are faster in guiding the user to a target in the periphery than ambient guidance cues in the peripheral vision of the user.

On a virtual ship bridge, moved and static acoustical pointers were applied to announce the need to check an instrument. Participants with nautical experience steered a virtual freight ship through a fjord with some traffic. Two weather conditions were performed with respect to different stress levels: sunny vs. rainy and windy. During this, they had to answer radio calls and check the pointed instruments. Radio calls were realized by a speech perception test with adaptive speech levels. Acoustical pointers were sequences of a synthesized xylophone sound that pointed to an instrument that was located at either +60° or -60° azimuth. The background noise was a realistic ship noise. Pointers and speech were presented simultaneously. Moving pointers always started at 0° azimuth. Speech was either presented from 0° or the current target direction (+-60° az). The time to first fixation on target area after a pointer was measured by eye tracking. Results indicate that moving pointers lead to reduced times to first fixation. At the same time, participants judge the urgency lower than for static pointers. Movements of the pointers did not influence the intelligibility of the radio calls.

We developed a light display for a horizontal multi-monitor setup, as commonly found on ship bridges, that is controlled by eye-tracker input to guide the attention of a user from the currently focused display to another display, that is in demand of attention. Together with HCI experts for light displays we designed, implemented, and evaluated three different strategies for attention guidance with our light display in a user study. We found that ambient guidance cues that begin at the current focus of the user are faster in guiding the user to a target in the periphery than ambient guidance cues in the peripheral vision of the user.

In Chapter 6, we presented an adaptation of an existing monitoring assistant system that could cope with information displays of varying information complexity and used it to rate the situational perception of a nautical officer based on eye tracking data. Based on this we supported nautical officers with a simple attention guidance system during a maneuvering scenario in a ship bridge simulator. In this work, we present our adaptation of the monitoring assistant system, parameters to use it in the maritime scenario ”takeover with traffic encounter” and the results of a preliminary user study in a ship bridge simulator. Finally, we described a simplistic approach for the live selection of guidance cues based on the current context. The approach is based on decision matrices and sensor input. The implementation and testing of the proposed context-aware cue selection system is out of the scope of this thesis and is left for future work.

7.2 Contributions

We make the following contributions to assistance systems for guiding attention. Through Accident Report Analysis using natural language processing techniques, we compiled a ranking of human factors that impede Situation Awareness in maritime accidents. For the ecological validity of our study results three combineable apparatuses for lab testing were implemented, which simulate the visual, auditory, and tactile properties of a real-world ship bridge. In lab experiments using eye-tracking and standardized questionnaires, we created a set of visual, auditory, and tactile cues for spatial attention guidance on ship bridges. From the experiments and literature research, we composed a list of design guidelines for spatial attention guidance cues. In the following, we describe our contributions to the research questions in more detail.

RQ 1: What are the main factors for a lack of attention that lead to maritime accidents?

Our results confirm that Situation Awareness Level 1 is the most prominent source of Human Error in maritime accidents. Likewise, it is the most prominent one of the three levels of Situation Awareness. All in all, the SA Demons with the highest proportion in the investigated sample were *WOFAS* with fatigue as the main cause, *errant mental models*, and *attention tunneling*. We were not able to find accidents caused by *requisite memory trap*, *misplaced salience* or *complexity creep*, however we still think that these exist. Unfortunately detecting these SA Demons in maritime accident investigation reports will remain difficult, unless it becomes part of the investigation itself. We advise taking special care of the SA Demons *WOFAS*, *errant mental models*, *data overload* and *attention tunneling* when designing new interfaces for ship bridges. Our findings might also be beneficial for the design of user interfaces for Vessel Traffic Management

(VTM) centers.

RQ 2: How can we simulate a ship bridge including its visual, auditory, and tactile noise conditions in a lab environment?

We contribute three simulator systems, each targeting a different modality: a mobile ship bridge system, an artificial acoustic scene of a ship's bridge, and a vibration platform and engine vibration signal. These simulators specifically mimic realistic visual, acoustic, and tactile properties of a ship's bridge, ensuring a high ecological validity of results. As our apparatuses are based on real ship characteristics from our reference ship and were developed complying with the relevant standards (cf. Section 2.5), we find our apparatuses and the way we combined them in the chapters (Chapter 5 and Chapter 6) to be a valid answer to research question 1.2: *How can we simulate a ship bridge including its visual, auditory and tactile noise conditions in a lab environment?*.

RQ 3: What is the design space of guidance cues for exogenous orienting of overt attention?

Spatial Attention Guidance, is the spatial reorientation of overt attention (cf. Section 2.2) triggered and guided by cues. We focus on cues that utilize exogenous orienting (cf. Section 2.4), as these cope better with human factors such as fatigue. The design space of Spatial Guidance Cues is limited to the three modalities visual, tactile, and auditory, as they are the only cue modalities, that allow for spatial localization or mapping in 3D space. Concerning cue placement, we distinguish between cues placed onbody and cues placed in the environment.

According to the Guidelines on Ergonomic Criteria for Bridge Equipment and Layout (MSC/Circ.982) by the International Maritime Organization (IMO), the preferred viewing area (+/-15° horizontally) and the immediate field of view (+/-35° horizontally) are reserved for information from displays and should not be occluded [Mar00]. Figure 2.3 in Section 2.5 visualizes these areas. Not blocking the foveal vision is also important in other domains. That is why we decided to investigate visual cues in the peripheral field of view. Peripheral vision comes with different characteristics than foveal vision. The color perception is more limited, there is no sharp vision, and the perception of changes and motions is stronger than the perception of details. Therefore we focused on investigating visual cues rendered by low resolution light displays.

Tactile cues are widely used for conveying directions for navigation [TY04, MMUW15, HHBP08], which shows their high potential for successfully conveying spatial information. There are different ways to implement tactile cues, we focused on vibro-tactile cues (vibration) and pneumatic cues (pressure). For the highest effectiveness, the placement of tactile cues should be limited to positions that allow for simple direction mapping. Further, close proximity to intimate body areas should be avoided, to avoid unpleasant user experiences.

Auditory cues are spatially locatable by humans, however, the quality of 3D audio is limited by hardware. There are two ways to render 3D audio, either through a surround-sound speaker setup or through headphones. Headphones have the disadvantage of physically limiting the perception of environmental sounds, such as face-to-face communications, VHF radio calls, and environmental sounds. Bone conduction speakers are alternative speaker hardware that allows for the simultaneous perception of environmental sounds. Unfortunately, they are not technically suitable for rendering 3D audio, as the sound does not travel through the outer ear but rather through a bone to the inner ear. That is why we decided to focus on auditory cues rendered in the environment through a surround-sound speaker setup, to ensure 3D localization of sounds while maintaining high speech intelligibility.

RQ 4: What are effective visual, auditory, and tactile cue implementations for cuing onbody or in the environment?

In Section 5.3, we looked into visual and vibro-tactile onbody cues. We found that the combination of visual and tactile cues led to increased workload and should be avoided in situations and environments, where the workload is already high. Instead of the concurrent combination of modalities, we propose to combine modalities consecutively and use vibration for attention arousal and peripheral light for the shift. As for the use of single modalities, tactile cues tend to have a faster total response time than visual cues. Further, on-body cues should be paired with cues at the target position to allow for accurate localization, as we found in pre-tests and implemented in our study setups.

In Section 5.5, we observed that static and moving conditions triggered different behavior in our participants. Static acoustical pointers led to a more chaotic gaze pattern and head movements searching for the source of the signal, whereas moving patterns led to a more stable and smooth head and gaze movement towards the target. This is also reflected in the shorter target acquisition times for moving acoustical pointers. That is why we recommend using moving acoustical pointers rather than static acoustical pointers.

In Section 5.2, we presented three different guidance strategies (trace, call, pickup) for spatial attention guidance in multi-monitor systems. We implemented and compared these strategies through the example of a ship bridge using a light display. Our findings indicate that ambient guidance cues that begin at the current focus of the user are faster in guiding the user to a target in the periphery than ambient guidance cues in the peripheral vision of the user. Combined with our findings from Section 5.5, we recommend for visual and auditory cues in the environment to begin guidance at the current focus of attention and guide continuously towards the target.

RQ 5: When should guidance cues be triggered?

We found that on ship bridges some information has to be perceived once, some has to be checked in a fixed interval and for some information, it depends on the situation (e.g. distance to other ships), how frequent it demands attention (see Table 6.1). Therefore, we decided together with domain experts to base the frequency for the latter on the Time to Closest Point of Approach (TCPA), a common time distance measure from the maritime domain.

Fortmann et al. defined the *demand for attention* (DfA) [FM14] based on Wickens SEEV-Model [WM07]. They further presented a tool called MAS, that calculates and ranks the *demand for attention* of multiple areas of interest (AOIs) online based on live eye tracking data. As the goal is to support regular monitoring, the neglect time, the time since the last check of the information, is taken into account for the calculation of the DfA score. Therefore, the DfA of an *information element* is calculated based on the task-relevance of an information element, a value between zero and one, the maximal neglect time for the monitoring interval of the information element, and the actual neglect time, as measured by eye tracking. For further details on the calculation, see Fortmann and Mengeringhausens paper [FM14].

On ship bridges, the complexity of information varies drastically between displays (e.g. radar or turn rate indicator), therefore we introduce two new parameters: The *fixation quotient*, which reflects the number of fixations on the display and the *fixation duration quotient*, which reflects the duration of the visual inspection of the display by the operator. Both parameters were introduced to cope with the complexity of the displays, as van de Merwe et al. found, that the fixation rate and dwell time are good indicators for situation awareness [vdMvDZ12]. Depending on the complexity of a display, there are more areas of interest AOIs on it, and the time to comprehend the information on it might be longer. The information of an information display is recognized as "perceived" by the system, if either the *fixation quotient* or the *fixation duration quotient* reaches a value of one. This is to cope with measurement errors of the eye tracker and to avoid unnecessary cues.

Seven Recommendations for Spatial Attention Guidance in Monitoring Assistance

Based on our research we formulate the following seven recommendations for spatial attention guidance:

1. Avoid the concurrent combination of light and vibration (cf. Section 5.3).
2. Combine light and vibration consecutively: Vibration for arousal of attention and light for shifting attention (cf. Section 5.3).
3. Use moving acoustical pointers rather than static acoustical pointers (cf. Section 5.5).

4. Combine on-body cues with cues at the target position (cf. Section 5.3).

5. Begin guidance at the current focus of attention and guide continuously towards the target (cf. Section 5.2, 5.5).

6. Guide attention on a regular basis, but based on the current situation and context rather than on a fixed interval (cf. Chapter 6).

7. Consider the information complexity as a relevant factor for monitoring intervals (cf. Chapter 6).

7.3 Reliability and Validity

Parts of this work have been evaluated in sophisticated simulator environments (see Apparatus chapter), specifically mimicking realistic visual and acoustic properties of a ship's bridge. Further, tasks and scenarios for the studies in these simulator environments were designed to be realistic, as they were derived by a contextual inquiry, expert interviews, activity analysis, and goal-directed task analysis. This practice contributes to the ecological validity of the presented work regarding sensory noise and workload . However, we did not investigate cross-modal effects.

Further, we conducted strongly controlled lab studies without simulating the ship bridge environment. We did this to achieve a high internal validity, identifying trustworthy cause-effect relationships. But this is also a limitation towards the ecological validity of these results.

Another Limitation of our work is that we did not perform experiments with strongly fatigued participants, which is why we cannot infer the validity of our results concerning their effectiveness for strongly fatigued operators. Though we considered this requirement in every step of our cue and guidancestrategy designs, an evaluation under conditions of fatigue remains as critical future work. In Section 7.4 we described, how we would approach that.

Further, we used eye-trackers to objectively track the overt attention of participants in our studies. Hereby, we assure the actual effectiveness of the guidance cues that we investigated. However, we did not investigate the long-term effectiveness of the guidance cues.

All necessary data, software, and hardware documentation, for our simulator environments, have been either published in peer-reviewed journals or made otherwise publicly available. This allows other researchers to continue or replicate our work.

7.4 Future Work

We see potential for further research in spatial attention guidance, especially in the context of monitoring assistance, but also in other contexts, such as Augmented and Virtual Reality applications. The following six paragraphs describe the research topics, which we find to be the most interesting future steps tied to our work.

Masking of Tactile Cues by Environmental Vibration

Although first tests on our vibration platform did not show any effect on the perceptibility of vibro-tactile cues, it is possible that there is an effect for smaller vessels. The reference ship (2999 GT) that we used had a vertical distance of 12 meters between the bridge room floor and the engine. Compared to large container ships, this is rather close, so we do not expect any effects there either. However, for smaller ships it is still possible and thus should be investigated that the engine vibration masks the tactile display.

Context-aware Cue Selection

Future work should answer the question of ”How to decide, which cues should be selected based on the current context?”. Section 6.2 proposes a possible solution for the context-aware selection of cues. However, the proposed solution has to be implemented, evaluated, and compared to other techniques to give a proper answer to the aforementioned research question.

Workload-aware Guidance Control

Previous works have shown that workload can be estimated by pupil dilation [PFSK16, KGDR16]. As the proposed system already uses an eye tracker for gaze tracking, this workload estimation technique can de easily integrated. Incorporating the current workload into context-aware guidance control could enhance the fitness of the cue selection for the current context even more, making the spatial attention guidance even more effective.

System Status & Failure Handling

The general idea behind a monitoring assistance system applying spatial attention guidance is that it guides the attention of the user based on a model of the Situation Awareness of the user. Therefore, cues are only triggered, if there is a demand for attention. This means an experienced OOW might get cues less often than an inexperienced or fatigued OOW. This raises the question of how to cope with system failure. How does the user know the system is still running? This is an interesting and important topic to research, as it is critical for the reliability of the monitoring assistance system.

Field Tests

Conducting field tests of the presented work for a longer period would further validate the presented results. Even though we simulated environmental factors in our study, a simulation can only mimic the real world to a certain degree and does hardly cope with cross-modal effects. While we can induce workload, certain other human factors, such as fatigue, are hard to emulate in laboratory studies. A field test could provide further insights into how people react to spatial guidance cues while suffering from fatigue.

Laboratory Study on the Effect of Fatigue

While a field test could provide further insights into how people react to spatial guidance cues while suffering from fatigue, as mentioned above, a laboratory study would allow for testing under extreme conditions that would not be possible in a field test for safety reasons. In a lab study, fatigue could be induced by voluntary 24 hours sleep deprivation before starting the study. This would not be safe to do in a field test. We left this for future work, as it would have limited the participant pool severely and therefore made no sense this early in the exploration of the design space of spatial attention guidance cues. However a future system based on our design recommendations (Section 7.2) and cue designs should be evaluated with fatigued personnel in a safe simulator environment.

Application in other Domains

The focus of this thesis is a specific control room in the maritime domain, namely the command bridge of a ship. However, the approach might also be applicable to control rooms in other domains, such as air traffic control, nuclear power plant control, and emergency call center. Even applications outside of control rooms are feasible, as we explored in a pedestrian warning system that makes pedestrians aware of approaching cars from their back [GSJ+18, JLC+18].

Augmented and Virtual Reality

With Augmented and Virtual Reality becoming more and more common in working environments as well as our daily lives, it is interesting how the presented work can be extended into partly or fully virtual environments. We started exploring this field of research by creating tools [SGB18, GSHB17] for simple and fast prototyping, looked into fundamental on-display visualization parameters in Virtual Reality [GHS+18], investigated immersion preserving guidance cues for VR [LSGB20], and explored visual light cues for Augmented and Virtual Reality [GSA+18, GSPH18]. We encourage future researchers working in this field to think outside the box and consider alternative concepts to the state-of-the-art modalities of current Virtual and Augmented Reality systems.

7.5 Closing Remarks

Our research offers design recommendations for all components of a monitoring assistance system utilizing spatial guidance cues. Building on our results, integrating such a monitoring assistance system into a ship bridge should be feasible and effective. Such a system should implement different cues and include context-aware cue selection as sketched in Section 6.2. This should ensure the long-term effectiveness of the cues, as it creates variation in the cues.

Figures

1.1 Collision of *Marti Princess* and *Renate Schulte* 2
1.2 Thesis Structure 10

2.1 Situation Awareness in dynamic decision making 12
2.2 Three-dimensional representation of the structure of multiple resources. The fourth dimension (visual processing) is nested within visual resources (cf. [Wic91]). 15
2.3 Field of view reglementations on ship bridges 19

3.1 Activity Diagram 22
3.2 The ship's bridge of research vessel Sikuliaq 24
3.3 Design Space: Ship bridge 25
3.4 Contextual Inquiry: Photos of Orcana 27
3.5 Activity Diagram: Avoidance of Collisions 28
3.6 Activity Diagram: Avoidance of Groundings 28
3.7 Time for Situation Awareness, decision making and implementation 30
3.8 Scenario: Takeover on a canal with traffic encounter 38
3.9 Goal tree for the scenario 39

4.1 Mobile Bridge schematic 48
4.2 Virtual Handles 49
4.3 Mobile Bridge on research vessel Zuse 50
4.4 Mobile Bridge: Simulator Setup 51
4.5 Dimensions of the simulated bridge room 53
4.6 Photo of the acoustic virtual reality laboratory 54
4.7 Vibration platform 55
4.8 Waveform and frequency spectrum of vibration signal 56
4.9 Measurement of vibration amplitude under different load 57
4.10 Measurement apparatus for attention shifting 59

5.1 Photo of luxmeter 62
5.2 Guidance strategy implementations for light cues in the environment 66
5.3 Lightdisplay 68
5.4 Study setup: Light cues in the environment 69
5.5 Comparison of TTFFs between light patterns 71
5.6 Onbody vibrotactile and peripheral light display 73
5.7 Plots of vibration and light patterns 76
5.8 Study setup: Onbody cues, seated, 90° 79

5.9 Button press response times 80
5.10 Study setup: Onbody cues, standing, 360°; Marker Pillar 82
5.11 Arousal time and shift speed per cue 85
5.12 Perceived workload and usability of the cues 85
5.13 The pneumatic system of the prototype. 88
5.14 Path directives 89
5.15 Placement of the prototype on the back 90
5.16 Participant wearing prototype, headphones and an input device . . 91
5.17 Rating distribution for perceived annoyance and perceived urgency 92
5.18 Usability and error rate for ShoulderTap and vibration 94
5.19 Audio cue waveform 98
5.20 Speaker setup in the anechoic chamber 99
5.21 Study setup: Ship simulator in anechoic chamber 100
5.22 Dimensions of the simulated bridge room 102
5.23 TTFFs for each cue condition 105
5.24 Rating distribution for perceived annoyance, urgency, alarmingness, and pleasantness 106

6.1 Simulator scenario: Takeover on a canal with traffic encounter . . . 113
6.2 Goal tree of the scenario 115
6.3 Study setup: Ship bridge simulator 117
6.4 Dynamic Weighted Decision Matrix 119
6.5 Factors for cue selection 119

Tables

2.1 Overview of Related Work: Spatial Attention Guidance 17

3.1 Activity Analysis 23
3.2 Overview of the retrieved text corpus 31
3.3 Keywords for each SA Demon 34
3.4 Composition of the boolean search queries for each SA Demon . . 35
3.5 Retrieved occurrences of SA Demons in MAIB Corpus 35

4.1 Noise level limits in dB(A) for navigation spaces on ships 53

5.1 Cue modality - placement combinations 63
5.2 Urgency, annoyance, confidence, helpfulness, and intuitiveness ratings 93
5.3 Noise level limits in dB(A) for navigation spaces on ships 102

6.1 Overview of task, information, relevance and maximum neglect time112
6.2 TCPA to maximum neglect time conversion 113

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