Mälardalen University Doctoral Dissertation 351

Information Visualization Using Transparent Displays in Mobile Cranes and Excavators

Taufik Akbar Sitompul

MÄLARDALEN UNIVERSITY
SWEDEN

Mälardalen University Press Dissertations
No. 351

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2022

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School of Innovation, Design and Engineering

ISBN 978-91-7485-539-5
ISSN 1651-4238
Printed by E-Print AB, Stockholm, Sweden

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Akademisk avhandling

som för avläggande av teknologie doktorsexamen i datavetenskap vid Akademin för innovation, design och teknik kommer att offentligen försvaras onsdagen den 12 januari 2022, 13.15 i Lambda och on-line via Zoom/Teams, Mälardalens högskola, Västerås.

Fakultetsopponent: Professor Philippe Palanque, IRIT

MÄLARDALEN UNIVERSITY
SWEDEN

Akademin för innovation, design och teknik

Abstract

Operating heavy machinery, such as mobile cranes and excavators, is a complex task. While driving the machine, operators are also performing industrial tasks, e.g. lifting or digging, monitoring the machine's status, and observing the surroundings. Modern heavy machinery is increasingly equipped with information systems that present supportive information to operators, so that they could perform their work safely and productively. Supportive information in heavy machinery is generally presented visually using head-down displays, which are placed in lower positions inside the cabin in order to avoid obstructing operators' view. However, this placement makes visual information presented using head-down displays tend to be overlooked by operators, as the information is presented outside their field of view.

This dissertation investigates the possible use of transparent mediums for presenting visual information on the windshield of mobile cranes and excavators. By presenting information on the windshield, operators are expected to acquire visual information without diverting their attention away from the operational area. The design process includes (1) observing heavy machinery operators in natural settings through available videos on the Internet, (2) conducting an empirical study on the impact of different information placements, (3) reviewing the state of the art of display technologies that could be used to visualize information around the windshield of heavy machinery, (4) reviewing relevant safety guidelines to determine what kinds of critical information that operators should know, (5) conducting design workshops to generate visualization designs that represent critical information in operations of mobile cranes and excavators, (6) involving professional operators to evaluate and improve the proposed visualization designs, and (7) developing a functioning transparent display prototype that visualizes one kind of critical information that professional operators considered as the most important one.

The main finding from the observation using online videos suggested that heavy machinery operators spent considerable amount of time looking through the front windshield, and thus the front windshield could be used as a potential space for presenting visual information. The main finding of the empirical study also indicated that presenting information closer to the line of sight produced higher information acquisition and lower workload, compared to when information was presented farther from the line of sight. Based on the evaluation with professional operators, there seemed to be a good match between the proposed visualization designs and the operators' way of thinking, since the operators were able to understand and use the proposed visualization designs with little explanations. On the basis of the three most important findings above, there is a strong indication that placing the developed transparent display on the front windscreen of heavy machinery would make it easier for operators to perceive and process the presented information.

ISBN 978-91-7485-539-5
ISSN 1651-4238

"Solving a problem simply means representing it so as to make the solution transparent".

Simon A. Herbert [59, p. 132]

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Abstract

Operating heavy machinery, such as mobile cranes and excavators, is a complex task. While driving the machine, operators are also performing industrial tasks, e.g. lifting or digging, monitoring the machine's status, and observing the surroundings. Modern heavy machinery is increasingly equipped with information systems that present supportive information to operators, so that they could perform their work safely and productively. Supportive information in heavy machinery is generally presented visually using head-down displays, which are placed in lower positions inside the cabin in order to avoid obstructing operators' view. However, this placement makes visual information presented using head-down displays tend to be overlooked by operators, as the information is presented outside their field of view.

This dissertation investigates the possible use of transparent mediums for presenting visual information on the windshield of mobile cranes and excavators. By presenting information on the windshield, operators are expected to acquire visual information without diverting their attention away from the operational area. The design process includes (1) observing heavy machinery operators in natural settings through available videos on the Internet, (2) conducting an empirical study on the impact of different information placements, (3) reviewing the state of the art of display technologies that could be used to visualize information around the windshield of heavy machinery, (4) reviewing relevant safety guidelines to determine what kinds of critical information that operators should know, (5) conducting design workshops to generate visualization designs that represent critical information in operations of mobile cranes and excavators, (6) involving professional operators to evaluate and improve the proposed visualization designs, and (7) developing a functioning transparent display prototype that visualizes one kind of critical information that professional operators considered as the most important one.

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the front windshield, and thus the front windshield could be used as a potential space for presenting visual information. The main finding of the empirical study also indicated that presenting information closer to the line of sight produced higher information acquisition and lower workload, compared to when information was presented farther from the line of sight. Based on the evaluation with professional operators, there seemed to be a good match between the proposed visualization designs and the operators' way of thinking, since the operators were able to understand and use the proposed visualization designs with little explanations. On the basis of the three most important findings above, there is a strong indication that placing the developed transparent display on the front windscreen of heavy machinery would make it easier for operators to perceive and process the presented information.

Sammanfattning

Att köra stora mobila maskiner, exempelvis mobilkranar och grävmaskiner, är en komplex uppgift. Förutom att köra maskinen utför operatörerna också andra arbetsuppgifter, t.ex. lyfta eller gräva, övervaka maskinens status och observera omgivningen. Moderna stora maskiner blir i ökande grad utrustade med informationssystem som presenterar stödinformation för operatörerna så att de ska kunna utföra sitt arbete säkert och produktivt. Informationsstödet i stora maskiner presenteras visuellt med hjälp av displayer som placeras i lägre positioner inuti kabinen, s.k. *head-down*, för att inte hindra operatörens sikt genom vindrutan. Den låga placeringen gör att operatörer tenderar att missa information som presenteras på head-down-skärmar eftersom informationen presenteras utanför deras synfält.

Den här avhandlingen undersöker hur transparenta skärmar kan användas för att presentera visuell information på vindrutan på mobilkranar och grävmaskiner. Genom att presentera information på vindrutan förväntas operatörerna inhämta visuell information utan att avleda deras uppmärksamhet från operationsområdet. Designprocessen omfattar att (1) observera operatörer av stora maskiner i naturliga miljöer genom tillgängliga videor på Internet, (2) genomföra en empirisk studie om effekterna av olika informationsplaceringar, (3) granska den senaste tekniken inom displayteknik som kan användas för att visualisera information på vindrutan hos stora maskiner, (4) granska relevanta säkerhetsriktlinjer för att avgöra vilken typ av kritisk information som operatörerna bör känna till, (5) genomföra designverkstäder för att generera visuell design som representerar kritisk information vid drift av mobilkranar och grävmaskiner, (6) involvera professionella operatörer för att utvärdera och förbättra de designförslagen och (7) utveckla en fungerande transparent displayprototyp som visualiserar den sorts kritisk information som professionella operatörer ansåg vara viktigast.

Det viktigaste fyndet från observationen med hjälp av online-videor visade att operatörer av stora maskiner främst tittar genom den främre vindrutan, därmed utgör potentiellt vindrutan en yta för presentation av visuell information. Det

viktigaste resultatet från den empiriska studien indikerade också att information som presenterades närmare siktlinjen gjorde att användare inhämtade mer information med lägre arbetsbelastning jämfört med när information presenterades längre från siktlinjen. Baserat på utvärderingen med professionella operatörer tycktes det finnas en bra överenstämmelse mellan de föreslagna informationsvisualiseringarna och operatörernas sätt att tänka, eftersom operatörerna kunde förstå och använda de föreslagna informationsvisualiseringarna med korta små förklaringar. Med utgångspunkt i de tre viktigaste fynden ovan finns det en stark indikation till att en transparent display, placerad på den främre vindrutan på stora maskiner, underlättar för operatörer att uppfatta och bearbeta den presenterade informationen.

Acknowledgments

The research presented in this dissertation was part of a European project called Immersive Visual Technologies for Safety-critical Applications (ImmerSAFE)[1], which was funded through the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No. 764951. First of all, I would like to thank all EU taxpayers and the European Commission for funding this research project. I would also like to thank my former employer, CrossControl AB, for hiring and giving me complete freedom to decide how to work on this research project.

I would like to thank my principal supervisor, Assoc. Prof. Rikard Lindell, for all his guidance and patience throughout my doctoral studies. Although the past three and half years were not a smooth journey for both of us, I am really grateful that you always looked after my interests from the beginning to the end. I would also like to thank my assistant supervisor, Prof. Björn Lisper, for willing to supervise me, even though his research field is far from the topics presented in this dissertation. I am really thankful for all his support, especially when Rikard was occupied with family matters.

I used six papers that were published during my doctoral studies as the foundation of this dissertation. Although this dissertation was written by one person, the six included papers were produced out of the combined efforts from multiple people. I would like to thank my collaborators in those six papers: Dr. Markus Wallmyr from CrossControl AB, Simon Roysson from Mälardalen University, José Rosa from Beneq Oy, Antti Siren from Forum for Intelligent Machines ry, and Tobias Holstein from Darmstadt University of Applied Sciences, for their willingness to be involved in my research. Without their collaborations, this dissertation could not have been composed like this.

When writing this dissertation, I also received additional feedback from outside the supervision team. I would like to thank Prof. Thomas Porathe from Norwegian University of Science and Technology for his extensive guidance through-

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[1] https://cordis.europa.eu/project/id/764951

out the writing process of this dissertation. I would also like to thank Dr. Annica Kristofferson from Mälardalen University for her valuable work as an internal reviewer and making sure this dissertation was ready to be defended.

I would like to express my gratitude to my office mates and also fellow doctoral students at Room U1-049 (ordered based on who joined earlier): Václav Struhár, Nitin Desai, Soheila Sheikh Bahaei, Shahriar Hasan, Van-Lan Dao, Zeinab Bakhshi Valojerdi, and Shaik Mohammed Salman, for making my daily life as a doctoral student very enjoyable. I could not remember a single day that we spent at the office without any laugh. Special thanks to Jean Malm and Robbert Jongeling for arranging many social events for fellow doctoral students, which made my doctoral journey even more enjoyable. I wish you all the best on your future endeavors and hopefully our paths will cross again in the future.

The last but definitely not the least, I would like to thank my family and relatives for their unconditional and infinite support throughout my doctoral studies.

Taufik Akbar Sitompul
Västerås, 29 November 2021

List of Publications

Papers Included in This Dissertation[2] [3]

Below is the list of published papers that I included to compose this dissertation. Brief descriptions about my contributions can be found below each paper.

Paper A: T. A. Sitompul and M. Wallmyr. Analyzing online videos: A complement to field studies in remote locations. In *Proceedings of the 17th IFIP TC.13 International Conference on Human-Computer Interaction (INTERACT)*, 2019. Springer. DOI: 10.1007/978-3-030-29387-1_21.

I was responsible for reviewing the literature, searching and filtering the videos, analyzing the selected videos, and authoring the manuscript.

Paper B: M. Wallmyr, T. A. Sitompul, T. Holstein, and R. Lindell. Evaluating Mixed Reality Notifications to Support Excavator Operator Awareness. In *Proceedings of the 17th IFIP TC.13 International Conference on Human-Computer Interaction (INTERACT)*, 2019. Springer. DOI: 10.1007/978-3-030-29381-9_44.

I was responsible for conducting eight out of fifteen user tests, analyzing the collected data, and authoring the manuscript.

Paper C: T. A. Sitompul and M. Wallmyr. Using Augmented Reality to Improve Productivity and Safety for Heavy Machinery Operators: State of the Art. In *Proceedings of the 17th ACM SIGGRAPH International Conference on Virtual-Reality Continuum and Its Applications in Industry (VRCAI)*, 2019. ACM. DOI: 10.1145/3359997.3365689.

I was responsible for searching and filtering the literature, reviewing 60% of the selected literature, and authoring the manuscript.

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[2] The included papers have been reformatted to comply with the layout of this dissertation.

[3] Paper A, Paper B, and Paper C were reprinted with permission from their respective publishers. The copyrights of Paper D, Paper E, and Paper F are held by the authors.

Paper D: T. A. Sitompul, R. Lindell, M. Wallmyr, and A. Siren. Presenting Information Closer to Mobile Crane Operators' Line of Sight: Designing and Evaluating Visualization Concepts Based on Transparent Displays. In *Proceedings of the 46th Graphics Interface Conference (GI)*, 2020. CHCCS/SCDHM. DOI: 10.20380/GI2020.41.

I was responsible for reviewing the literature, conducting the design workshops, recruiting and interviewing the participants, analyzing the collected data, and authoring the manuscript.

Paper E: T. A. Sitompul, M. Wallmyr, and R. Lindell. Conceptual Design and Evaluation of Windshield Displays for Excavators. *Multimodal Technologies and Interaction*, 4(4), 2020. DOI: 10.3390/mti4040086.

I was responsible for reviewing the literature, conducting the design workshops, recruiting and interviewing the participants, analyzing the collected data, and authoring the manuscript.

Paper F: T. A. Sitompul, S. Roysson, and J. Rosa. Developing a Windshield Display for Mobile Cranes. In *Proceedings of the 37th International Symposium on Automation and Robotics in Construction (ISARC)*, 2020. IAARC. DOI: 10.22260/ISARC2020/0200.

I was responsible for reviewing the literature, developing the physical prototype, integrating the mobile crane simulation with the physical prototype, and authoring the manuscript.

Other Publications

Below is the list of papers that were also published during my doctoral studies, but they were not included in this dissertation.

Paper G: T. A. Sitompul and M. Wallmyr. Augmented Reality for Encouraging Environmentally Sustainable Behaviors: A Survey. In *Proceedings of Interaction Latin America 2018*, 2018. Galoá. DOI: 10.17648/ila-2018-98087.

Paper H: M. Wallmyr, T. A. Sitompul, and L. Chuang. 1st Workshop on User Interfaces for Heavy Vehicles: Let's Get to Work. In *Adjunct Proceedings of the 11th International ACM Conference on Automotive User Interfaces and Interactive Vehicular Applications (AutomotiveUI)*, 2019. ACM. DOI: 10.1145/3349263.3350757.

Paper I: S. M. Salman, T. A. Sitompul, A. V. Papadopoulos, and T. Nolte. Fog Computing for Augmented Reality: Trends, Challenges, and Opportunities. In *Proceedings of the 2020 IEEE International Conference on Fog Computing (ICFC)*, 2020. IEEE. DOI: 10.1109/ICFC49376.2020.00017.

Paper J: V. Forsman, M. Wallmyr, T. A. Sitompul, and R. Lindell. Classifying Excavator Collisions based on Users' Visual Perception in the Mixed Reality Environment. In *Proceedings of the 5th International Conference on Human Computer Interaction Theory and Applications (HUCAPP)*, 2021. Scitepress. DOI: 10.5220/0010386702550262.

Paper K: M. Saghafian, T. A. Sitompul, K. Laumann, K. Sundnes, and R. Lindell. Application of Human Factors in the Development Process of Immersive Visual Technologies: Challenges and Future Improvements. *Frontiers in Psychology*, 12, 2021. DOI: 10.3389/fpsyg.2021.634352.

Paper L: S. Roysson, T. A. Sitompul, and R. Lindell. Using Artificial Neural Network to Provide Realistic Lifting Capacity in the Mobile Crane Simulation. In *Proceedings of the 22nd Engineering Applications of Neural Networks Conference (EANN)*, 2021. Springer. DOI: 10.1007/978-3-030-80568-5_37.

Contents

Part I

Dissertation

Chapter 1

Introduction

Heavy machinery (or heavy equipment) is a generic term that refers to a diverse group of vehicles built for various industrial tasks, such as lifting, digging, harvesting, etc [25]. Heavy machinery shares similarities with on-road vehicles, but driving is more like a secondary task in heavy machinery, while the primary task remains on the industrial task that the machine should perform [161]. These machines have revolutionized our ways of working, where work that used to require many people or animals can now be done with a single machine. A notable impact of this revolution can be observed in the agriculture sector, where the invention of machines called combined harvesters reduced the population percentage of farmers in the US from 38% to less than 3% within one century [18].

Operating heavy machinery is a complex task, as operators need to perform multiple tasks simultaneously [162]. In addition to driving their machines, operators are also performing the industrial task, monitoring the machine's status, observing the surroundings, and possibly cooperating with ground workers or other machines. To help operators performing their work, modern heavy machinery is increasingly equipped with sensors and adequate computing capability that can provide supportive information to be used by operators [95]. This digitalization trend is driven by the needs for more features that could improve productivity and safety in heavy machinery operations [136].

Supportive information in heavy machinery is generally presented using head-down displays that exist inside the cabin. As the name suggests, head-down displays are usually placed in lower positions in order to avoid obstructing operators' view [160]. See the small monitors in Figure 1.1 for the examples of head-down displays in heavy machinery. However, prior studies indicate that operators generally pay little attention to the information presented using head-down displays, while controlling their machines [62, 149, 160]. As

Figure 1.1: The left image shows the heat map of eye fixations when felling a tree, while the right image shows the heat map of eye fixations when cutting a tree into smaller logs [149, CC BY-SA 4.0]. The colors change from green to red based on the fixation frequency (from low to high) on specific areas. The images were taken from a forest harvester's cabin.

illustrated in Figure 1.1, operators fixated their eyes most frequently on the operational area, where the industrial task is happening, and they rarely fixated their eyes on the head-down displays. On one hand, when operators focus on the operational area, they are not fully aware of the information presented on head-down displays. On the other hand, operators need to move their attention away from the operational area whenever they look at the presented information. None of these situations are desirable, since operators' ability to mitigate upcoming hazards accordingly might be jeopardized. When accidents occur, the losses are not only in terms of life and property, but also in indirect forms, such as allocating extra resources for accident investigations and finding replacements [55].

Considering the current situation, there is a need for different ways of presenting information in heavy machinery, which could help operators to acquire supportive information without obstructing their views and diverting their attention away from the operational area. One way to achieve this objective is by presenting supportive information directly on the windshield, since this is the area where operators are looking the most [136, 149, 160]. Despite the aforementioned potential, this kind of visualization could also affect operators negatively. For instance, presenting information closer to the line of sight has the potential to clutter operators' view with information, which could then lead to performance deterioration [70]. Operating modern heavy machinery, such as forest harvesters, already requires comparable workload as operating fighting planes [10]. Therefore, there is a need to present supportive information cautiously in order to avoid producing even higher workload for operators. To achieve such objective, we need to determine which information that should be presented, how it should be visualized, when it should be presented, and where it should be presented [32, 39]. This approach is expected to allow operators to perform necessary operations, while maintaining good awareness of their machines and surroundings.

1.1 Research Scope

As described above, there is a problem of presenting supportive visual information using head-down displays in heavy machinery. One of possible alternatives to this problem is by delivering supportive information to operators through different modalities, such as haptic or auditory. However, it is important to note that heavy machinery generally produces loud noise and strong vibration due to working engines and performed operations [12, 13, 129, 162], which could reduce the effectiveness of haptic and auditory information. Moreover, increasing the number of haptic or auditory information should be done cautiously, since multiple modalities may cause conflict and interference, which could deteriorate operators' performance [107]. Taking these factors into account, the focus of this dissertation remains on the use of visual modality to deliver supportive information to operators.

As mentioned in the beginning of Chapter 1, heavy machinery consists of diverse machines that can be used for various industrial tasks. Investigating the visualization on the windshield of all types of heavy machinery would be an enormous work, and thus the scope of this dissertation must be well defined. This dissertation focuses on mobile cranes and excavators, since both types of heavy machinery contributed significant amounts of accidents compared to other types of machines [69, 100]. To further narrow down the scope, this dissertation focuses on operators inside the cabin, as mobile cranes and excavators, in some cases, are used in collaboration with ground workers and even other machines [136, 152]. Therefore, the interaction between operators, ground workers, and other machines is also beyond the scope of this dissertation. Brief information about mobile cranes and excavators, which is relevant to this dissertation, is respectively described in Section 1.2 and Section 1.3.

1.2 Mobile Cranes

Mobile cranes are typically found in construction sites and they have a vital role in lifting and distributing materials around the worksite. Unlike tower cranes that require some preparations before they can be used, mobile cranes can be mobilized and utilized quickly. Mobile cranes are generally more suitable for constructing low-rise buildings, while tower cranes are needed for constructing high-rise buildings. Note that the term "mobile cranes" used in this dissertation refers to all types of cranes that can be moved around, including both wheeled and crawler ones (see Figure 1.2). The major difference between wheeled and crawler cranes is the presence of outriggers. Wheeled cranes have outriggers, which refer to the extended beams that improve the machine's stability (see the left image in Figure 1.2). On the other hand, crawler cranes do not require dedicated outriggers as their tracks already serve as outriggers (see the right image in Figure 1.2).

Figure 1.2: The left image shows a wheeled crane [157, CC0 1.0], while the right image shows a crawler crane [17, CC BY-SA 4.0].

Mobile cranes are complex machines. When lifting a material, mobile cranes require a wide workspace and operators must lift carefully in order to avoid any collision with nearby objects, for instance, existing structures, other machines, or people. Operators must also prevent their machines from tipping over, as the center of balance of their machines constantly changes depending on several factors, such as height and weight of the lifted material, ground's surface, and wind [102]. The operation is increasingly complex, since operators need to interact with ground workers. In lifting operations, ground workers are responsible for giving signals to mobile crane operators, hooking the crane's cable with the lifted material, and placing pads under the crane's outriggers [80].

Operators' mental workload remains high due to the complexity in mobile cranes operations [41]. Here, mental workload is defined as the limited information processing capacity of the brain, which is consumed to a certain extent in order to perform a task [166]. Repetitive tasks and long working hours further make operators vulnerable to fatigue and distraction, which could lower their ability in mitigating upcoming hazards [41]. King [72] found that 43% of crane-related accidents between 2004 and 2010 were caused by operators. Moreover, mobile cranes are also recognized as the most dangerous type of machines in the construction sector, since about 70% of all crane-related accidents involved mobile cranes [97], where the most common types of accidents are electrocution due to contacts with power lines, struck by lifted objects, struck by crane parts, and collapsing cranes. See Figure 1.3 for a crane-related accident that was caused as the result of operating a mobile crane beyond the permissible limit.

Figure 1.3: A mobile crane collapsed on a bridge construction project in Fairbanks, USA [36, CC BY 2.0]. This mobile crane lost its balance as its boom was extended beyond the permissible limit [119].

1.3 Excavators

Excavators are another type of heavy machinery that can be found in construction sites. As the name implies, excavators are originally built for digging operations. However, by using different attachments, excavators can be used for various purposes, such as lifting, drilling, demolishing, and even cutting. Thanks to their versatility, excavators are also used in mining and agriculture sectors. Similar to mobile cranes, excavators are also available as wheeled excavators and crawler excavators (see Figure 1.4). Crawler excavators are more suitable for unpaved environments and uneven surfaces, as their tracks offer better traction and stability (see the left image in Figure 1.4). Although less suitable for unpaved environments, wheeled excavators offer better mobility, as they have higher moving speed and can be driven on normal roads (see the right image in Figure 1.4).

Figure 1.4: The left image shows a crawler excavator [33, CC BY 2.0], while the right image shows a wheeled excavator [34, CC BY 2.0].

Operating excavators is also a complicated task. While controlling their machines, operators must observe the surroundings and possibly cooperate with nearby ground workers or other machines. For example, excavators dig the ground, then lift and pour the dirt onto the dump truck's bed for further transportation. When performing digging operations, excavators cause changes on the soil structure, which could create unstable ground [83]. See Figure 1.5 for an excavator accident that was caused as the result of operating an excavator on unstable ground. When performing digging operations in urban environments, operators must consider the presence of underground infrastructures, such as power lines and water pipes [150]. Damaging underground facilities would not only harm operators and surrounding workers, but also cause service disruptions to nearby residents.

When excavators are used for lifting a material, operators must be cautious on how much the machine is currently lifting. Excavators have a concept of maximum lifting capacity, which refers to the maximum weight that excavators can lift. The value of the maximum lifting capacity constantly changes based on three factors: (1) the height of the lifted material, (2) the distance between the lifted material and the center of the machine, (3) and whether the lifting direction is

Figure 1.5: A crawler excavator collapsed, as it was operated on unstable ground [113, CC0 1.0].

facing along or across the undercarriage, which refers to the moving component below the machine's body [145]. For example, the further the material is lifted from the machine's center, the maximum lifting capacity further decreases, and vice versa. Lifting something heavier than the maximum lifting capacity would make the machine lose its balance, and then collapse.

In addition to complicated operations, long working hours and monotonous work further make excavator operators vulnerable to fatigue and boredom, which may hinder operators' ability to quickly identify possible hazards and act accordingly [84]. Kazan and Usmen [69] found that excavators contributed 24.8% of total accidents among earth-moving machinery, such as backhoes, bulldozers, etc. Common fatal accidents that involved excavators are related to struck by excavator parts, struck by the lifted material, and collapsing excavators [96].

1.4 Similarities between Mobile Cranes and Excavators

While mobile cranes are primarily used for lifting and excavators have various usages, we can see that there are similarities between mobile cranes and excavators based on the description in Section 1.2 and Section 1.3. Firstly, when excavators are used for lifting, they share a similar lifting mechanism as mobile cranes. The lifting capacity of both machines constantly changes depending on the machine's state, such as the height of the lifted object and the distance between the lifted object to the center of the machine. Secondly, both types of machines share similar types of accidents, which are struck by the machine's parts, struck by the lifted material, and the loss of balance. These similarities could suggest that operators of both types of machines may face similar challenges. Consequently, solutions for addressing challenges in the context of mobile cranes could be possibly used for addressing similar challenges in the context of excavators, and vice versa.

Chapter 2

Problem Statement

Considering how supportive information is currently presented in heavy machinery in general and both mobile cranes and excavators in particulars (see Chapter 1), it could be beneficial for operators to have the supportive information presented closer to their line of sight. Previous studies indicate that operators spent most of their time looking through the windshield [136, 149, 160], and thus the windshield could be a potential space for presenting supportive information. Devices that use transparent screens, such as head-mounted displays and head-up displays, could be used to present supportive information on the windshield, as they do not occlude the windshield with their physical presence. Therefore, operators could acquire the supportive information without getting their view obstructed.

Although presenting the supportive information near operators' line of sight has its own merits, this approach also has its own challenges. For example, the presence of information near the line of sight may visually and cognitively distract operators from their primary work [44]. In this case, visual distraction refers to when operators look away from the operational area for an extended period, while cognitive distraction refers to when operators' attention is absorbed by any thought in a way that they start failing to work safely. Therefore, there is a need to present information cautiously, where the right information is presented in the right form, at the right time, and at the right place [32, 40]. To accommodate this requirement, the following five research questions (RQs) were defined:

RQ1. What Has Been Proposed in the Heavy Machinery Domain and What Are the Lessons Learned?

Like in any research projects, it is important to understand the past before proposing something new. Having an overview about the current practice in modern heavy machinery and what has been proposed and reported within scientific communities is essential to guide the direction of my doctoral research.

RQ2. How Can Different Information Placements Influence Operators' Perception and Cognition?

The central proposition for presenting supportive information closer to operators' line of sight is to allow operators perceive the information without diverting their attention away from the operational area. In other words, by doing so, it should be easier for operators to perceive the information. However, the perceived information would still need to be processed by operators, so that they could understand and make use of it [32, 164]. Therefore, it is important to investigate how different information placements, for example, closer or further from line of sight, would influence operators' ability to perceive and process the information.

RQ3. How Can the Critical Information Be Formed into Iconic Designs?

To avoid overloading operators with information, the amount of information to be presented on the windshield should be carefully limited [32, 67]. Therefore, only critical information that should be presented on the windshield, while less-critical information could still be presented in other locations, for instance, on existing head-down displays inside the cabin. Since this dissertation covers two types of heavy machinery, it is also important to know which critical information is applicable to either or both types of machines. The critical information should then be transformed into iconic designs. Since the technology used for presenting the information highly influences how the information could be formed and presented to operators, the iconic designs should be proposed after taking into account both visual capability and limitation of the selected display technology [32, 98].

RQ4. How to Ensure that the Proposed Iconic Designs Correctly Represent the Machines' Operations?

This research question focuses on determining whether the proposed iconic designs correctly represent what the machines do. In other words, how do we know that the proposed iconic designs have the right forms? This research question is relevant, since presenting information in the right form would facilitate operators to process and make use of the information [154, 164].

RQ5. How Can the Proposed Iconic Designs Be Transformed into a Functioning Prototype?

There are three reasons why it is relevant to build a functioning prototype out of the proposed iconic designs. Firstly, the process of building a functioning prototype requires the act of bridging between what is desirable and what is technically possible [87, 90]. For example, things that we really want may not be technically possible, and vice versa. Secondly, building a functioning prototype is needed in order to demonstrate finer details and dynamic experience that the proposed iconic designs could not offer [90]. Thirdly, the functioning prototype would serve as a concrete and plausible proposal on how a particular problem could be addressed [175].

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Chapter 3

Background

This chapter presents an overview of different topics that are relevant in this dissertation. Section 3.1 presents an overview of how human receives visual information and how such information is processed in the brain. Section 3.2 and Section 3.3 respectively introduce situation awareness and mental workload, which are two cognitive concepts that may be affected by the presence of supportive information [154]. Section 3.4 and Section 3.5 respectively describe human-centered design and research through design. Human-centered design is a design approach that aims to make useful and usable products [64], while research through design is a design approach that focuses on knowledge production [175].

3.1 Human Perception and Attention

Both human eyes together provide a field of view slightly more than 180° [163], which can be further divided into central and peripheral areas [165]. The central area is the area that we focus on when we see something, in which visual details are perceived by our eyes. However, this area is quite small, approximately the size of our thumbnail at an arm's length [164]. As our eyes only perceive visual details in one tiny space at a time, our eyes constantly move around to perceive visual details from potential areas. The remaining of our field of view, which is not part of the central area, is called peripheral area [165]. Visual details that exist peripherally are still perceived by our eyes, but less visual details can be perceived the farther away from the central area. Note that the size of central and peripheral areas is sensitive to cognitive load. Williams [169] found that the size of both central and peripheral areas shrunk when people performed tasks with higher cognitive load.

Although less visual details can be perceived peripherally, we actually rely more on our pheripheral area in order to obtain the gist of the world around us [165]. Larson and Loschky [82] found that people still understand what they are looking at when the central area of the image is obscured, but the remaining area is visible. On the other hand, it is more difficult for people to understand what they are looking at when the central area of the image is visible, but the remaining area is obscured. Peripheral vision is also more sensitive to motion, since motion in the peripheral area is detected faster than motion in the central area [163, 165].

When our eyes perceive visual stimuli, such stimuli are then processed further in the brain so that relevant information can be extracted. Although half of our brain's capacity is occupied to process visual stimuli [165], such processing capacity is able to process less than 5% of perceived visual stimuli [164]. Then how does the brain decide which visual stimuli that should be further processed and which ones that should be ignored? The process of transforming visual stimuli into relevant information can be described with two models: bottom-up and top-down information processing models (see Figure 3.1).

The bottom-up model refers to the information processing driven by visual stimuli that enter our eyes. When we open our eyes, we automatically register dif-

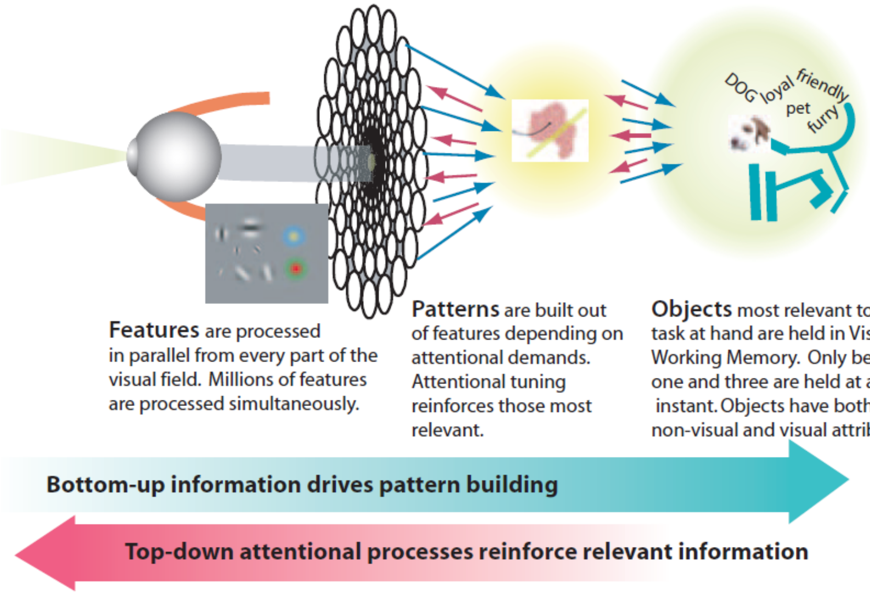

Figure 3.1: How our brain processes visual stimuli can be classified into bottom-up and top-down information processing [164, used with permission from the publisher].

ferent kinds of information from the visual scene, such as color, size, brightness, location, etc (also known as features). The millions of features that we perceive simultaneously are then filtered and the selected ones form patterns. The selected patterns are organized, and then filtered again into a small number of visual objects. The low number of visual objects that we could perceive is due to the small capacity of our visual working memory. Therefore, which patterns that form visual objects highly depend on the ongoing task, as our attention suppresses less relevant patterns and reinforces more relevant ones. The obtained visual objects are then linked with non-visual attributes that we already know. For example, we may also associate the visual object of a dog with other non-visual attributes, such as pet, loyal, or friendly (see Figure 3.1). Of course, the linkage between visual objects and their non-visual attributes highly depends on individuals' experience.

On the other hand, the top-down model refers to the information processing driven by our attention when we try to accomplish something [164]. In this model, our brain provides a crude guidance on what kinds of information that we would like to obtain. Although our eyes perceive different kinds of visual stimuli, the crude guidance leads our eyes towards features and patterns that should be further processed. If no relevant features and patterns are found in one spatial area, our eyes then move to other potential spatial areas in order to find more relevant visual stimuli for the ongoing task.

Understanding how visual stimuli are perceived by our eyes and interpreted in the brain is important, since they have practical design implications. To support our information processing capability, visual information should be designed in a way that enables rapid and correct visual queries for all cognitive tasks that the information is intended to support [164]. To achieve that, we need to understand cognitive tasks that people would like to solve and what kind of visual queries that they should perform. Central and peripheral visions also have some implications regarding information placement [165]. For example, if we want users to focus on one area, we should not place animated information in their peripheral area, since it may distract them. The opposite applies if the goal is to attract users' attention away from the area of focus, then it is appropriate to present animated information peripherally.

3.2 Situation Awareness

Situation awareness generally means to have enough information to understand the current situation, and then act accordingly. For example, when driving a car, the driver needs to be aware of various things simultaneously, such as the vehicle's status, the route ahead, other cars, road signs, pedestrians, and other obstacles that may be present. When the driver is aware of all relevant information, the driver can act accordingly while driving a car [52]. However, when there is too much or too little information that should be comprehended, there is an increased risk of mistakes or even accidents. The concept of maintaining responsiveness to a set of complex information in real-time tasks, such as driving a car, has been described as situation awareness (SA) [26, 52].

As a concept, SA has long been criticized. For example, Sarter and Woods [127, p. 55] state that “the concept has become a ubiquitous phrase and the frequent topic of research projects even without consensus on its meaning or much knowledge about existing problems that need to be addressed”. Despite the long debate, the term SA has been widely used in many domains outside aviation and military, where it was originally used [31, 124]. Moreover, the loss of SA has also been acknowledged as one of influential factors in human-related accidents [132].

The seminal definition of SA was proposed by Endsley [29, p. 792], where SA is defined as “the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning, and the projection of their status in the near future”. See Dominguez [23] or Salmon et al. [125] for a review of other formal definitions of SA. Endsley [30] further proposes three levels of SA: (1) perception, (2) comprehension, and (3) projection. Level 1 SA is the perception of the elements in the environment. At this level, the information is perceived through our senses as it is, without any additional interpretation. Level 2 SA is the comprehension of the current situation, where we are aware of the available information and understand the meaning of the information. Level 3 SA, and also the highest level, is the projection of near-future situations. At this level, we can predict near-future events based on the understanding of existing information.

The three levels of SA also indirectly imply how information should be designed and presented to the user. To achieve Level 1 SA, the information should be perceivable through human senses [32]. In case of visual information, information should have large enough size, has enough contrast against other visual elements in the environment, and exists within field of view. This issue is more prominent in complex systems, such as heavy machinery, where various kinds of information compete for operators’ attention [161]. To reach Level 2 SA, information should be presented in a comprehensive way in relation to the objective [32]. For example, when a mobile crane is lifting a material, it is relevant to show lifting-related information to operators [134]. To arrive at Level 3 SA, i.e., to correctly predict the near-future event, some domain knowledge is required to understand how different elements in the environment may influence each other [32]. This limitation could be compensated, for instance, by also informing users about possible future consequences [60]. Therefore, novice users know what could happen in the near future if the ongoing situation persists. Time also plays an important role for achieving Level 2 and Level 3 SA [32]. In practice, we filter information that we attend to not only based on space, e.g., how close the element is, but also based on time, e.g., how soon the element would affect our task. Therefore, information should also be presented at the right time in order to support users achieving Level 2 and Level 3 SA.

As described above, the way we design and present information to users may influence their SA. Hence, it is also important to discuss how users' SA can be measured. There are various SA-measurement methods that have been proposed within scientific communities and they can be classified into query-based methods, rating-based methods, performance-based methods, and process-indices methods [123]. The following paragraphs describe both pros and cons for each measurement category.

Query-based methods allow the observer to query participants on their perception of the situation at randomly selected times [65]. However, this approach is intrusive, since queries are done during test scenarios and this could influence participants' performance. The level of intrusiveness is even higher with the pausing-based method, as test scenarios must be paused when questions are given. Situation Present Assessment Method (SPAM) [28] is an example of without-pausing query-based methods, while Situation Awareness Global Assessment Technique (SAGAT) [29] is an example of with-pausing query-based methods.

Rating-based methods allow participants or the observer to rate their perception of participants' SA after test scenarios have been completed [65]. Although this approach is not intrusive, there is a probability that the result does not reflect participants' actual SA. If participants rate their own perceived SA, e.g., using Situation Awareness Rating Technique (SART) [151], their perceived SA may not reflect their actual SA. The same issue exists in observer-rating methods, such as using Situation Awareness Behaviourally Anchored Rating Scale (SABARS) [146], since the observer may not accurately interpret participants' behavior as their actual SA.

Performance-based methods use participants' performance as an indirect measurement of their SA [30]. The main advantage of this measurement category is the lack of intrusiveness [65], as the data can be collected without pausing test scenarios or giving users an extra task to do. However, there is also a major issue with this approach, since performance is the end result of cognitive process and there are factors, such as mental workload, decision-making process, or system capabilities, that could influence participants' performance [30]. Although SA can be considered as a factor that increases the chance of having good performance, there is no guarantee that maintaining SA will always result in better performance or vice versa [32].

Lastly, process-indices methods measure SA by analyzing processes that participants use to develop their SA [123]. Two notable examples of this approach are verbal protocols and eye tracking. Verbal protocols require participants to verbalize their thoughts, while completing the given task [32]. This method is useful to understand how participants conceptualize the on-going task and their cognitive process when performing the task, but participants' performance may deteriorate because of the extra cognitive load to verbalize their thoughts. In addition, analyzing the obtained data requires a lot of time and the result may be biased due to the subjectivity of the analysis process. On the other hand, eye tracking devices offer a non-intrusive approach to assess users' attention and SA through their eye movement [48]. However, analyzing the collected data requires a lot of time and certain level of expertise to interpret the data [32].

3.3 Mental Workload

Mental workload is a concept that describes the limited information processing capacity of the brain, where a certain level of this capacity is occupied in order to meet the cognitive demand when performing a task [166]. When cognitive demand does not exceed the capacity, performance remains unaffected. Performance deterioration may occur as the result of cognitive demand that exceeds this capacity. While causing excessive mental workload is something that should be avoided, having none or too little mental workload could also cause performance deterioration [115]. In such case, we become disengaged with the task, and thus unable to mitigate incoming hazards accordingly.

The level of mental workload generally correlates to the complexity of the task being performed [166]. However, the level of mental workload is not fixed to the task, since there are factors that could influence the actual level of mental workload. For example, Paxion et al. [112] found that experience and skills influence the level of mental workload in the driving context. In their experiment, the performance of experienced drivers did not deteriorate, even though the complexity level was increased. In contrast, the performance of novice drivers deteriorated when the complexity level was increased. This is because, for skilled people, the information processing is done quickly and automatically, and thus they do not need to occupy much of the information processing capacity to perform their task [171]. On the other hand, for less-skilled people, the task at hand occupies a significant level of their information processing capacity. Hence, their performance is deteriorating as soon as the task complexity is increasing.

Although the main intention of having information systems in our daily life is to help us performing our tasks, it is important to note that the extra information would, to some extent, occupy the information processing capacity [171]. In case of heavy machinery, despite the presence of information systems inside the cabin, operators still have to perform active control and decision making, which lead to high mental workload [161]. For example, operating forest harvesters already requires considerable workload from operators, which is comparable to operating fighter planes [10]. In a study of fighter planes, Svensson et al. [147] found that more complex information leads to higher mental workload and poorer performance. To avoid this issue, it is important to present information in a way that facilitates efficient information processing, so that less information processing capacity would be occupied to process the presented information [154].

Talking about the level of mental workload, it is also important to discuss how mental workload can be measured. There are various methods that can be used for measuring mental workload and they can be grouped into three categories: self-rating methods, performance-based methods, and physiological methods [21]. The following paragraphs introduce the various methods for measuring mental workload, including their pros and cons.

Self-rating methods require participants to report their perceived mental workload after performing the given task [21]. Self-rating methods can be divided into unidimensional scales and multidimensional scales. For unidimensional scales, participants are required to report their mental workload for each task. Rating Scale Mental Effort (RSME) [173] and Modified Cooper Harper (MCH) Scales [167] are two examples of unidimensional scales. In contrast, multidimensional scales contain several subscales that represent someone's mental workload. The overall mental workload is obtained by calculating the ratings in all subscales. Unlike unidimensional scales, multidimensional scales can be used to assess mental workload for one task or the whole system. NASA Task Load Index (TLX) [54] and Subjective Workload Assessment Technique (SWAT) [117] are two examples of multidimensional scales. NASA-TLX, SWAT, and MCH are the most frequently used methods in this category and they all have good face validity [21, 168]. However, choosing which method(s) to be used highly depends on what kind of information that we want to obtain. For example, Hendy et al. [57] suggest that, if what we want is the overall mental workload, unidimensional scales are more sensitive to the overall mental workload than the multidimensional ones.

Performance-based methods use participants' performance as the representation of their mental workload [21, 166]. To measure participants' mental workload, secondary tasks are introduced as something that participants should perform in addition to primary tasks. Participants' performance on secondary tasks is then used to represent their mental workload. However, it does not mean that we can choose any tasks to be used as secondary tasks. Firstly, we should avoid choosing secondary tasks that may impose too much intrusion on primary tasks [166]. Secondly, suitable secondary tasks should be demanding enough and competing for the same cognitive resource as primary tasks [21]. For example, in the driving context, adding auditory-related secondary tasks would not be sufficient, since driving is a primarily visual task.

The last category is physiological-based methods, which measure participants' mental workload based on their physiological states [21, 166]. Heart activity, brain electrical activity, eye fixation, and pupil diameter are some physiological states that could indicate someone's mental workload. Physiological-based methods enable continuous data collection while the experiment is being conducted, and thus participants are not required to spend extra effort to report their mental workload or to perform any secondary task. However, physiological-based methods require specific equipment and skills, since data produced from these methods are sensitive to noise.

3.4 Human-centered Design

Design is a creative process that has practical consequences [91]. When we design something, we consciously or unconsciously affect people's lives. Therefore, designers need to be conscious about the possible impact of their work on other people's lives and communicate with people who would use the design artifact [8]. In case of heavy machinery, human-machine interface is the instrument that informs operators on what the machine does and what operators should do [161]. Although the main intention of installing human-machine interfaces in heavy machinery is to improve operators' productivity and safety, they may also cause negative effects to operators' wellbeing, such as divided attention, information overload, and increased stress [137]. To prevent any possible negative effect, designers need to consider operators and other relevant factors that may influence the effectiveness of human-machine interface [9].

Human-centered design is an approach that considers human needs, abilities, and behaviors, and then incorporates them into design solutions [103]. The term was originally coined as "user-centered system design" by Rob Kling [73] in 1977, which emphasizes meeting users' needs when designing software. Since then, the term has grown in popularity and has been perceived as the ideal way of doing design [63, 103]. There has also been a shift towards using the term human-centered design, since there could be other groups of people beyond users who may be affected as well [81, 118]. Such situation is prominent in industry, as users are often not the ones who make decision whether to adopt new things or not [81, 122]. The main argument to follow human-centered design is that users, other stakeholders, and suppliers could receive economic and social benefits from highly usable products [64, 78]. For example, users could benefit from becoming more productive in their work, while organizations could benefit from better return of investment. All these would ultimately help suppliers to increase the sales of their products and stay competitive in the market.

Despite apparent benefits that could be obtained from embracing human-centered design, being human-centered is not an easy task. First of all, there are typical obstacles that could hinder stakeholders from being involved at all, such as the difficulty in finding relevant stakeholders and the lack of resources (personnel, time, and money) [51, 122]. Even if designers manage to get sufficient resources and relevant stakeholders on board, designers may still face difficulties in obtaining the right information from stakeholders, compromising between conflicting interests among stakeholders, and keeping them motivated throughout the design process [122, 170]. As such, designers usually adjust the level of stakeholders' involvement based on what they need or expect from stakeholders [143]. Kaulio [68] identified three levels of stakeholders' involvement in the design process:

1. Design for stakeholders: designers derive requirements out of stakeholders' data and create products that meet such requirements. At this level, stakeholders are not involved in the design process.

2. Design with stakeholders: designers interact with stakeholders at some phases in the design process. For example, designers present a prototype to stakeholders to determine in what ways the proposed prototype should be improved.

3. Design by stakeholders: stakeholders are actively involved in formulating and bringing out solutions for their problems. At this level, stakeholders also act as designers.

There is no agreement in the literature on what kind of design activities or processes that should be done in human-centered design. Just to name a few, IDEO [63] proposes a generic three-phase process that consists of inspiration, ideation, and implementation, while Norman [103] proposes a cycle of four activities: observing, generating ideas, prototyping, and testing. In contrast, Benyon [8] proposes three interrelated activities: understanding, envisionment, and design, in which he also emphasizes that there should be evaluation within each activity. ISO 9241-210:2010 [64] further suggests four interrelated activities:

1. Understand and specify the context of use.
2. Specify the user requirements.
3. Produce design solutions that match the context of use and the user requirements.
4. Evaluate the design solutions against the requirements

There are two similarities that can be observed among the four models presented above, even though they used different labels, different number of design activities, and whether the relationship among design activities is cyclical or interrelated. Firstly, all the models presented above emphasize the importance of iteration as part of the process, since it is rarely that designers could come up with the right solution on the first attempt. Moreover, none of the models presented above dictate which methods are appropriate for each design activity. In other words, it is entirely up to designers to choose their methods based on the complexity of their projects. See Maguire [93] or IDEO [63] for a list of methods that designers could employ across different activities in human-centered design.

3.5 Research through Design

There has been a long struggle to connect "research" and "design", since they tend to be considered as two opposing endeavors within scientific communities [142, 174]. Generally speaking, research is a systematic enquiry that primarily aims to generate knowledge to be used by others [4]. The knowledge is obtained through generalizing patterns that emerge from observable data [76]. As such, the generated knowledge is abstract and generalizable. Especially in natural science, researchers are also expected to act as observers, where the collected data and their analyses should be void from researchers' influences. In contrast, design is an activity that primarily aims to produce artifacts [90], where the produced artifact serves as the embodiment of how designers attempt to address a specific situation [45]. Artifacts are never abstract, since they possess details that describe how they would possibly fit into a specific situation [76].

Despite the differences presented above, research and design do have some similarities. Firstly, both activities aim to generate something new, which is built upon what is known so far [142]. Secondly, design does exist in research, and vice versa. For example, researchers must design their experiments and sometimes they also need to design new apparatus to be used in their experiments [37, 49]. With respect to design, both evaluation and analysis are research activities that can be found in a design process, even though designers tend to pay less attention to these activities, compared to the produced artifact [142]. Thirdly, both research and design tend to be an iterative process. Conducting experiments is the common way for researchers to extract knowledge from the studied phenomenon and it is rarely that researchers could set up the right experiment on the first attempt [49]. As such, researchers continuously learn from data that they currently have and redesign the experiment as many as needed until the studied phenomenon can be observed and measured accordingly. The same thing also applies in design, since it is very unlikely that designers could come up with the right solution in one go [8]. In practice, designers continuously adjust their actions based on what they know so far and repeat this process until they achieve the desirable outcome [49, 130].

Putting the debate between research and design aside, there are two notable types of research that emerge from investigating design: (1) research into design and (2) research through design [128]. In research into design, designers are the object of research. Here, researchers observe how designers work and knowledge is produced by extracting generalized patterns from designers' activities. As such, the knowledge generated from research into design is philosophically similar to the knowledge produced from research in general (see the first paragraph in this section). It is also important to note that researchers in this type of research are not involved in the design process. With respect to research through design, knowledge is produced by doing design, in other words, making artifacts [43, 128]. Since research through design is one of the central topics in this dissertation, the remaining of this section further discusses what research through design is, what kinds of knowledge that it could produce, and its implications on research practice.

Zimmerman et al. [174, p. 167] formally define research through design as "an approach to conducting scholarly research that employs the methods, practices, and processes of design practice with the intention of generating new knowledge". The intention of knowledge production plays an important role here, since it distinguishes research through design from typical design practice, which primarily aims towards creating commercial products [175]. Although research through design was originally introduced within art and design communities (see Frayling [43]), it has been progressively developed as a research approach within human-computer interaction and interaction design communities [142, 174]. Researchers in these communities often develop novel interactive artifacts that could be used for research purposes [37]. While transforming ideas into a concrete artifact, researchers in these communities are also confronted with opportunities and constraints that exist around the specific situation, where their artifact is supposed to fit into [141, 144]. Handling such a complex situation is the nature of design practice, as problems are rarely well-defined and designers must constantly make sense of the situation by navigating through complexity that surrounds their work [130].

Since both design practice and research through design produce artifacts as the outcome of the activities, Zimmerman et al. [175] outline two characteristics that distinguish artifacts from research through design and design practice. Firstly, in research through design, artifacts are produced in order to investigate research question(s), instead of focusing on meeting clients' needs. Secondly, artifacts produced from research through design should also be of significant inventions. To be considered as significant inventions, artifacts should be designed after considering various knowledge, theories, or models that are relevant for such research question and be well-positioned with respect to the current state of the art.

In research through design, artifacts are not only seen as the outcome of the design activity. In addition, they are also considered as implicit and theoretical contributions, which materialize designers' understanding on the research question and serve as proposals that present plausible ways to transform the current state of the world into a preferred future [45, 175, 176]. This view on the value of artifacts is in contrast to the mainstream way of doing research within the human-computer interaction community, where artifacts are often developed due to the necessity to conduct user evaluations [37, 90]. In this case, the research contribution tends to be about how artifacts are used, while the description about the process of transforming ideas into concrete artifacts is often neglected. Zimmerman and Forlizzi [174] identify that designers integrate at least three types of knowledge when designing artifacts: (1) technical opportunities to realize artifacts, (2) behavioral knowledge about prospective users, and (3) knowledge about real-world situations, in which artifacts are supposed to fit into. The insights on how designers integrate these different types of knowledge and how they deal with other constraints that surround their work are something that can be made explicit and shared with others who investigate related research questions [142]. To put it concisely, research through design considers both the insights on how artifacts are used and the process to design them as research contributions [37, 45].

After analyzing seven well-known projects that could be classified as research through design projects, Stappers and Giaccardi [142] conclude that there is no standardized way of practicing research through design. Krogh et al. [77] also arrive at the same conclusion after analyzing ten doctoral dissertations that explicitly employed research through design. The diversity in employing research through design is expected, since practitioners need to adjust their actions based on the ongoing situation and the findings that they have so far. Nevertheless, Zimmerman and Forlizzi [174] suggested five generic steps for anyone who would like to employ research through design:

1. Selecting a worthy research question to be investigated. This is done after reviewing relevant literature and knowing the the state of the art for the selected research question.
2. Conducting design activities to generate new ideas and continuously refining the generated ideas into a final artifact.
3. While designing, continuously evaluating and criticizing the generated ideas until the final artifact has been produced.
4. Documenting all actions taken throughout the design process, including the rationales for taking those actions.
5. Repeatedly investigating the same research question until the desired result is obtained.

In the broadest sense, the quality of research is usually assessed based on two criteria: validity and reliability [71]. Here, validity refers to the extent we accurately measure what we claim or explain, while reliability means the extent that other researchers could obtain the same result if they follow the same procedure. Both criteria are relevant for research through design, but they cannot be applied based on the definitions above, since doing research through design is not exactly the same as the classic way of doing research.

As briefly mentioned earlier, artifacts produced from research through design serve as the embodiment of how designers attempt to address a specific situation. As such, the process in bringing artifacts into existence is never free from designers' influence. Therefore, it is inappropriate to apply the concept of validity mentioned above as defined above, since it expects designers to take neutral values on whatever they interpret [38]. In his seminal book, Krippendorff [75] proposes five types of validity that designers could use to back up what they claim (ordered from the lowest to the highest validity):

- Demonstrative validity. This kind of validity refers to how designers could show how an artifact is supposed to function and what kind of qualities that it could possibly have.

- Experimental validity. To fulfill experimental validity, an artifact should afford interaction with its prospective users. Therefore, designers could experimentally assess to what extent prospective users would benefit from the qualities that the artifact offers.

- Interpretative validity. Here, designers justify the qualities that an artifact offers based on established theories and published findings from relevant scientific disciplines, for example, ergonomics, anthropology, or engineering.

- Methodological validity. To be considered methodologically valid, designers need to show that they have: (1) explored most (if not all) possible alternatives before proposing the final artifact and (2) consulted the right stakeholders.

- Pragmatic validity. In design, there is no better evidence than the fact that stakeholders are willing to adopt the proposed artifact. However, pragmatic validity is fulfilled only if designers could explain that such willingness is not made because of misinformation or unrealistic expectation.

Speaking of design practice in general, there is no guarantee that different designers would end up with the same outcome, even if they employ the same process [38, 175]. As such, there is no expectation for reliability in research through design [174, 175]. However, it is nonetheless important to document the used methods and the rationales for choosing them, so others could observe what happened throughout the design process and possibly criticize the design process [37, 174, 175, 176]. Making the design process transparent is particularly important, since design is sometimes seen as a "black box" [37], where the outcome is clear, but the process that leads to such outcome is obscure.

In addition to the transparency of design process, Zimmerman et al. [175] propose three additional criteria for assessing research contributions from research through design: (1) significant invention, (2) relevance, and (3) extensibility. As mentioned earlier, one of the two criteria that distinguishes artifacts produced from research through design and design practice is that artifacts from research through design should be of significant invention. This requires designers to demonstrate that their artifacts have been designed after considering relevant knowledge and be well-situated in relation to the state of the art. Regarding relevance, designers need to sufficiently describe the motivation for investigating their research question(s), the description about the current situation, and the reason why the proposed future is the desired one. The final criterion is extensibility, which refers to the ability that other researchers could utilize research contributions generated from our research project. To fulfill this criterion, research contributions should be documented and disseminated to the community.

Chapter 4

Methods

This chapter describes the methods that have been employed to address the research questions in Chapter 2. Some of the methods described here were conducted by myself, while the others were conducted in collaboration with my co-authors. To highlight the work distribution, the word "I" is used for work that I did alone, while the word "we" is used for work that I carried out with my co-authors. This chapter also presents the employed methods in a chronological manner to emphasize my research process.

Note that the main findings from the employed methods presented in this chapter are described in Chapter 5. However, this chapter shortly presents in what ways the findings from the previous methods motivated the subsequent methods in order to highlight the relationship between the employed methods.

4.1 Online Ethnography

Before starting my doctoral research, I had no experience related to heavy machinery. Like in any design project in general, it is important to have sufficient domain knowledge to design something properly [15, 172]. The situation was further complicated due to the lack of access to interact with professional operators and the lack of possibility to conduct field studies. To mitigate this issue, I used a method called online ethnography, or also known as "netnography", as an alternative method to understand how heavy machinery is typically used. The main difference between traditional ethnography and netnography is that researchers observe or interact with their research subjects via Internet forums, blogs, and social media [74]. This approach was possible thanks to the abundance of available user-generated data on the Internet, where researchers can use the available data to carry out their research [94].

For the formal study, I used forest harvesters as the type of heavy machinery that I wanted to investigate. Note that, at this stage, I still did not have specific ideas on what types of heavy machinery that I should focus on for the rest of my doctoral research. I decided to investigate forest harvesters, since they are used in remote locations, and thus adding an extra factor that makes conducting traditional field studies difficult to do. I searched the relevant videos on YouTube using a search string, and then collected the first 500 videos. Out of 500 videos, I found 26 videos that fulfilled the following criteria:

1. The video must be recorded from inside the cabin.
2. The resolution of the video must not be smaller than 360 pixels.
3. The duration of the video must not be shorter than three minutes.

My co-author and I separately analyzed the selected videos (see Figure 4.1 for an example of the chosen videos.). When we conducted this study, I still had less than one year of experience in this topic, while my co-author already had about fifteen years of experience. The different levels of experience were useful to avoid having blind spots, as people with the same background tend to focus on similar things [6]. While manually analyzing the videos, we were checking whether the videos contain the answers for the questions below:

1. How the operators actually operate the forest harvesters?
2. How are the situations where the operators work?

Figure 4.1: An example of videos on YouTube that shows the situation inside the cabin of heavy machinery [156]. This figure also appears in **Paper A**.

3. Where are the operators looking at when operating the forest harvesters?
4. What are the problematic areas in operating the forest harvesters?

When we found something relevant to the questions presented above, we documented the findings in a note. The process was very similar to when making notes in traditional field studies, where researchers take note for every finding that they obtain while observing their research subjects [159]. After analyzing the videos separately, we met and compared our findings. We immediately accepted the similar findings and we checked the videos once again to determine whether the different findings should be accepted or discarded. We then evaluated the effectiveness of this method by comparing the findings from this method with the findings from five field studies in related contexts [62, 104, 133, 140, 160].

More information about how we conducted the online ethnography can be found in **Paper A**. The main findings from this method are described in Section 5.1, while the reflections on the use of this method as a way to understand the current practice of heavy machinery are discussed in Section 6.1.1.

4.2 Comparative Usability Test (A/B Test)

One of the main findings from the online ethnography described in Section 4.1 is that operators spend most of their time by looking through the front windshield (see Section 5.1). Based on this finding, I was interested to investigate how placing information on the front windshield would influence operators' performance. My co-author and I then decided to conduct a comparative usability test (or also known as A/B test). A/B test is usually conducted to compare two or more solutions in order to identify both strengths and weaknesses of each solution [27]. Therefore, we could determine which solution that yields the most desirable result.

To facilitate the A/B test, we used a mixed reality environment that simulated an excavator operation. The mixed reality simulation was originally developed by Kade et al. [66], and then updated with three information placements: (1) on the physical head-down display, (2) on the physical windshield, (3) and virtually projected on the ground (see Figure 4.2). We selected these three information placements, as the variation of these setups is often used in research related to head-up displays and mixed reality interfaces in the automotive domain [110, 111].

The test scenario in the mixed reality simulation was to drive the virtual excavator through a construction site, while trying to avoid colliding with construction workers, traffic cones, and other objects along the passage (see Figure 4.3). Each

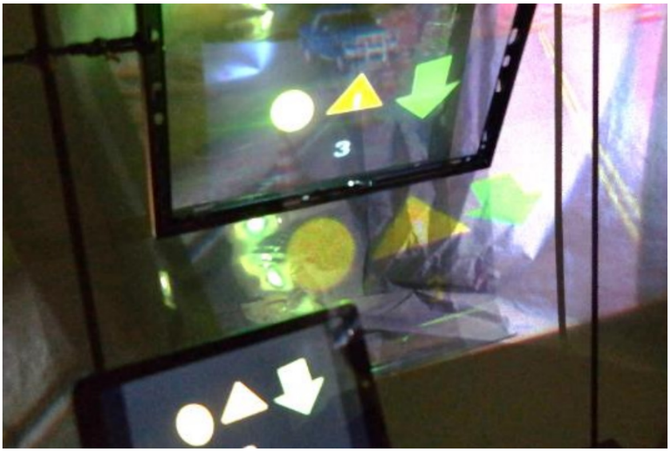

Figure 4.2: The image shows the supportive information presented on three different placements: head-down display, head-up display, and projected on the virtual ground. Note that only one placement was used in one experiment. The image also shows how the virtual environment looks from the participant's point of view. This figure also appears in **Paper B** [162].

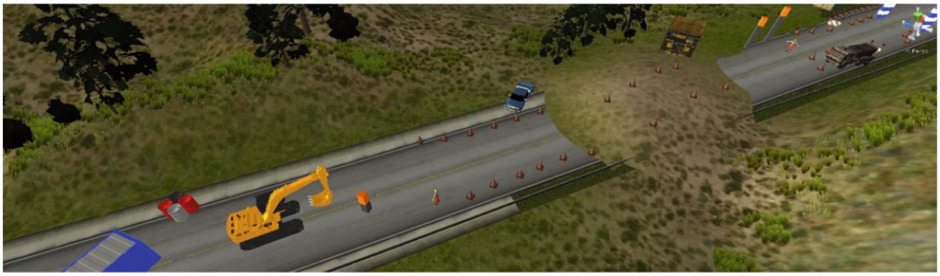

Figure 4.3: The bird's-eye view of the virtual environment used in the A/B test. The participants had to drive the virtual excavator, while trying to avoid colliding with any obstacles. This figure also appears in **Paper B** [162].

information placement shown in Figure 4.2 presented four types of information that could support the participants to complete the test scenario. Note that the four types of information appeared based on the following conditions:

1. A green arrow that pointed to where the participants should drive the excavator.
2. A yellow triangle that appeared when there was an obstacle near the excavator.

3. A red octagon replaced the yellow triangle when the collision between the excavator and the obstacle was imminent.

4. A yellow circle was also shown in addition to the signs above only if the obstacle was a virtual human.

We recruited fifteen participants from the university environment in the A/B test, with the assumption that recruiting more than 10-12 participants would be sufficient to produce significant results [92]. The test scenario shown in Figure 4.3 was relatively similar to a driving scenario, which all the participants were already familiar with. Moreover, the meanings of the presented information were very obvious to the participants and thus they immediately knew how to make use of the information. Therefore, we concluded that it was appropriate to involve non-operator participants in this experiment.

Before conducting the experiment, we informed the participants about the purpose of this experiment, the equipment, the controls, and the test scenario that the participants had to complete. We also informed them that we would collect background information (gender, age, and prior experience with heavy machinery, industrial simulations, and mixed reality simulations), their eye gazes while completing the test scenario, and their perceived workload, which we would anonymize afterwards. Note that, considering the experimental setup and the list of information that we wanted to collect, this experiment did not require an ethical approval from the Swedish Ethical Review Authority (see the Swedish Law (2003:460) [148]). Therefore, it was sufficient to conduct the experiment after receiving informed consent from the participants. Twelve participants were male and the other three were female. Most of the participants were between 26 and 35 years old, while the remaining ones were older than 35 years old. Two participants had some experience with excavators, seven had experience with industrial simulations, and six had experience with mixed reality headsets.

We recorded the participants' eye gazes while completing the test scenario using an eye tracker called Pupil Core[1] to determine how frequent the participants were looking at the presented information. This kind of insight is useful to indicate whether the areas of interest become more noticeable or more relevant to complete the task scenario [114]. We manually analyzed the recorded videos from the eye tracker by counting how many times the participants glanced at the presented information, including at which areas of the test scenario that the participants perceived the information. Note that we had to exclude the eye tracking data from three participants, since we were unable to record their eye gazes properly.

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[1] https://pupil-labs.com/products/core/

We used the NASA Raw Task Load Index (NASA-RTLX) questionnaire to measure the participants' workload induced by different information placements. We decided to use the NASA-RTLX instead of the traditional NASA-TLX because of its ease of use and straightforwardness. In the traditional NASA-TLX, participants have to firstly rate the six subscales of workload, and then choose which subscales are more important for their overall workload through a pairwise comparison in order to get the overall workload [54]. On the other hand, the pairwise comparison is removed in the NASA-RTLX, as the six subscales of workload are simply added and averaged in order to obtain the overload workload [53]. Taking this into account, the NASA-RTLX is relatively easier to fill in and it can also be administered using pens and papers. Moreover, the results from the NASA-RTLX were suggested to be strongly correlated to the results generated from the traditional NASA-TLX [11]. We asked the participants to fill in the NASA-RTLX questionnaire after completing the test scenario with each information placement.

Each participant completed the test scenario three times, i.e., one for each for information placement. The order of the information placements to be used was randomized. More information about how we conducted the A/B test can be found in **Paper B**. The main findings from this method are described in Section 5.2, while the reflections on the obtained findings are discussed in Section 6.1.2.

4.3 Literature Review

One of the main findings that we obtained from the A/B test presented in Section 4.2 is that, by bringing information closer to line of sight, the participants looked at the presented information more frequently and had lower perceived workload (see Section 5.2). After obtaining these findings, I was interested to investigate whether other research in the heavy machinery domain also discovered similar findings. Note that we had looked at relevant literature before conducting the A/B test described in Section 4.2, but I would not say that we had covered all relevant research in the heavy machinery domain.

Like in any research project, it is essential to understand what has been proposed and discovered within scientific communities. Therefore, I could be sure in which direction I should pursue the rest of my doctoral research. I then decided to look for all relevant literature that focused on the use of augmented reality and transparent interfaces in heavy machinery. I was interested in these technologies, as they offer possibilities to present information closer to operators' line of sight, without fully obstructing their view. I searched for relevant publications using a list of search strings on Google Scholar. I did not put any time limitation, thus all publications up to September 2019 were considered. This activity provided me a total of 233 publications. I then filtered the publications by excluding publications that do not mention about presenting something to operators' view, either as concepts, within simulated environments, or in real-world settings. This elimination process produced a list of 39 publications to be reviewed. More information about these searching and filtering processes can be found in **Paper C**.

My co-author and I divided the selected publications and reviewed them separately. When reviewing the publications, we took note about what types of display technologies were used, in which heavy machinery the technologies were proposed, how the studies were conducted, and the findings that other researchers have reported. We then shared our findings with each other after reviewing the selected publications. The main findings from the literature review are presented in Section 5.1.

4.4 Safety Guidelines Review

Based on the literature review described in Section 4.3, we found that other researchers selected various types of information to be presented to operators. Some researchers chose to present generic information, for example, fuel status, while others decided to present task-specific information (see Chapter 5.1). Without emphasizing one approach over the other, it is nonetheless important to carefully select which information to be presented to avoid overloading operators with less necessary information [32, 67].

Before investigating which information to be presented to operators, I had to decide what types of heavy machinery I would like to focus on. Note that the types of heavy machinery investigated in the online ethnography and the A/B test were so far chosen mainly due to pragmatism. The online ethnography in Section 4.1 is about forest harvesters, because they are used in remote locations. The location remoteness increases the relevance of using online ethnography. On the other hand, the A/B test in Section 4.2 is about excavators, since the existing mixed reality simulation is for excavators (see Kade et al. [66]).

To increase the relevance of my doctoral research, I decided to choose the types of heavy machinery based on their severity level. For that purpose, I referred to studies that analyzed accidents related to heavy machinery. Kazan and Usmen [69] compared the accident data that involved four types of earth-moving machinery in the U.S. Their results show that excavators were involved in 24.8% of 1200 reported accidents, where about half of those excavator-related accidents led to fatalities. As such, our prior decision to make the A/B test in the context of excavators was justified. Based on the findings from McCann et al. [97], I found that mobile cranes are considered as the most dangerous machine in the construction industry, since they were involved in 78% of 611 crane-related accidents. From this point onwards, I decided to focus my research on both mobile cranes and excavators. I also decided to move my focus away from forest harvesters, since they tend to have low rates of accidents [46].

I used four safety guidelines for mobile cranes [80, 85, 105, 121] and four safety guidelines for excavators [16, 56, 106, 145] to assist me specifying what kinds of information that should be presented in mobile cranes and excavators. Note that five of these safety guidelines were published by relevant government agencies, and each of the remaining three was published by a professional association, a training institute, and a machine manufacturer. These guidelines also come from different parts of the world, such as Australia, Germany, Hong Kong, and the UK. I took this approach because of two main reasons. Firstly, heavy machinery operations are heavily regulated, and thus it is relevant to take into account how regulations or recommendations dictate the operation of these machines. Secondly, the safety guidelines serve as a baseline, as they are applicable to all operators regardless of different preferences and operational styles.

Some of the safety guidelines describe information that is also applicable to various roles, such as operators, supervisors, maintenance workers, ground workers. However, in this review, I focused on determining what operators should know while operating their machines, so that they could prevent unwanted events from happening. For every unwanted event, I looked for what kind of factors that may cause the event to occur. For example, operating a mobile crane in the strong wind weather may make the crane collapse [85], and thus I assumed that it is important for operators to know the wind speed. I decided to focus on the cause-effect relationship, since this aspect would remain applicable regardless whatever technologies or procedures being used [32].

Similar descriptions about how I conducted the safety guidelines review can be found in **Paper D** for mobile cranes and **Paper E** for excavators. The main findings from this method are presented in Section 5.3. The reflections on the use of this method as a way to specify the list of information, which operators of mobile cranes and excavators should know, are discussed in Section 6.1.3.

4.5 Technology Review

Another main finding that we found from the literature review described in Section 4.3 is that other researchers have proposed the use of diverse display technologies in heavy machinery. This finding is aligned with the availability of display technologies that can be used to present information closer to operators' line of sight, such as head-mounted displays and head-up displays.

Choosing the suitable display technology plays a vital role here, since the display heavily influences how the information can be formed and visualized to operators, as well as how the display could fit into operators' working environments [32]. I conducted a technology review of available display technologies, e.g., head-mounted displays and head-up displays, to discover both advantages and disadvantages of each available display technology in the context of heavy machinery. I also used the findings from the literature review as an additional input to discover what would and would not work in practice.

Similar descriptions about how I conducted the technology review can be found in **Paper D** for mobile cranes and **Paper E** for excavators. The result from this method is presented in Section 5.3, while the discussion about pros and cons of each available display technology is presented in Section 6.1.4.

4.6 Design Workshops

Through the safety guidelines review in Section 4.4, I managed to gather a list of information that operators of mobile cranes and excavators should know in order to prevent unwanted events from happening (see the list of information in Section 5.3). Note that, although there are different kinds of information in the list, they are relevant to prevent two kinds of unwanted events: (1) colliding with surrounding objects and (2) losing the machine's balance.

Along with two co-authors, we conducted two separate design workshops, where each of the workshops was assigned for one type of the machines. We used the list of information gathered from the safety guidelines as the boundary of our design space. In other words, we only generated visualization ideas for the information included in the list. Through sketching, we explored a plethora of visualization ideas that could assist operators to avoid collisions with surrounding objects and help them to maintain the machine's balance. At the same time, we also scrutinized the sketches based on their suitability to represent operations of mobile cranes and excavators.

After conducting the technology review in Section 4.5, I found that self-emitting transparent displays to be the suitable display technology in the context of heavy machinery, as operators do not require to wear any extra equipment and the information is generally still visible in bright environments due to their light-emitting feature (see Section 5.3). However, self-emitting transparent displays also brought technical constraints that influence how the information could be designed and visualized to operators. For example, they have a limited number of segments and these segments can be either illuminated or not. The combination of illuminated segments should visually represent something meaningful, since this is the information that operators would see. Moreover, the position of the segments cannot also be changed once the display has been manufactured [1].

As part of the design workshops, we selected some of the visualization ideas that we have generated, and we then refined their visual appearances and behaviors based on the technical constraints presented above. See Figure 4.4 for some sketches that we generated in one of the workshops. Similar descriptions about how we conducted the design workshops can be found in **Paper D** for mobile cranes and **Paper E** for excavators. The main results of the design workshops are presented in Section 5.3.

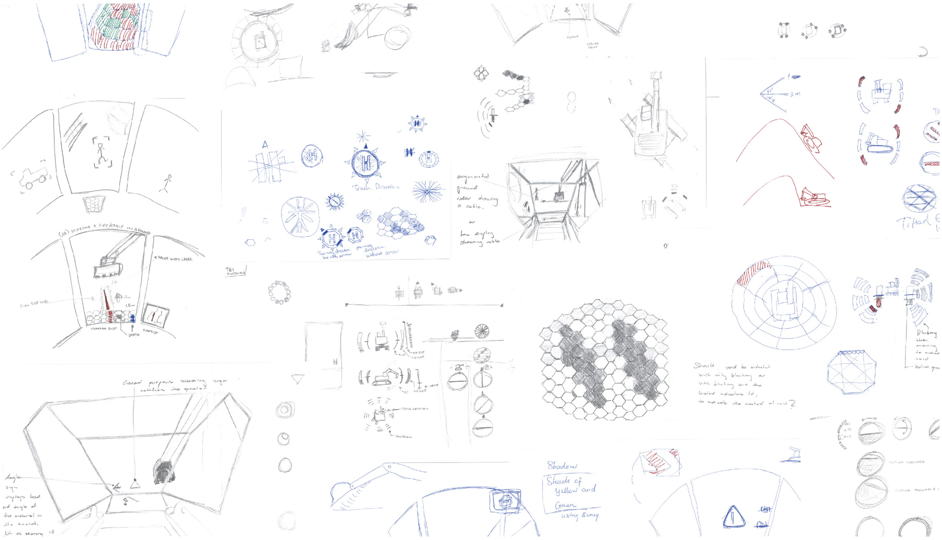

Figure 4.4: Some sketches that we generated from the design workshop in the context of excavators. We drew the sketches on the left side as if the entire windshield could work as a display, which is currently not possible due to the limitation of transparent displays. We drew the remaining sketches in ways that closely resembled the appearance and the limitation of transparent displays. In the design workshops, we also explored how the visualization should change based on the performed operations. This figure also appears in **Paper E** [138].

4.7 Exploratory Usability Tests

The design workshops described in Section 4.6 produced ten visualization designs that match the context of use and fit with the constraints from the chosen display technology (see Section 5.3). Note that some of the proposed visualization designs are applicable to both mobile cranes and excavators, while some of them are applicable to one type of the machines. To evaluate the proposed visualization designs, I involved six mobile crane operators and seven excavator operators in two separate series of exploratory usability tests, where each of the series was dedicated for one type of the machines. Exploratory usability tests are usually done in the early phase of the development process in order to identify good and bad designs [27]. In these tests, I focused on evaluating to what extent the proposed visualization designs matched with the operators' way of thinking. In short, I wanted to know to what extent the operators could understand the meaning of the visualization designs. Investigating this issue is important, since less complex information tend to produce lower mental workload [147] and better situation awareness [32, 108].

I presented the proposed visualization designs as paper prototypes. I made this decision, since they were easy to produce and using papers was adequate to show the variations of the visualization designs (see Figure 4.5 for the examples of the paper prototypes). Moreover, since paper prototypes are still far from final products, participants are generally less hesitant to criticize and tweak the proposed designs [120, 139]. Before starting the tests, I firstly explained the meaning of the proposed visualization designs to the operators. To avoid any misunderstanding between the operators and I as the facilitator, I used a set of tools to

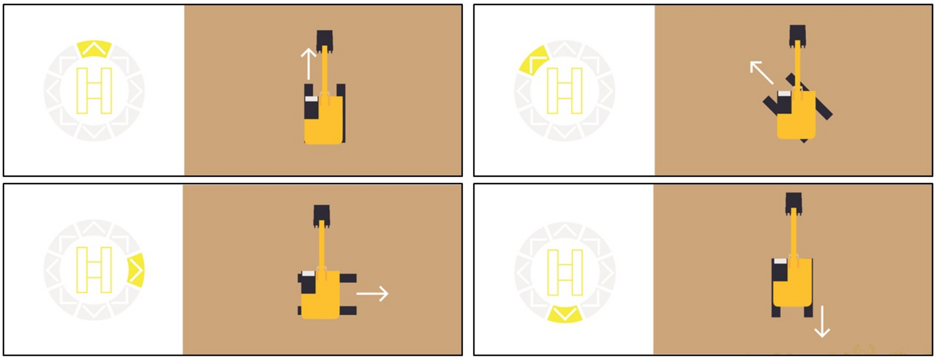

Figure 4.5: Some examples of the visualization designs that were printed on papers. The left-side images show a variation of visualization designs, while the right-side images illustrate the meaning of the visualization designs. Note that, during the evaluation, the right-side images (the ones with excavators) were hidden and the operators only saw the left-side images. The right-side images were shown only when the operators could not correctly guess the meaning of the visualization designs. This figure also appears in **Paper E** [138].

demonstrate the meaning for each visualization design (see Figure 4.6 for the tools that were used in the exploratory usability tests). While presenting the proposed visualization designs, I also moved the tools so that they could convey the meaning of the visualization designs. This approach enabled the operators and I to express our thoughts without verbally describing everything.

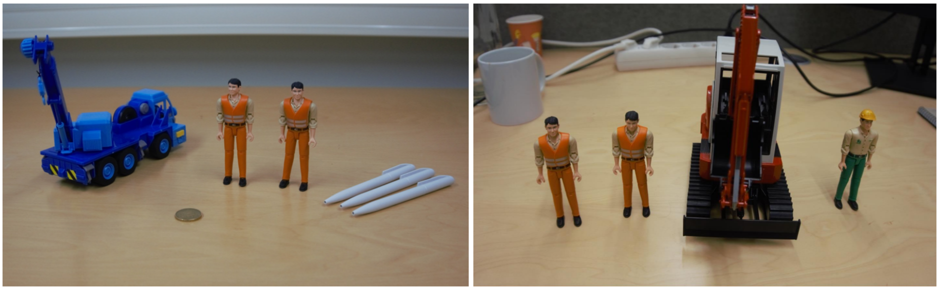

Figure 4.6: The left image shows the tools that were used for the tests in the mobile crane context, while the right shows the tools that were used for the tests in the excavator context. The left image and the right image also respectively appear in **Paper D** [134] and **Paper E** [138].

Before conducting the exploratory usability tests, I informed the operators about the purpose of the tests and the test procedure. I also informed them that I would collect their background information (gender, age, experience) and their photographs (without faces) when they were interacting with the given tools, and record our verbal discussions. All the seven tests in the excavator context were carried out in Sweden. In the mobile crane context, two tests were done in Sweden, while the remaining four tests were conducted in Finland. Considering the test setup and the kinds of information that I wanted to collect from the operators, these tests did not require an ethical approval from the Swedish Ethical Review Authority (see the Swedish Law (2003:460) [148]) or from the Human Sciences Ethics Committee in Finland [42]. Therefore, it was sufficient to conduct the tests after receiving informed consent from the operators. The mobile crane operators were aged between 37 and 61 years old with working experiences between 7 and 31 years. Five out of six mobile crane operators were familiar with automotive head-up displays. The excavator operators were aged between 22 and 64 years old with working experiences between 2 and 50 years. Six out of seven excavator operators were familiar with automotive head-up displays.

After presenting the meaning of the proposed visualization designs and the operators confirmed that they understood what I explained and demonstrated earlier, I provided a set of printed visualization designs to the operators. For each of the printed visualization designs, the operators were asked to move the given tools according to what they deemed as the correct answers. Using this approach, I could determine whether the operators interpreted the proposed visualization designs as what we intended. See Figure 4.7 for the examples on how the tests were conducted. This process was repeated until every printed visualization design was tested. After that, I gave the opportunity to the operators to give feedback on the proposed visualization designs.

In the last part of the tests, I presented a paper with the picture of a mobile crane or excavator cabin printed on it. I also presented the proposed visualization designs that were printed on a transparent film and were cut into several pieces. I then asked the operators to choose which visualization designs that they would like to have and indicate in which area of the windshield the visualization designs

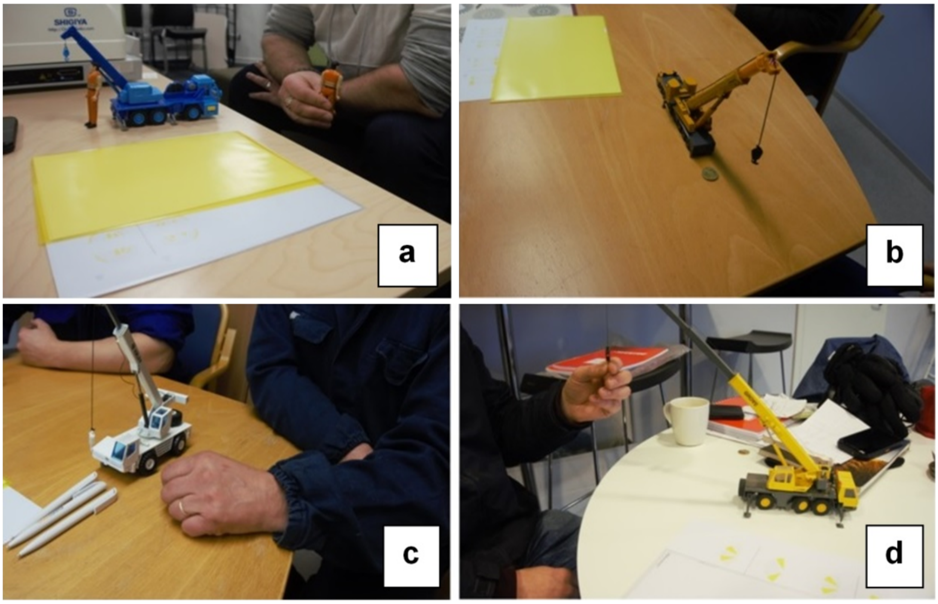

Figure 4.7: Some pictures that show how the exploratory usability tests in the mobile crane context were conducted. The operators had to move the given tools according to how they interpreted the visualization designs printed on the papers. **(a)** The operators were asked to move the human toy(s) to the position where the obstacle was located. **(b)** The operators were asked to move the coin to where the machine's center of balance was supposed to be. **(c)** The operators were asked to arrange the tip of the pens to indicate the wind direction, while the number of pens represent the wind intensity (1 pen = weak wind, 2 pens = medium wind, and 3 pens = strong wind). **(d)** The operators were asked to move the hook of the replica to show how much the lifted material was swinging. This figure also appears in **Paper D** [134].

should be presented. The placement was done by moving the pieces of transparent film on top of the printed cabin image (see Figure 4.8 for an example of this activity). I also gave them the freedom to exclude any visualization designs that they deemed less necessary. Finally, I requested the operators to describe the reasons behind their decisions.

Figure 4.8: The operators were asked to choose which of the visualization designs (provided in the form of pieces of transparent film) that they preferred to have and place the selected ones on top of the printed cabin image. This figure also appears in **Paper D** [134].

More information about how I conducted the exploratory usability tests can be found in **Paper D** for mobile cranes and **Paper E** for excavators. The main findings from this method are presented in Section 5.4, while the reflections on the use of paper prototypes to evaluate the proposed visualization designs are discussed in Section 6.1.5.

4.8 High-fidelity Prototyping

Based on the operators' feedback from the exploratory usability tests presented in Section 4.7, I found that the visualization design that indicates the relative lifting capacity (see Figure 4.9) is applicable for both mobile cranes and excavators. All the operators also commented that having this kind of information is very important to prevent their machines from collapsing. Taking this comment into account, I selected this visualization design to be further developed into a high-fidelity prototype.

In this context, there are at least three reasons why it is relevant to build a

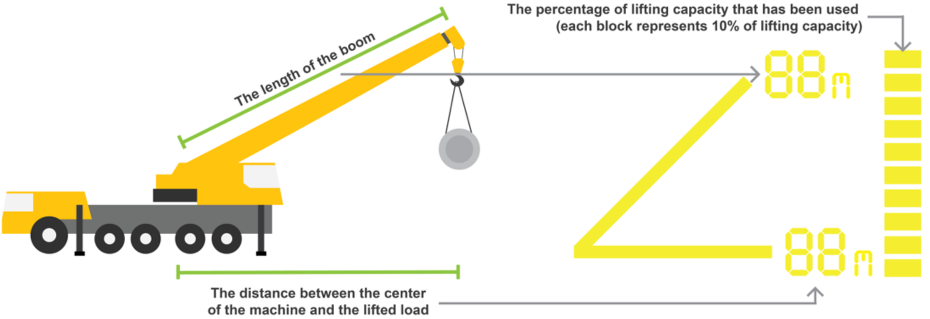

Figure 4.9: The meaning for each kind of information in the visualization design that indicates the relative lifting capacity. Although a mobile crane is shown here, a similar mechanism also applies in excavators. This figure also appears in **Paper F** [135].

high-fidelity prototype. Firstly, the high-fidelity prototype could serve as an example of material exploration [47, 142]. One of the main findings from the literature review is that there is only one out of 39 reviewed publications that investigates the use of self-emitting transparent displays in the heavy machinery domain (see Section 5.1). Therefore, developing a high-fidelity prototype inspired from this display technology would further explore how this display technology could be used in the heavy machinery domain. Secondly, the process of building a high-fidelity prototype serves as the way to demonstrate the possible realization of the design space [61, 141]. For example, although we already considered the technical constraints of self-emitting transparent displays when creating the visualization designs (see Section 4.6), the prototyping process would demonstrate to what extent the visualization design that indicates the relative lifting capacity could be built as what we originally intended. Thirdly, the high-fidelity prototype could be used in future user evaluations [37, 120, 142].

I decided to use mobile cranes as the use case for this prototyping activity, since they are primarily used for lifting, while excavators can be used for various purposes. Nevertheless, the visualization design shown in Figure 4.9 is also applicable to excavators when they are used for lifting operations. I built the prototype using off-the-shelf components, such as thin glasses, 5 mm x 5 mm light-emmitting diodes (LEDs), insulated copper wires, and an Arduino. I attached the LEDs on a 20 cm x 12 cm glass with the thickness of 1 mm. I initially wanted to use the 2 mm x 2 mm LEDs, since that would enable me to use glasses with smaller dimension. However, it was extremely difficult to solder them manually, and thus I decided to use the 5 mm x 5 mm ones. After that, I attached the LEDs on the glass using superglue, and then arranged them in a way that visually resembled the design of the relative lifting capacity (see Figure 4.10). The connection between the LEDs was made using insulated copper wires with diameter of 0.1 mm. Although the wires were not transparent, they did not obstruct the visualization design due to their tiny size. Note that the quality of the transparent display prototype was still far behind the commercial version of self-emitting transparent displays.

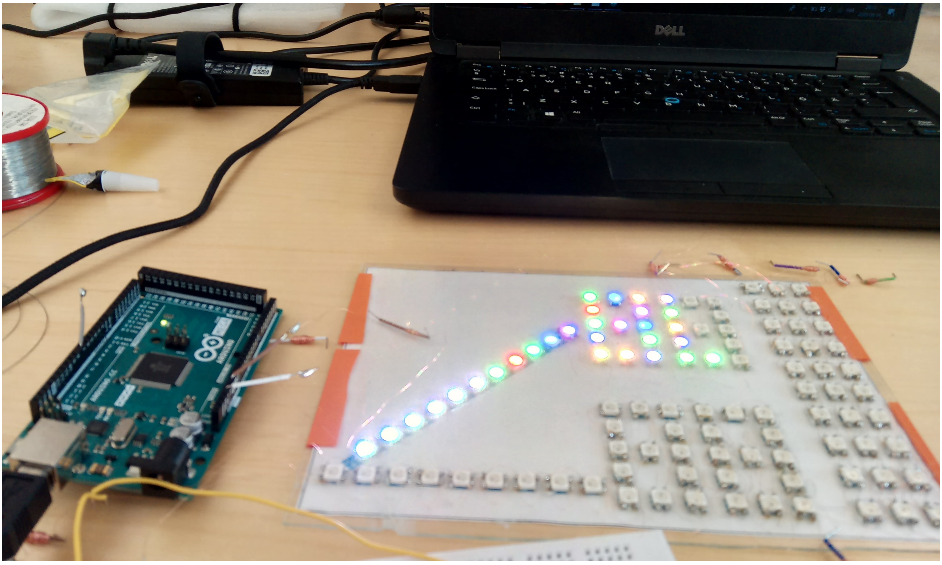

Figure 4.10: The Arduino controlled which LEDs that should be illuminated, which color that should appear, and how bright the light should be illuminated.

Since we did not have any access to real mobile cranes, we used a mobile crane simulation developed in the Unity game engine to make the transparent display prototype functional. The simulation had a 3D mobile crane model that resembled the Liebherr LTC 1050-3.1 crane (see Figure 4.11), and thus we also imported the data from the load charts for this particular crane model (see [86, pp. 23-47]) into the simulation. Load charts are documents provided by crane manufacturers that record the maximum lifting capacity of a mobile crane in various states of boom length and load radius. In this context, boom length refers to how far the boom is extended, while load radius refers to the distance between the lifted object and the crane's center. By incorporating the data from relevant load charts into the mobile crane simulation, we could ensure that the information shown on the transparent display prototype would not be arbitrary. Our approach was in contrast to what Kvalberg [79] did with his transparent display prototype, as the user had to manually input the information that would be shown on his

Figure 4.11: The virtual mobile crane that exists inside the simulation. The virtual mobile crane closely resembles the Liebherr LTC 1050-3.1 crane [86]. This figure also appears in **Paper F** [135].

prototype. We then added a virtual version of the relative lifting capacity shown in Figure 4.9 as a graphical user interface (GUI), which can be viewed from inside the cabin of the virtual mobile crane. Whenever we operated the virtual mobile crane, the information shown inside the virtual mobile crane also automatically changed.

Finally, I used a Unity game engine plugin called Uduino [155] to enable data communication between the Unity game engine and the Arduino. Based on the input data from the Unity game engine, the Arduino automatically decided which LEDs to be illuminated, so that the combination of illuminated LEDs could visually represent the current boom length, the current load radius, and the current lifting percentage. Here, the physical prototype would replicate what was shown inside the cabin of the virtual mobile crane. More information about the prototyping process can be found in **Paper F**.

Chapter 5

Results

This chapter presents the main results that have been obtained from the methods presented in Chapter 4. To facilitate the reading of this chapter, the results are presented according to which research questions they are associated with.

5.1 The Current Situation and Scientific Progress in the Heavy Machinery Domain

This section presents the answers for "RQ1. What has been proposed in the heavy machinery domain and what are the lessons learned?" described in Chapter 2. This section presents the main findings from the online ethnography (see Section 4.1) and the literature review (see Section 4.3).

The videos, which were analyzed in the online ethnography described in Section 4.1, showed a diverse set of forest harvesters, including various brands of forest harvesters, skills of operators, and work environments. Getting such a diverse set of samples in traditional field studies would require an enormous work. Through this approach, I was able to gain a broad understanding on how operators performed their work, what their work environments were, and what kind of practical and ergonomic issues that existed in their operations. Therefore, it could be concluded that it was possible to obtain a certain level of domain knowledge by analyzing available videos on the Internet.

Specifically related to the research theme of this dissertation, this approach enabled me to learn about how operators distributed their attention and what kind of supportive systems that existed inside their cabins. The videos showed that the operators spent most of their time looking through the front windshield, which is understandable, as most of the operation happened right in the front of the cabin. The operators sometimes looked through left, right, and rear windshields to find possible obstacles and pathways. From the videos, it was visible that most heavy machinery has been equipped with at least one head-down display on the dashboard inside the cabin. There were even five videos that showed cabins with multiple head-down displays. This finding suggested that visual information is still used as the most common way to deliver supportive information in heavy machinery. However, due to the limited camera's field of view and the limited video resolution, it was not possible to observe how the use of information was affected by what was happening in the surroundings and to determine what kind of information that the operators may overlooked. The complete results from the online ethnography can be found in **Paper A**.

From the literature review described in Section 4.3, I found that the idea of presenting information closer to operators' line of sight in the heavy machinery domain has been investigated since almost two decades ago. Since then, the idea has been investigated in diverse types of heavy of machinery, although the approaches taken varied significantly between the studies. The type of information to be presented also greatly differed depending on the type of heavy machinery. Some researchers decided to present generic information, for example, fuel status, while others presented information related to industrial tasks that heavy machinery should perform. The main findings from the literature review are described in the following paragraphs, while the complete results can be found in **Paper C**.

Based on the reviewed literature, I found that head-up displays and head-mounted displays are the most frequently types of displays to be proposed in the heavy machinery domain. Monitors and tablets were also proposed, even though they were mainly used for remote operations only. However, the majority of the experiments was conducted entirely in simulated environments, where no physical prototypes were developed to demonstrate the realization of the proposed visualizations. This decision enabled researchers to evaluate their ideas safely, but it was unclear to what extent the proposed visualizations could be implemented in real machines.

There were three studies that developed the physical visualization systems, but none of them were evaluated by operators. Fernandez et al. [126] and Palonen et al. [109] explored the use of head-mounted displays to be used in tractors. Kvalberg [79] considered the use of self-emitting transparent displays to be used in off-shore cranes. However, these three studies were limited to technical evaluations of the proposed visualization systems. Moreover, as no operators were involved in these three studies, it was unclear to what extent the proposed visualization systems would help operators to perform their work.

There were three studies that developed the physical visualization systems and involved professional operators in their experiments. Based on these three studies, there were some problems regarding the deployment of visualization systems in real machines. Rakauskas et al. [116] developed a projection head-up display for snowplow trucks. Since the projected information deteriorated in the presence of sunlight, they had to conduct their experiment in the night. Englund et al. [35] also developed a projection head-up display for forest harvesters and they carried out their experiment in the daytime. The operators commented that the contrast between the projected image and the environment was low, which made the presented information difficult to see. Fang et al. [39] proposed the use of an 11-inch tablet in mobile cranes. The operators commented that the tablet size was still considered too small and its physical presence could also obstruct their view.

The involvement of operators was generally low across the reviewed literature, since only eleven out of 39 publications that involved operators in their studies. The number of operators involved was also low, where the highest was eleven operators and the average was six operators. Moreover, the operators' involvement was mostly limited to the end of the design process, where they were asked to use the developed visualization systems in either virtual or physical settings. Only four out of 39 publications involved operators in the early stage of the design process.

Although not all the reviewed literature reported user evaluations, the meta-review of the experimental findings can still be presented. In the context of in-cabin operations, where operators work inside their machines, the experiments were usually done to investigate the impact on operators' performance based on two conditions: (1) with or without the supportive information and (2) presenting the supportive information on the windshield or near the object of interest. Based on the experiments that compared whether the supportive information was absent or present, the literature suggested that the presence of the supportive information produced better safety-related performances, such as lower speed, shorter response time, and making more responses on the machine's controls. However, there was no significant difference whether the information was presented on the windshield or near the object of interest.

5.2 The Impacts of Different Information Placements on Perception and Cognition

This section presents the findings from the A/B test (see Section 4.2) that are relevant to address "RQ2. How different information placements influence operators' perception and cognition?" described in Chapter 2. The complete results from the A/B test can be found in **Paper B**.

As part of the A/B test, we recorded the participants' eye gazes while completing the test scenario using different information placements by using an eye tracker. Based on the eye tracking data, the mean total numbers of glances were 6.3 (SD: 8.6) for the head-down display, 12.0 (SD: 8.3) for the head-up display, and 13.3 (SD: 7.6) for the projection display[1]. Generally speaking, the participants glanced at the presented information more frequently when it was presented closer to their line of sight, i.e. using the head-up display and the projection display, compared to when the information was presented further away from their line of sight, i.e. using the head-down display.

Looking at certain areas in the virtual environment, the results showed that there were different levels of glances at the presented information depending on the situation (see the top-right image in Figure 5.1). The situation was relatively easy in the beginning of the test scenario (see "To first pile" in Figure 5.1) and all the participants noticed the information presented on each type of displays.

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[1] The mean total numbers of glances are rounded down in Paper B, while the numbers here are presented with one decimal.

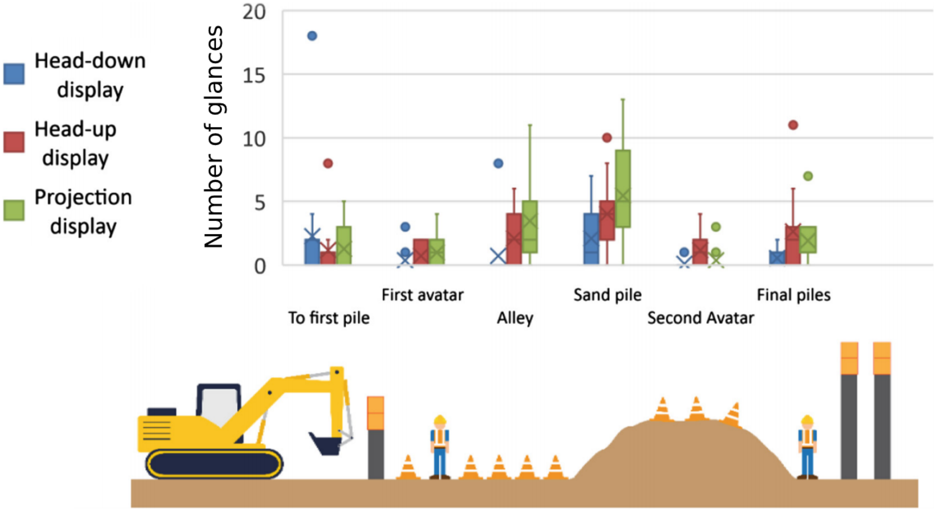


Figure 5.1: The amount of glances using different information placements based on specific areas in the virtual environment. The X sign represents the mean and the median is marked with a line that separates the second and the third quartiles. The whiskers indicate the largest and the smallest data, while the dots outside indicate the outliers. This figure also appears in **Paper B** [162].

One participant had difficulties at this area, and thus glanced at the display more frequently than the other participants. The mean numbers of glances at this area were 2.3 (SD: 5.4) for the head-down display, 1.2 (SD: 2.4) for the head-up display, and 1.3 (SD: 1.8) for the projection display.

When the participants approached the first avatar (see Figure 5.1), the participants started to glance at the information presented using the head-up display and the projection display more frequently than the head-down display. Here, the mean numbers of glances were 0.4 (SD: 0.9) for the head-down display, 0.7 (SD: 0.9) for the head-up display, and 1 (SD: 1.3) for the projection display. A similar finding was also found when the participants passed through the alley (see Figure 5.1), where they increasingly glanced at the presented information on the head-up display and the projection display. At this area, the mean numbers of glances were 0.7 (SD: 2.4) for the head-down display, 2.1 (SD: 2.2) for the head-up display, and 3.5 (SD: 3.6) for the projection display.

When the situation became more complex, the number of glances at the presented information was increased across different information placements, since the participants started to look for more guidance. When the participants moved through the sand pile (see Figure 5.1), the participants still glanced at the information presented using the head-up display and the projection display more frequently than the head-down display. The mean numbers of glances at this area were 2.1 (SD: 2.7) for the head-down display, 4 (SD: 3.0) for the head-up display, and 5.5 (SD: 3.8) for the projection display.

When the participants approached the second avatar (see Figure 5.1), most of them did not glance at the presented information, except when the head-up display was used. Here, the mean numbers of glances were 0.1 (SD: 0.3) for the head-down display, 1.2 (SD: 1.3) for the head-up display, and 0.4 (SD: 0.9) for the projection display. When the participants approached the final piles (see "Final piles" in Figure 5.1) and tried to knock down the orange boxes on the top of the piles, they glanced at the information presented using the head-up display and the projection display more frequently, compared to when they used the head-down display. At this area, the mean numbers of glances around the final piles were 0.5 (SD: 0.8) for the head-down display, 2.6 (SD: 3.3) for the head-up display, and 1.9 (SD: 2.0) for the projection display.

Judging from the numbers of glances that the participants made at different areas in the virtual environment, the participants were able to perceive the presented information more frequently when they used the head-up display and the projection display, compared to when they used the head-down display. The only exception to this finding is when the participants move towards the first pile (see Figure 5.1), where the mean number of glances using the head-down display was higher compared to the head-up display or the projection display.

As described in Section 4.2, we asked the participants to report their perceived workload after completing the test scenario using each information placement. Based on the NASA-RTLX data, the mean overall workloads were 62.3 (SD: 21.1) for the head-down display, 50 (SD: 18.7) for the head-up display, and 42.3 (SD: 16.9) for the projection display. Therefore, the participants had lower overall workload when the information was presented closer to their line of sight, i.e. using the head-up display and the projection display, compared to when the information was presented further away from their line of sight, i.e., using the head-down display.

In the NASA-RTLX questionnaire, there are six subscales that represent the components of workload: mental demand, physical demand, performance, temporal demand, effort, and frustration. As shown in Figure 5.2, both the head-up display and the projection display produced lower scores compared to the head-down display in all the subscales. The largest difference among the subscales was observed in terms of physical demand, where the mean scores were 9.4 (SD: 6.7) for the head-down display, 6.5 (SD: 4.9) for the head-up display, and 5.8 (SD: 4.6) for the projection display. This result was probably due to the participants had to move their heads whenever they looked at the head-down display, while such head movement was reduced when the head-up display and the projection display were used.

As shown in Figure 5.2, the projection display produced lower scores than the head-up display in all the subscales in the NASA-RTLX questionnaire. Based on

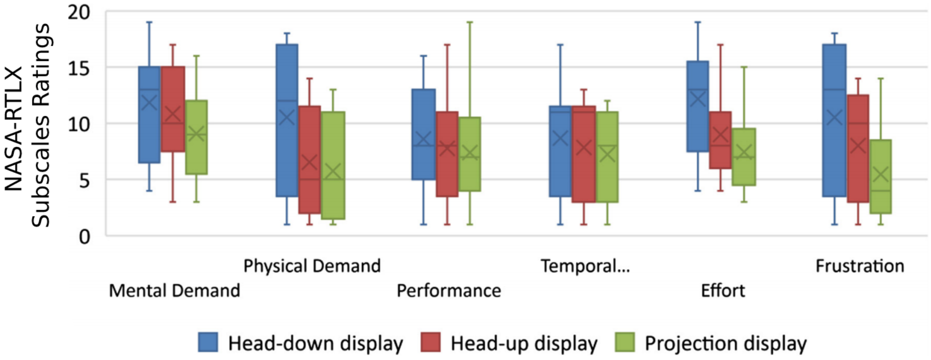


Figure 5.2: The perceived workload based on the subscales in the NASA-RTLX for each information placement. The X sign represents the mean and the median is marked with a line that separates the second and the third quartiles. The whiskers indicate the largest and the smallest data. This figure also appears in **Paper B** [162].

the mean total numbers of glances, the participants also looked at the information presented using the projection display slightly more frequently than when they used the head-up display. One participant commented that the projection display was perceived as more user friendly than the head-up display, while the remaining participants did not comment about the different experience between the head-up display and the projection display.

5.3 Transforming the Critical Information into Iconic Designs

This section provides the answers for "RQ3. How can the critical information be formed into iconic designs?" described in Chapter 2. This section presents the key results from the safety guidelines review (see Section 4.4), the technology review (see Section 4.5), and the design workshops (see Section 4.6).

After reviewing the safety guidelines for mobile cranes and excavators (see Section 4.4), it was clear that there are some similarities between mobile cranes and excavators. Generally speaking, the safety guidelines are provided to prevent two kinds of incidents: collision and loss of balance, and there are some similarities on the influencing factors that cause the incidents. To prevent any collision, operators of mobile cranes and excavators must know the presence of nearby ground workers, existing structures, nearby machines, and be fully aware about what their machines are about to do. To avoid their machines from losing balance, operators of mobile cranes and excavators must know the current state of the machine and never operate the machine beyond permissible conditions, such as steep ground, unstable ground, and lifting an excessive load. Specifically for mobile cranes, operators are only allowed to perform lifting operations in permissible weather conditions, as the wind could influence the balance of their machines.

Considering the information obtained from the safety guidelines, I believed that it is important for operators to have information about the factors that may lead to incidents. Below is the list of critical information that I have gathered as the results of the safety guidelines review (the parentheses indicate for which type of machines the information is applicable for):

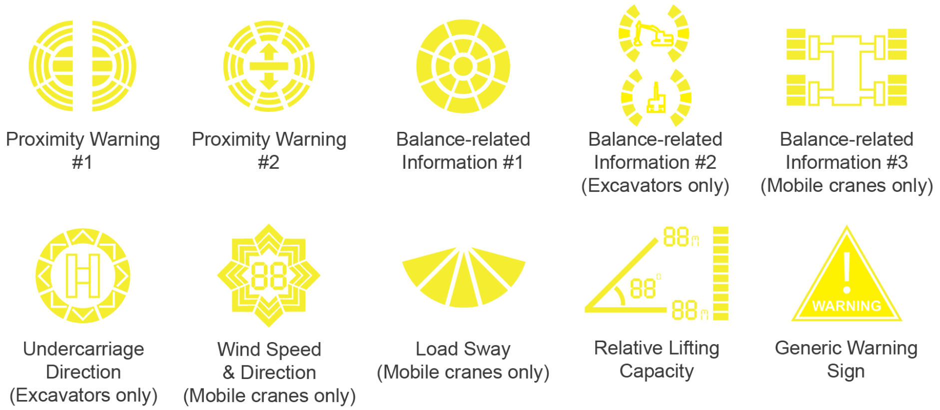
1. Proximity warning (for both types of machines): it indicates whether there are obstacles around the machine with respect to the direction of the cabin.

2. Balance-related information (for both types of machines): it indicates how the machine's balance is affected by the ongoing operation.

3. Undercarriage direction (for excavators only): it indicates the direction of the undercarriage with respect to the direction of the cabin.
4. Wind speed and direction (for mobile cranes only): it indicates the intensity of the wind and its direction with respect to the direction of the cabin.
5. Load swinging (for mobile cranes only): it indicates how much the lifted load would swing based on the ongoing operation.
6. Relative lifting capacity (for both types of machines): it indicates how much weight that the machine can lift based on the current states of the machine.
7. Generic warning sign (for both types of machines): it notifies that an incident is imminent to occur.

Since display technologies highly influence how the supportive information could be formed and presented to operators, it is important to choose the display technology that suits to mobile cranes and excavators the most. In the technology review described in Section 4.5, I reviewed two kinds of display technologies: head-mounted displays and head-up displays. Specifically for head-up displays, I further distinguished head-up displays that rely on reflection (referred to as "projection displays") and head-up displays that emit their own light (referred to as "transparent displays"). Considering both advantages and disadvantages of the reviewed display technologies, as well as the lessons learned from prior studies (see Section 5.1), I assumed that transparent displays to be the display technology to proceed with due to two important factors: (1) operators do not need to wear an extra equipment and (2) the information is generally visible in bright environments. Moreover, the use of transparent displays is still underexplored in the heavy machinery literature (see Section 5.1), and thus pursuing this direction could also be interesting from the research point of view.

In the design workshops described in Section 4.6, we generated visualization designs that could inform operators about the list of critical information presented earlier in this section. We also used the design constraints from the transparent displays to filter and refine the visualization ideas. As the results of the design workshops, we generated two designs for the proximity warning and three designs for the balance-related information. For the remaining five visualization designs, we were satisfied with proposing one design for indicating one kind of information (see Figure 5.3). The complete description about the meaning of the proposed visualization designs can be found in **Paper D** for mobile cranes and **Paper E** for excavators.



Proximity Warning #1
Proximity Warning #2
Balance-related Information #1
Balance-related Information #2 (Excavators only)
Balance-related Information #3 (Mobile cranes only)
Undercarriage Direction (Excavators only)
Wind Speed & Direction (Mobile cranes only)
Load Sway (Mobile cranes only)
Relative Lifting Capacity
Generic Warning Sign

Figure 5.3: The visualization designs that have been generated from the design workshops. The visualization designs that have no parentheses are applicable for both mobile cranes and excavators, while the ones with parentheses are applicable for one type of machines only.

5.4 Ensuring the Proposed Iconic Designs to Correctly Represent the Machines' Operations

This section addresses "RQ4. How to ensure that the proposed iconic designs correctly represent the machines' operations?" described in Chapter 2. This section presents the main findings from two separate series of exploratory usability tests presented in Section 4.7, which were conducted to determine whether the meaning of the proposed visualization designs (see Figure 5.3) matched with the operators' way of thinking.

The findings of the exploratory usability tests suggested that the proposed visualization designs matched well with the operators' way of thinking, since the operators could correctly move the given tools according to what they saw on the printed papers (see Figure 4.7 for the examples of this activity). However, there was an exception to this, as the operators had difficulties to use the proximity warning designs shown in Figure 5.3 when there were multiple obstacles around the machine. The operators then gave suggestions on how the proposed visualization designs could be improved, so that the proposed designs could further match their way of thinking. See Figure 5.4 for the comparison between the visualization designs before and after incorporating the operators' feedback. The complete results of the exploratory usability tests, including the motivations for improving the visualization designs, can be found in **Paper D** for the tests in the context of mobile cranes and **Paper E** for the tests in the context of excavators.

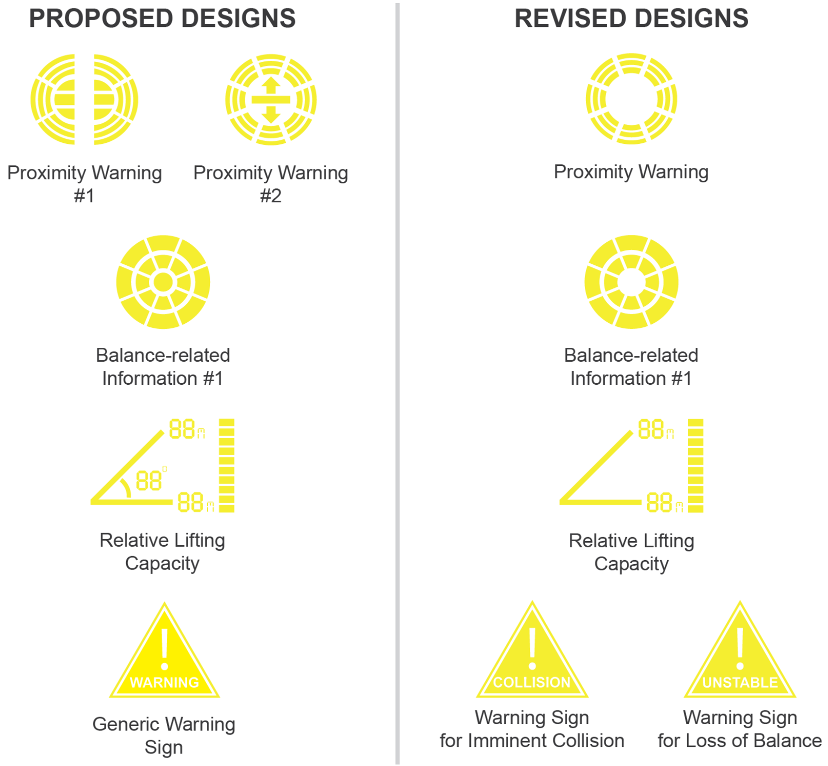


Figure 5.4: The comparison between the proposed designs and the revised designs. The visualization designs, which did not require revisions, are not shown here. The reasons behind these changes can be found in **Paper D** [134] and **Paper E** [138].

As part of the exploratory usability tests, I also asked the operators to exclude any of the proposed visualization designs that they considered less necessary. All the operators agreed that all types of information derived from the safety guidelines (see Section 5.3) are important for safety. However, the operators had diverse opinions on what kinds of information that should be included or excluded. Four out of six mobile crane operators excluded the visualization design that indicates the load swinging (see "Load Sway" in Figure 5.3), even though this visualization design was easily understood and did not require any revision. The operators commented that they could obtain this information by directly looking at the lifted material and they could also estimate how the motion would affect the machine's balance. In the context of excavators, four out of seven excavator operators excluded the visualization design that indicates the undercarriage direction (see Figure 5.3), even though this visualization design was recognized instantly and did not require further revision. The operators explained that this visualization design was considered unnecessary for experienced operators, but could be useful for novice operators.

Putting the disagreement among the operators aside, each operator included at least three visualization designs to be presented on the windshield. Out of ten visualization designs that were proposed, only the relative lifting capacity (see Figure 5.4) that was included by all the operators, as this kind of information was considered very important to prevent the machines from collapsing.

5.5 Transforming One of the Proposed Iconic Design into a Functioning Prototype

This section addresses "RQ5. How can the proposed iconic designs be transformed into a functioning prototype?" described in Chapter 2. This section presents the outcome of the high-fidelity prototyping (see Section 4.8).

Considering the main findings from the exploratory usability tests (see Section 5.4), I decided to build a high-fidelity prototype in order to demonstrate the realization of the proposed design. As described in Section 4.8, I selected the revised design of the relative lifting capacity (see Figure 5.4) as the information to be visualized using the prototype. I made this decision, since this information is applicable for both types of machines and also because all the operators considered this information as important to prevent their machines from collapsing.

We developed the high-fidelity prototype in two versions: virtual and physical. For the virtual prototype, we used the mobile crane simulation made in the Unity game engine, and then placed the revised design of the relative lifting capacity on the windshield of the virtual mobile crane (see Figure 5.5). As shown in Figure 5.5, the virtual prototype presented three kinds of information about the virtual mobile crane:

1. The upper numbers indicate the current boom length measured in meters.
2. The lower numbers indicate the current load radius measured in meters.
3. Ten blocks that represent the lifting percentage. Each of the block indicates 10% of the lifting percentage.

The current boom length and the current load radius are relevant to show, as they constantly influence the maximum weight that a mobile crane is permitted to lift. In principle, the maximum lifting capacity is decreasing if the boom length and the load radius are increasing, and vice versa. Here, the lifting percentage

Figure 5.5: The view taken from inside the cabin of the virtual mobile crane. We placed the visualization that indicates the relative lifting capacity on the right side of the front windshield.

was calculated by using the weight of the lifted load divided by the maximum lifting capacity, and then multiplied by 100. Since each block indicates 10% of the lifting percentage, one block is illuminated if the lifting percentage is anywhere between 0.1% and 10.0%. For example, when the lifting percentage is 20.1%, then the first three blocks from the bottom are illuminated. To prevent the machine from collapsing, operators need to ensure that the top block is not illuminated, since that means the mobile crane is approaching its limit.

As described in Section 4.8, the physical prototype was made using off-the-shelves components. The outcome of the prototyping process showed that it was possible, to some extent, to visually realize the proposed visualization design (see Figure 5.6). However, it is important to note that some minor changes had to be made due to the physical constraints of the materials that I have selected. Firstly, instead of having straight lines, I had to be satisfied with having dotted lines, since the wiring between the LEDs took some space. Secondly, due to the size of the LEDs, the numbers that indicate the boom length and the load radius became slightly bigger than what I initially planned.

To make the physical prototype functional, I connected the mobile crane sim-

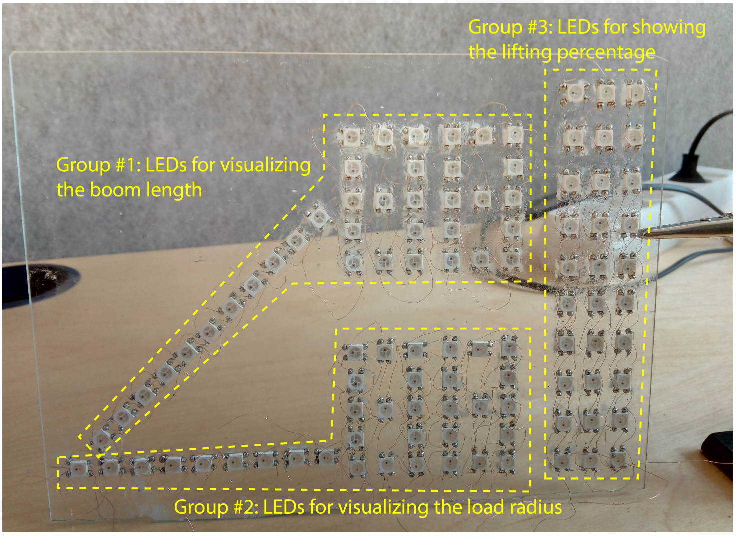


Figure 5.6: The LEDs were attached on a glass and arranged to visually resemble the visualization design of the relative lifting capacity. The LEDs were divided into three groups and each group was assigned to visualize specific kinds of information. This figure also appears in **Paper F** [135].

ulation and the Arduino using the Uduino plugin. This approach enabled the physical prototype to replicate the same information presented on the virtual prototype (see Figure 5.7 for the examples). The information on the physical prototype automatically changed whenever the information in the virtual prototype changed. Using this approach, we were able to simulate how the physical prototype would work in a real mobile crane, even though it was not installed in a real mobile crane.

To further describe how the prototype would work, I present two examples that demonstrate how the situation inside the mobile crane simulation would be reflected on the physical prototype. Note that the virtual mobile crane was using a 4.8-tonne counterweight and lifting a 1-tonne load in both examples. As shown in the left image of Figure 5.7, the boom length and the load radius of the virtual mobile crane were respectively 19 meters and 14 meters. The maximum lifting capacity for these states was 6.3 tonnes, and thus 15.87% of the maximum lifting capacity was occupied in order to lift a 1-tonne load. Since the value of 15.87% is between the interval of 10.1% and 20%, the first two LED rows from the bottom were illuminated. The right image in Figure 5.7 shows that the boom length and the load radius of the virtual mobile crane were respectively 36 meters and 30 meters. The maximum lifting capacity for these states was 1.2 tonnes, and thus

Figure 5.7: The examples that show the integration between the virtual transparent display and its physical counterpart. The physical prototype would present the same information as the information presented on the windshield of the virtual mobile crane. This figure also appears in **Paper F** [135].

83.3% of the maximum lifting capacity was occupied in order to lift a 1-tonne load. Since the value of 83.3% is between the interval of 80.1% and 90%, the first nine LED rows from the bottom were illuminated. More information about the produced prototype can be found in **Paper F**.

Chapter 6

Discussions

This chapter consists of four sections. Section 6.1 presents my reflections on the methods that I had employed throughout my doctoral research. Section 6.2 discusses design implications that are relevant to know if other researchers and practitioners are interested in using self-emitting transparent displays in the heavy machinery domain. Section 6.3 assess the quality of research described in this dissertation based on the criteria mentioned in Section 3.5. Finally, Section 6.4 emphasizes limitations in my research and outlines possible future work beyond this dissertation.

6.1 Reflections on the Employed Methods

This section presents my reflections on the methods that I had employed throughout my doctoral research.

6.1.1 Using Available Videos on the Internet as a Means to Understand the Current Practice of Operating Heavy Machinery

By analyzing relevant videos on YouTube, I was able to obtain broad knowledge about the current practice of operating heavy machinery, for example, the operational procedures, the worksite conditions, and the possible issues in heavy machinery operations (see Section 5.1). Moreover, through the videos that were recorded using cameras attached on top of the operators' heads, I was also able to observe with my own eyes that operators generally paid less attention to the head-down displays inside the cabin, as they spent most of their time looking through the windshield. Similar findings could surely be obtained by referring to the literature, such as [62, 149, 160], but obtaining this finding with my own observation gave me confidence to investigate this particular problem. Nevertheless, having explicit understanding about operators, their tasks, and their working environments fits nicely with one of the principles in human-centered design [64].

To evaluate the effectiveness of this method, we compared the findings from this method with the findings from five field studies in related contexts [62, 104, 133, 140, 160]. Compared to traditional field studies, this method has advantages in terms of large and diverse datasets, flexibility, safety, privacy, and the lack of intrusiveness. On the other hand, this method has disadvantages in terms of the lack of immersion of being on-site, missing interaction with the operators, and the fact that the visual information is limited to the video resolution. Nonetheless, since this method was originally chosen due to the lack of access to professional operators and the lack of domain knowledge, I could say that this approach has served its purpose really well. Moreover, it is also interesting to find that this approach becomes more relevant, especially during the ongoing COVID-19 pandemic, since many researchers currently have difficulties to conduct traditional field studies.

As presented in Section 4.4, I decided to focus on mobile cranes and excavators for the remaining of my doctoral research. Although the online ethnography was about forest harvesters, some of the findings are extensible to other types of heavy machinery. For example, regarding the finding about where operators are looking at when operating their machine, I expect that a relatively similar finding could still be obtained even if we change the type of heavy machinery that we want to investigate. Wallmyr [160] used eye tracking to investigate how frequent operators of forestry harvesters, wheel loaders, excavators, and dump trucks glanced at the head-down display inside the cabin. He found that the glance frequencies at the head-down display were relatively low across different types of heavy machinery.

6.1.2 Evaluating the Impact of Different Information Placements through the A/B Test

The results from the A/B test suggested that bringing information closer to the participants' line of sight helped them to perceive the information more frequently and also produced lower workload (see Section 5.2). This finding is aligned with the findings from an excavator study that using head-up display produced lower workload [3]. Similar findings have also been reported in the automotive domain that the use of head-up displays helped the participants to perceive the information [2] and produced lower workload [99].

Despite the positive impacts, bringing the information into the participants' line of sight did not always make the information detected by the participants. There seems to be a pattern that the information acquisition was dependent on the need for support and the current workload. For instance, in the beginning of the test scenario, the situation was relatively simple and the participants were reactive to the information presented on the head-up display and the projection display. As they approached the more complicated parts (see between the sand pile to final piles in Figure 5.1), the participants had to pay more attention to the machine's surroundings. Here, some of the participants consciously glanced at the displays as they moved, while others checked the presented information when their eyes naturally passed the displays. In the latter case, the participants were more prone to miss the presented information.

6.1.3 Using Safety Guidelines to Derive the List of Critical Information

To determine what kinds of information to be presented on the windshield, I referred to eight safety guidelines [16, 56, 80, 85, 105, 106, 121, 145], which were published by five government agencies, one professional association, one training institute, and one manufacturer from different parts of the world. Using this approach, I was able to indirectly consider what other stakeholders would emphasize with respect to safety in these two machines. This approach is aligned with human-centered design, which emphasizes the consideration of other stakeholders in addition to the user [64].

It is important to note that the safety guidelines were selected based on their availability on the Internet. Although these safety guidelines provide extensive information, there is no guarantee that they cover all possible safety aspects in operations of mobile cranes and excavators. On the other hand, gathering the same amount of information directly from operators would be an enormous work and there is also no guarantee that the information from a handful of operators would cover all possible aspects in these two machines. Although we could obtain rich information from experienced operators, note that much of their knowledge could be tacit, and thus their knowledge may not be easily articulated [24, 158]. It requires a well-trained person in the domain of interest in order to uncover information from what is not explicitly stated [20].

As part of the exploratory usability tests presented in Section 5.3, I presented the list of critical information that I have derived from the safety guidelines to the operators. I then asked the operators if there was any safety-related information that they would like to have, but was not presented here. All the operators commented that the presented list of critical information was sufficient. Some of the operators even commented that a few of the presented information was not really critical, and thus could be removed. Taking this feedback into account, I could say that reviewing the safety guidelines was an efficient method to derive the list of critical information, which we then used as the boundary of our design space in the design workshops (see Section 4.6).

6.1.4 Using a Commercially Available Display Technology to Inform Our Visualization Designs

The visualization designs, which were proposed and evaluated in the exploratory usability tests, were made by taking into account the visual appearance and technical constraints of a commercially available display technology called self-emitting transparent displays. As mentioned in Section 5.3, this display technology was chosen because of two notable benefits. Firstly, as the display is attached on the windshield, operators do not need to wear an additional equipment. Secondly, since the light is self-emitted, the information is generally visible in bright environments [1]. Head-mounted displays were not selected, since operators must wear protective helmets and wearing multiple headgears would give uncomfortable experience to operators. Although latest head-mounted displays usually offer better ergonomics, they are still not comfortable enough for long-hour usage [22, 131]. Projection head-up displays have the same advantage as self-emitting transparent displays, since they also do not require operators to wear an extra equipment. However, as this display technology relies on the light reflection, the projected information may deteriorate in bright environments [153]. This issue was also reported in the experiments that used projection head-up displays in heavy machinery (see Section 5.1). Taking this into account, projection head-up displays were not selected as well.

From the literature review, I found that the majority of the reported experiments were done entirely virtual, and thus no physical prototypes were built to demonstrate the possible realization of the proposed visualization (see Section 5.1). Using this approach, other researchers were able to demonstrate their visualization ideas and conduct their experiments, but it is also unclear what kind of display technologies that should be used and what kind of trade-offs that should be dealt with. By making visualization designs that considered visual appearance and technical constraints of an available display technology, I aimed to propose something that could actually be deployed not only in simulated environments, but also in real machines at a later stage.

6.1.5 Evaluating the Proposed Visualization Designs in the Form of Paper Prototypes

In usability tests that use paper-based prototypes, there is usually a person who acts as a facilitator and this facilitator would arrange paper prototypes based on participants' inputs [27, 139]. I slightly changed the role in the exploratory usability tests, where the operators were asked to move the provided tools according to the papers that I presented. By interacting with the provided tools, it was easy for the operators to demonstrate their understanding, as they could just move the tools to show what they meant. Although all the involved operators were fluent in English, many of them had difficulties in describing specific things related to the machines, for example, undercarriage or counterweight, in English. This situation was understandable, as their working languages were not English. Using this arrangement turned out to be very effective in this kind of situation, since we could communicate through the tools, instead of relying on verbal communications only. Therefore, misunderstandings between the operators and I as the facilitator could be avoided.

I used paper prototypes to present and evaluate the visualization designs, as it was easy to incorporate any feedback into the visualization designs [7, 120]. This approach was also in contrast to the common research practice in the heavy machinery domain, where operators were involved when the proposed visualizations have been developed and researchers wanted to conduct their experiments (see Section 5.2). Through the exploratory usability tests, I managed to get valuable feedback on how the proposed visualization designs should be revised to better match with the operators' way of thinking (see Section 5.4). The involvement of mobile crane and excavator operators in the exploratory tests and the fact that their feedback were incorporated into the visualization designs are aligned with human-centered design [64].

6.1.6 Making Artifacts as a Way to Generate Knowledge

The overarching methodology in this dissertation is research through design, in which the production of artifacts could also lead to new knowledge [174, 175]. The physical prototype shown in Figure 5.6 and Figure 5.7 is the final outcome of this research project. As the final artifact has been produced, what kinds of knowledge could be obtained from this artifact? In the simplest sense, the artifact is the answer to the "how (insert the name of the artifact) can be designed?" question [58, 88]. If I have to invent one "how to design" question for the final artifact, the question would be something like the following:

How to design an effective visualization of relative lifting capacity using a display technology that could present information near operators' line of sight and would also fit into the working environment of mobile cranes and excavators?

As an artifact has multiple facets, it could also answer questions from different perspectives [141]. For example, Zimmerman and Forlizzi [174] state that designers integrate at least three types of knowledge when designing artifacts: (1) technical opportunities to realize artifacts, (2) behavioral knowledge about prospective users, and (3) knowledge about real-world situations that artifacts are supposed to fit into. Following this division of knowledge, I could invent one question that relates to each type of knowledge:

1. Technical knowledge: how to build a self-emitting transparent display prototype that visualizes the relative lifting capacity of mobile cranes and excavators?
2. Behavioral knowledge: how to visualize the relative lifting capacity that matches with the way of thinking of mobile crane and excavator operators?
3. Real-world knowledge: what are the factors that influence the relative lifting capacity of mobile cranes and excavators?

Although the final artifact presented in Section 5.5 could serve as an answer to each of the questions mentioned above, note that it is not the only possible answer. I made many decisions throughout the design process and each decision led me towards the final artifact in this dissertation. The final artifact would be different if I take different decisions along the process, such as choosing other display technologies, coming up with different visualization designs than what is presented in this dissertation, or involving less or more operators, just to name a few. Therefore, the final artifact in this dissertation should be seen as one design proposal out of many design proposals that could possibly exist.

Then the question is, what makes this particular design proposal relevant for the problem of information visualization in heavy machinery? Based on the findings from my own research and the scientific literature, there are some benefits that could be expected from using the final artifact. Firstly, as the final artifact is meant to be installed on the windshield, it would help operators to perceive information more easily, compared to using head-down displays. This assumption was based on the findings from the heavy machinery domain (see Section 5.1) and the results of the A/B test (see Section 5.2). Consequently, using the final artifact would help operators to achieve Level 1 SA, since this level of situation awareness is about the ability to perceive information from the environment [30]. Secondly, through the exploratory usability tests, I have found that the visualization design for the relative lifting matched relatively well with the operators' way of thinking. Based on this finding, using the final artifact would help operators to achieve Level 2 SA, since this level is about the ability to understand the meaning of information with respect to the ongoing situation [29]. Finally, it is briefly described in Section 3.3 that more complex information led to higher mental workload [147]. Considering the fact that there was a match between the visualization design and the operators' way of thinking, as well as based on the finding reported in the scientific literature, there is thus a reasonable indication that the final artifact would cause an acceptable level of mental workload to operators.

6.2 Implications for Design

Through the exploratory usability tests described in Section 4.7, I have obtained insights on which information that the operators would like to have and where the information should be presented. In this section, I want to present some notable comments that I received from the operators and discuss to what extent the given comments could be technically and reasonably realized.

6.2.1 Which Information Should be Presented on the Windshield?

As briefly mentioned in Section 4.6, the information presented using self-emitting transparent displays cannot be changed once the display has been manufactured [1]. This technical constraint plays an important role, since the number of transparent displays installed inside the cabin would be equal to the number of information that we would like to present. This can be seen from the physical prototype presented in Section 5.5, which was specifically designed to visualize the relative lifting capacity. Assuming that we want to visualize another type of information, then another prototype would need to be produced.

Considering the technical constraint mentioned above, it is important to know which information that the operators would like to have, as there are limits on how many chunks of information that people could handle simultaneously. Miller [101] proposed the number of 7 ± 2 as the limit, while other researchers suggested four [19] and two [50] as the limits. As part of the exploratory usability tests (see Section 4.7), I gave an opportunity to the operators to exclude any information that they deemed less necessary and asked them to explain the reasons behind their decisions. From this activity, I was able to determine which information that should be presented on the windshield and understand the rationales for presenting the selected information.

Despite the diverse opinions among the operators, all the operators would like to have at least three types of information to be presented on the windshield. The most desirable one was the relative lifting capacity (see Figure 5.3), which was considered important by all the operators of both mobile cranes and excavators. The second place was the proximity warning (see Figure 5.3), where one excavator operator excluded this information due to the complexity of its visualization design. The remaining operators agreed that the proposed visualization design was still complex, but they decided to include the proximity warning due to its importance to prevent collisions with nearby objects. The third place was the balance-related information (see Figure 5.3), in which one excavator operator and one mobile crane operator excluded this information. The excavator operator commented that he could feel the machine's balance through the machine's movement, and thus this type of information was considered unnecessary. Interestingly, six out of seven excavator operators who included this information also commented a similar thing, but they explained that it would be nice to have something that could validate their gut feeling. The situation was slightly different in the context of mobile cranes, where five out of six operators preferred the outrigger-based visualization design (see the balance-related information for mobile cranes only in Figure 5.3). However, only four of them who wanted to have this particular visualization on the windshield, since the remaining two considered having this information on the windshield as redundant, as the head-down display in their machines already presents something similar.

Although the examples of opinions mentioned above were given for the proximity warning and the balance-related information only, they represent the whole discussions regarding which information should be presented on the windshield. Whether it was for accepting or refusing something, all the operators had reasonable motivations for doing so. See **Paper D** and **Paper E** for the complete discussions regarding which information that should be presented in mobile cranes and excavators, respectively. Therefore, it is probably best to say that there is no single correct answer that would apply to all mobile crane and excavator operators. As such, designers need to consult operators before placing the information on the windshield, so that the presented information would match with operators' needs. Nevertheless, the three types of information discussed in this section could be a good starting point. Furthermore, considering the limits on how many chunks of information that people could handle simultaneously, having at most three types of information to be presented on the windshield seems to be a reasonable number.

6.2.2 Where Should the Information be Presented on the Windshield?

In the end of the exploratory usability tests (see Section 4.7), I asked the operators to indicate which areas of the windshield that their preferred types of information should be presented (see Figure 4.8 for an example of this activity). Note that, in this activity, I did not inform the operators about technical limitations of self-emitting transparent displays.

Based on the placements that the operators have made, I could observe that the operators generally would like the information to be presented near the border of the windshield. In other words, the information should be presented peripherally. See Figure 6.1 and Figure 6.2 for the placements in mobile cranes and excavators, respectively. All the operators commented that the central area must be clear from any obstruction, otherwise it would harm their operations. This finding is technically suitable with how commercial self-emitting transparent displays are usually installed. Although the display is transparent, the electronic components that power and control the display are not transparent [1]. Hence, the display is

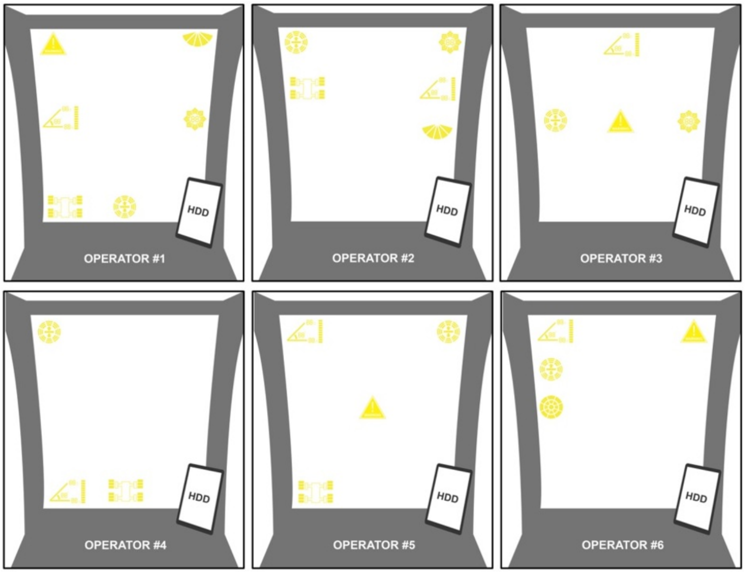


Figure 6.1: These images show which information that the mobile crane operators would like to have and where the information should be presented on the windshield. Note that "HDD" refers to the head-down display that already exists inside the cabin and the visualization designs presented here are the ones before revision. This figure also appears in **Paper D** [134].

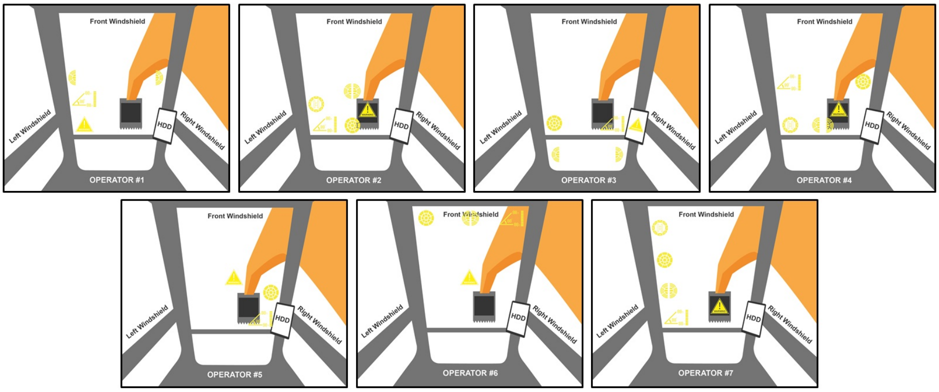


Figure 6.2: These images illustrate what kinds of information that the excavator operators would like to have and where they should be presented on the windshield. Note that "HDD" refers to the head-down display that already exists inside the cabin and the visualization designs shown in this figure are the ones before revision. This figure also appears in **Paper E** [138].

usually placed next to non-transparent structures, for example, on the car's dashboard [89], so that the display's non-transparent components would not occlude the windshield. This technical constraint was also the reason why I placed the relative lifting capacity next to the border of the windshield of the virtual mobile crane (see Figure 5.5).

Although the operators generally wanted the information to be presented peripherally, there seems to be one exception to this statement. Two mobile crane operators and five excavator operators would like to have the generic warning sign to be presented near the central area (see Figure 6.1 and Figure 6.2). Since the generic warning sign is meant to indicate that an incident is imminent to occur (see Section 5.3), these operators commented that placing the generic warning sign near the central area would enable them to notice it immediately. This preference is thoughtful, but may not be practically suitable due to the technical limitation mentioned in the previous paragraph. Regarding where the remaining types of information should be presented, I unfortunately could not get a firm indication, since the operators' preferences were quite diverse.

Specifically for excavators, the operators also commented that the information placement is highly influenced the operation being performed. For example, the operators would spend most of their time looking down in digging operations, and thus having the information presented on lower positions would be useful. On the other hand, the operators would mostly look above in lifting operations, and thus it would be useful to have the information presented on higher positions. The operators further commented that it would be great if the information could be moved around the windshield depending on their needs. Although this suggestion is well-founded, it is not something that could be easily implemented. Self-emitting transparent displays are meant to be installed in one fixed place, which is in a way similar to how head-down displays and projection head-up displays are installed inside the cabin. Changing the placement of transparent displays is technically possible, but operators would need the help from a technician to do so.

6.3 Assessing the Research Quality

This section presents the criteria for evaluating the quality of a research through design project (see Section 3.5) and discusses to what extent the research presented in this dissertation has fulfilled the evaluation criteria.

6.3.1 Validity

To evaluate the validity in this dissertation, I used the five types of validity proposed by Krippendorff [75] that designers could use to support their claims. Here, the five types of validity are ordered from the lowest to the highest validity.

Demonstrative Validity

Demonstrative validity refers to whether the produced artifact could indicate how it is supposed to function and what kind of qualities that it could have [75]. Considering that the final artifact is functional in both physical and virtual forms, operators could observe its properties and functionality. Therefore, the final artifact fulfills this level of validity.

Experimental Validity

This kind of validity refers to whether the produced artifact could afford interaction with its prospective users in a way that designers could empirically assess how prospective users would benefit from the artifact [75]. Although this dissertation does not report an empirical study using the final artifact, the virtual version of the final artifact could afford interaction with operators in a way that an empirical study within a virtual environment could be conducted. However, more work is still needed to make the physical artifact usable in an empirical study in a real-world setting, for instance, installing the physical artifact in a real mobile crane. Therefore, the final artifact partially fulfills this level of validity.

Interpretative Validity

Interpretative validity means that the kind of qualities that an artifact has is justified based on established theories and published findings from relevant scientific disciplines [75]. As discussed in Section 6.1.6, there are several benefits that could be expected from using the final artifact and all of them were inspired from the findings from my prior studies and the scientific literature. This indicates that the final artifact fulfills this level of validity.

Methodological Validity

Methodological validity is determined by two criteria: (1) designers could show that they have explored most possible alternatives before proposing the final artifact and (2) they have consulted the right stakeholders [75]. Throughout the design process, I have considered many possible alternatives, including different display technologies, various kinds of information to be presented, and different visualization designs. When deciding which alternatives to proceed with, I grounded my decisions based on the relevant aspects of heavy machinery operations. When deciding which display technology to be used, I relied on operators' feedback that were reported in the scientific literature. In terms of deciding which information to be presented, I relied on the findings from eight relevant safety guidelines. Finally, I involved thirteen operators in order to evaluate and improve the proposed visualization designs. The number of operators involved in the design process was also higher than the reported numbers in the literature, where the average number was six operators and the highest number was eleven operators (see Section 5.1). All these suggest that the process of designing the final artifact is methodologically valid.

Pragmatic Validity

Pragmatic validity is the validity that would be achieved if relevant stakeholders are willing to adopt the proposed artifact [75]. Since the final artifact has not been adopted by the stakeholders, this level of validity is not achieved.

6.3.2 Process Transparency

Process transparency refers to whether the procedure of employing specific methods and the rationale for choosing them are sufficiently described [175]. It was particularly difficult for me to assess the transparency of my own design process, since there may be things that I took for granted. Nevertheless, taking into account that all the papers used to form this dissertation passed the peer-review process, I could assume that the process documented in the individual papers had an acceptable level of transparency.

In this dissertation, I used Chapter 4 to describe the methods that have been employed throughout the whole design process. In addition to describing the process of conducting the selected methods, I also used Chapter 4 to describe the reasons for selecting them, the work distribution between my co-authors and I, as well as how the findings from the previous methods motivated and influenced the subsequent methods. These descriptions are provided so that readers could understand what happened throughout the whole design process.

6.3.3 Significant Invention

Significant invention is determined by two factors: (1) whether the artifact is developed after considering relevant knowledge and (2) whether the artifact is well-situated with respect to the state of the art [175]. As discussed in Section 6.1.6, the process of designing the final artifact was done by integrating the knowledge about operations of mobile cranes and excavators, the knowledge about what is technically and practically possible, and the knowledge about the operators' way of thinking. The idea of using self-emitting transparent displays as the inspiration of the final artifact was motivated by the findings from the literature review, in which the use of this display technology in the heavy machinery domain is still underexplored. All these suggest that the final artifact presented in this dissertation could be considered as a significant invention.

6.3.4 Relevance

Relevance refers to whether the motivation for investigating the research question, the description of the current situation, and the reason why the proposed future is the desired one are sufficiently described [175]. Chapter 1 presents the general situation in modern heavy machinery and the situations related to mobile cranes and excavators. Chapter 2 presents the list of research questions in this dissertation, including the description about why it is relevant to investigate each of them. Finally, Section 6.1.6 presents the expected benefits that operators could obtain from using the final artifact. All these indicate that the research described in this dissertation is relevant.

6.3.5 Extensibility

Extensibility refers to the ability that other researchers could utilize contributions of a research project for their own research [175]. To do so, research contributions should be documented and disseminated to the community. Considering that all the papers used to form this dissertation were published, other researchers could use the research contributions documented in the published papers for their own research. This implies that my research contributions are extensible.

6.4 Limitations and Future Work

Fifteen non-operator participants were involved in the A/B test study described in Section 4.2. It is of interest to replicate the same A/B test by involving professional operators to validate whether the existing findings would remain applicable or not. In the context of tele-operating cranes, Chi et al. [14] found that the crane operators and the non-operator participants required a similar amount of time to complete the given task. However, they observed that the crane operators performed the given task more cautiously, compared to the non-operator participants. In the context of underground drillers, Aromaa et al. [5] found that the expert participants spent more time to complete the given the task, compared to the novice participants. They noted that the novice participants paid less attention to the small details, and thus they completed the given task more quickly. On the other hand, the expert participants required more time, as they completed the given task with higher precision.

The exploratory usability tests described in Section 4.7 were still limited to determining to what extent the proposed visualization concepts matched with the operators' way of thinking. To further investigate the impact of the proposed visualization designs on operators' performance, a comparative evaluation study in certain operation scenarios, such as the A/B test in Section 4.2, would be needed. Unfortunately, at the time this dissertation was written, the operators that I was acquainted with were still reluctant to participate due to the ongoing COVID-19 pandemic.

In the effort to demonstrate the possible realization of the proposed visualization design, I developed a physical prototype of transparent displays (see Section 5.3). Since I had no access to real mobile cranes, I decided to integrate the physical prototype with a mobile crane simulation to demonstrate its practical feasibility. To further demonstrate its applicability in real machines, it would also be interesting to try installing the physical prototype on real machines. However, this work is beyond the scope of this dissertation.

As briefly described in Section 6.2.1, one excavator operator mentioned that he could know the the machine's balance based on the machine's movement, and thus he did not need the visual version of this information. This comment suggested that other modalities, such as haptic and probably auditory as well, could also be used as an alternative or complement to the visual information. Using different modalities as a way to relieve workload from the compromised or overwhelmed visual channel is an obvious idea, since the different modalities compete for different cognitive resources [32]. However, as briefly described in Section 1.1, heavy machinery generally produces loud noise and strong vibration due to working engines and performed operations [12, 13, 129, 162] and these factors could potentially reduce the effectiveness of haptic and auditory information. Therefore, to what extent the use of multiple modalities to support operators' information processing and prevent information overload is an open research area by itself.

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Chapter 7

Conclusion

The research theme in this dissertation is how supportive information in heavy machinery could be presented closer to operators' line of sight. Therefore, operators could acquire supportive information without diverting their attention away from the operational area. This was motivated from prior studies that indicate operators generally pay little attention to supportive information presented using head-down displays. Furthermore, prior studies also indicate that operators spend most of their time looking through the windshield, and thus the windshield could be used as a potential space for presenting supportive information. Although bringing supportive information closer to operators' line of sight has possible merits, this approach also has the potential to distract operators from their work. In order to avoid such disadvantage, there is a need to present information cautiously, where the right information is presented in the right form, at the right time, and at the right place.

Following the research through design methodology, I have developed one final artifact that could be placed on the windshield of heavy machinery. The final artifact presents information about the relative lifting capacity, which was considered as a very important piece of information in lifting operations by the operators. The information shown on the final artifact was also visualized with the right form, which was determined based on the feedback from the operators. Although I did not obtain a precise indication on the best area to place the final artifact on the windshield, the operators seem to want the information to be presented near the border of the windshield. This placement was deemed suitable, since the central area should be clear from any obstruction and they could still see the information peripherally. Although the final artifact has not been evaluated yet, there are some benefits that could be expected based on the findings from my prior studies and the scientific literature. Firstly, as the final artifact is meant to be installed on the windshield, it would allow operators to perceive the information more easily, and thus helping them to achieve Level 1 SA. Secondly, as the information was visualized with the right form, it would help operators to understand the meaning of the presented information, and thus supporting them to achieve Level 2 SA and processing the presented information would cause an acceptable level of workload.

In addition to the final artifact, which was published in **Paper F**, there are four more scientific contributions that were generated from the process of designing the final artifact. Firstly, an example of how online ethnography could be used as a method to study heavy machinery operators in natural settings (see **Paper A**). Secondly, an empirical study in the excavator context that suggests bringing information near line of sight produced better information acquisition and lower workload (see **Paper B**). Thirdly, a comprehensive overview of prior research that attempted to bring information closer to line of sight in the heavy machinery domain (see **Paper C**). Lastly, the visualization designs for ten types of critical information that matched with the way of thinking of mobile crane and excavator operators (see **Paper D** and **Paper E**).

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