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Supporting Time-Critical, Parallel, and Spatially Distributed Tasks Using Augmented Reality

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Zusammenfassung

In vielen industriellen Bereichen, insbesondere in der manuellen Fertigung, sind bestimmte Aufgaben auch bei fortschreitender Automatisierung noch immer von Menschenhand zu erledigen. Insbesondere Aufgaben wie der Zusammenbau von Bauteilen oder das Kleben erfordern oft eine Anpassungsfähigkeit, die die derzeitigen Automatisierungsmöglichkeiten übersteigt. Diese Aufgaben werden in der Regel unter Zeitdruck durchgeführt, wobei mehrere parallele Prozesse an verschiedenen Arbeitsplätzen ablaufen. In manuellen Produktionsumgebungen müssen beispielsweise mehrere Komponenten gleichzeitig geklebt, montiert und geprüft werden. Diese Komplexität wird durch die Notwendigkeit erhöht, diese Prozesse schnell, präzise und unter Einhaltung der Sicherheitsstandards durchzuführen. Darüber hinaus müssen Werker:innen häufig zwischen verschiedenen Arbeitsplätzen wechseln, z. B. zwischen Klebe-, Montage- und Qualitätskontrollstationen, was die Ausführung der Aufgaben zusätzlich erschwert. Der Erfolg hängt dabei von der Fähigkeit ab, komplexe Informationen schnell zu verarbeiten, Entscheidungen zu treffen und flexibel auf kritische Ereignisse zu reagieren.

In dieser Dissertation betrachten wir einen industriellen Anwendungsfall der manuellen Fertigung mit dem Schwerpunkt Kleben als repräsentatives Beispiel für die Bewältigung zeitkritischer, paralleler sowie räumlich verteilter Aufgaben. Dabei schlagen wir Augmented Reality (AR) vor und untersuchen, wie die Unterstützung gestaltet werden sollte, um die Komplexität dieser Aufgaben zu reduzieren. Wir verfolgen den Ansatz des Human-Centered Designs, wodurch wir bei der Entwicklung und Evaluation die potenziellen Anwender:innen zum Ausgangspunkt und zum Maßstab der Gestaltung machen. Dazu analysierten wir den Nutzungskontext durch direkte Beobachtung sowie Experteninterviews und identifizierten zentrale Herausforderungen wie die zeitliche Steuerung der Klebstoffaushärtung und die räumliche Ausrichtung der Fertigungsaufgaben. Aus den gewonnenen Erkenntnissen wurden drei Forschungsfragen abgeleitet, die im Rahmen der Dissertation untersucht werden sollen: (RQ1) Wie können zeitkritische und parallele Aufgaben innerhalb des Sichtfeldes visualisiert werden?, (RQ2) Wie kann die Aufmerksamkeit auf zeitkritische, parallele und räumlich verteilte Aufgaben außerhalb des Sichtfeldes gelenkt werden? und (RQ3) Wie können zeitkritische, parallele und räumlich verteilte Aufgaben überblickt werden?

Unsere Ergebnisse zeigen, dass AR die Komplexität von zeitkritischen, parallelen sowie räumlich verteilten Aufgaben reduziert und Anwender:innen bei der Ausführung unterstützt. Wir konnten zeigen, dass AR bei der Bearbeitung zeitkritischer Aufgaben bevorzugt wird und zu kürzeren Ausführungszeiten führt. Außerdem fanden wir heraus, dass die Visualisierung mehrerer Aufgaben gleichzeitig zwar die Gesamtausführungszeit reduziert, aber auch die kognitive Belastung erhöht. Wenn zeitkritische und parallele Aufgaben zusätzlich räumlich verteilt sind, reichen ortsgebundene AR-Visualisierungen nicht aus und die Unterstützung muss durch zusätzliche visuelle Hinweise in der Peripherie erfolgen.

In diesem Zusammenhang konnten wir zeigen, dass bestehende periphere AR-Hinweise mit zeitlichen Informationen kodiert werden können. Darüber hinaus ist ein hohes Maß an menschlicher Anpassungsfähigkeit erforderlich, wenn komplexe Aufgaben übernommen werden müssen, weil der/die ursprünglich zuständige Anwender:in den Arbeitsplatz verlassen muss. Für solche Übernahmesituationen konnten wir zeigen, dass Übersichten mit räumlicher Registrierung in AR die kognitive Belastung erheblich reduzieren und die Aufgabenleistung verbessern können, indem Kontextinformationen direkt in das Sichtfeld der Anwender:innen integriert werden.

Abstract

In many industrial environments, especially in manual manufacturing, certain tasks still need to be performed by humans, even as automation advances. In particular, tasks such as component assembly or bonding often require an adaptability that exceeds current automation capabilities. These tasks are typically performed under time pressure, with multiple processes running in parallel at different workstations. For example, in manual production environments, multiple components must be bonded, assembled, and tested simultaneously. This complexity is compounded by the need to perform these processes quickly, accurately and in compliance with safety standards. In addition, workers must frequently move between different workstations, such as bonding, assembly, and quality control stations, further complicating the task. Success depends on the ability to quickly process complex information, make decisions, and respond flexibly to critical events.

In this dissertation, we consider an industrial use case of manual manufacturing with a focus on bonding as a representative example for the management of time-critical, parallel, and spatially distributed tasks. We propose Augmented Reality (AR) and investigate how support should be designed to reduce the complexity of these tasks. We follow the Human-Centered Design approach, in which the potential users are the starting point and benchmark for the design during development and evaluation. To this end, we analyzed the context of use through observation and expert interviews and identified key challenges such as temporal control of adhesive curing and spatial orientation of production tasks. Three research questions were derived from the analysis, which will be investigated in the dissertation: (RQ1) How can time-critical and parallel tasks be visualized within the field of view?, (RQ2) How can time-critical, parallel, and spatially distributed tasks be guided outside the field of view?, and (RQ3) How can time-critical, parallel, and spatially distributed tasks be overviewed?

Our results show that AR reduces the complexity of time-critical, parallel, and spatially distributed tasks and supports users in their execution. We show that AR instructions are preferred over traditional (paper) instructions for time-critical tasks and lead to shorter execution times. We also found that supporting parallel tasks comes with a trade-off: presenting more than two tasks reduces overall execution time, but also increases cognitive load. When time-critical and parallel tasks are also spatially distributed and users have to switch workstations to perform them, location-based AR visualizations are not sufficient and support must be provided by additional visual cues in the periphery. In this context, we have shown that existing peripheral AR cues can be encoded with temporal information. In addition, a high degree of human adaptability is required when time-critical, parallel, and spatially distributed tasks have to be taken over because the originally responsible user has to leave the workplace. For such take-over situations, we have shown that overviews with spatial registration in AR can

significantly reduce cognitive load and improve task performance by integrating contextual information directly into the user's field of view.

Acknowledgments

I would like to take this opportunity to thank everyone who has supported and inspired me along the way.

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Contents

„The times are very bad. Very well, you are there to make them better.“

[Thomas Carlyle]

1 Introduction

In today's industrial environments, the increasing use of automation has significantly enhanced the efficiency of many work processes. Machines and robots perform routine tasks with high precision and speed, reducing human involvement in areas such as assembly lines and quality control. However, not all tasks can be easily automated. Due to their complexity, some tasks still require a seamless interaction between people, technologies, and processes. Therefore, despite increasing automation, human skills and adaptability remain essential for tasks that require making decisions under time pressure, coordinating parallel activities, or working across spatially distributed stations [Pfe07].

For example, consider a manual manufacturing process, where workers are tasked with assembling components at different workstations. These tasks may include preparing materials, applying adhesives, ensuring proper alignment of parts, and performing quality inspections – all within strict time frames to maintain process continuity. Workers must move between stations, gather tools and materials, and adapt to changing shop floor conditions. The complexity increases when tasks are time-critical, meaning they must be completed within a specific time frame to ensure product quality. In such cases, workers are challenged to manage multiple parallel activities under time pressure, significantly increasing their cognitive load.

Examples of such time-critical industrial tasks include glass manufacturing, where workers must lubricate molds within a certain time frame to prevent production downtime, and adhesive bonding, where components must be joined within a narrow window after adhesive application to ensure proper bonding [Ras12; Hab03]. The challenge of managing time-critical tasks is not unique to manufacturing. In healthcare, for example, time-critical interventions are common in emergency rooms or intensive care units, where medical staff must respond to alarms and treat multiple patients simultaneously [Cob21]. A simple, everyday example is cooking, where timing is critical: rice can become mushy or burnt if overcooked, or undercooked if we are too impatient to wait.

Overall, three main characteristics of task complexity factors can be identified from the manufacturing process described: they are time-critical, meaning they must be completed within a specific time frame; they are often parallel, requiring workers to perform multiple tasks simultaneously; and they are spatially distributed, requiring movement between locations. Managing these tasks requires not only technical skills, but also the ability to process complex information, make quick decisions, and adapt to unforeseen changes. The responsibility here is especially high because missing deadlines or making mistakes can have significant consequences, from material loss to production delays and safety risks. In addition, the cognitive demands of these environments can be overwhelming, as workers must constantly switch between tasks, monitor their progress, and respond to unexpected problems, all within strict time constraints.

In recent years, the use of Augmented Reality (AR) has shown significant potential in assisting workers with complex tasks in industrial environments, improving the efficiency and accuracy of assembly processes [BW19; BV19; CM92]. AR systems overlay digital information onto the real-world environment to provide real-time guidance and assistance to workers. While AR has demonstrated improvements, particularly in the execution of spatially distributed assembly tasks (e.g., [RP17; HS21]), factors such as time-critical constraints [Gow+23] and parallel activities, which further increase the complexity of these tasks, have received little attention. Despite technological advances, the full potential of AR in scenarios involving both time-critical and parallel tasks has yet to be fully explored.

This dissertation addresses this gap by focusing on an industrial use case involving manual production processes, specifically adhesive bonding, to investigate how AR can be used to reduce the complexity and cognitive load of managing time-critical, parallel, and spatially distributed tasks. By integrating AR into such environments, we aim to provide workers with the tools they need to better orient themselves in time and space, ultimately improving task performance and reducing the risk of errors. Through this research, we aim to contribute to the development of more effective AR systems that address the unique challenges of managing complex tasks in modern industrial environments.

Reading Hint:

I would like to use the term „we“ instead of „I“ in this work to avoid passive constructions that are difficult to read. Nevertheless, this work was written by me as the author and contains only contributions that were planned, implemented, and executed by me.

1.1 Motivation and Goals

To introduce and better understand the topic of time-critical, parallel, and spatially distributed tasks, we would like to briefly motivate our work in this section, using the concrete and simplified use case of a cooking process.

In the following, we will describe the preparation of a recipe using Figure 1.1 and then explain the various aspects that appear in the title of this thesis.

For example, let us prepare a vegetarian moussaka with fresh salad in a very simplified way, without specifying quantities. First, slice the eggplant, potatoes, and zucchini. Then chop the onion and garlic (1, 5). Preheat the oven (3). Heat some olive oil in a frying pan and fry the potato, eggplant, and zucchini slices on both sides until lightly browned (4). Meanwhile, precook and soak the lentils (4). While the vegetables are sizzling in the pan and the lentils are precooking, you can wash the lettuce, cucumber, tomatoes, and peppers (2) and cut them into bite-sized pieces (1, 5). Remove the potato, eggplant, and zucchini slices and drain on paper towels (1, 5). In a frying pan, sauté the chopped onion and garlic and add the tomato puree (4). Add the canned tomatoes and precooked lentils to the pan, season with salt, pepper, cinnamon, and oregano and bring to the boil (4). While the tomato sauce is simmering, make the béchamel sauce (4). Gently mix the butter and flour over medium heat, then carefully stir in the milk, salt, pepper, and nutmeg. While the tomato and béchamel sauces are cooking, grease the baking dish (1, 5). Layer the moussaka: one layer of potato slices, one layer of eggplant, one layer of zucchini, and one layer of tomato sauce. Repeat this process until all the ingredients are used up. Finally, pour the béchamel sauce evenly over the last layer and sprinkle with grated cheese. Place the baking dish in the preheated oven and bake the moussaka (3). While the moussaka is in the oven, prepare the salad (1, 5). Place the washed lettuce leaves, cucumber, tomatoes, and peppers in a bowl. To make the dressing, mix the lemon juice, olive oil, salt, pepper, and a little balsamic vinegar in a small bowl and pour over the salad. Toss well and refrigerate until moussaka is ready (6). Meanwhile, clean the countertops and rinse the dishes in the sink. When the moussaka is done, remove it from the oven and let it rest. Then we can arrange everything and enjoy the dish.

This example is a good illustration of the different aspects of this thesis. While we can do some tasks in parallel, such as washing the salad while roasting the vegetables and pre-cooking the lentils, we can get into time-critical situations where we lose sight of the roasting and cooking tasks because we are concentrating on the task of preparing the salad. At this point, however, very few of us would be waiting in front of the stove for the cooking and frying to be done, but would instead be working on other tasks in the recipe. So we work in parallel to bridge the waiting time and finish everything at the same time if possible. The different workstations in our example (1-6) make it clear that the tasks are spatially distributed and that we have to move back and forth between the different workstations to complete each task (cf. Section 2.2 and Section 3.3.2). However, the human field of view (FOV) is limited, so we cannot visually perceive tasks that are, for example, behind us. Again, tasks can become time-critical because we are simply not sensually aware of them at the moment (until we can clearly smell them). At first glance, this simple example may not seem like much of a challenge. However, when this task constellation is transferred from the private sphere to a real work process such as an industrial kitchen, multitasking, speed, and time pressure are the determining stress factors for chefs [LLH21], so that every second chef feels exhausted. For example, chefs report having to perform multiple tasks at the same time, working very quickly and often under pressure to meet deadlines and perform well. This overload can also lead to workplace accidents, such as burns from hot surfaces like the stove or oven. As described in the previous section, the responsibility for completing time-critical tasks is especially high because missing deadlines is not without negative consequences. For example, an industrial kitchen worker may have to throw out a dish, which can result in economic loss.

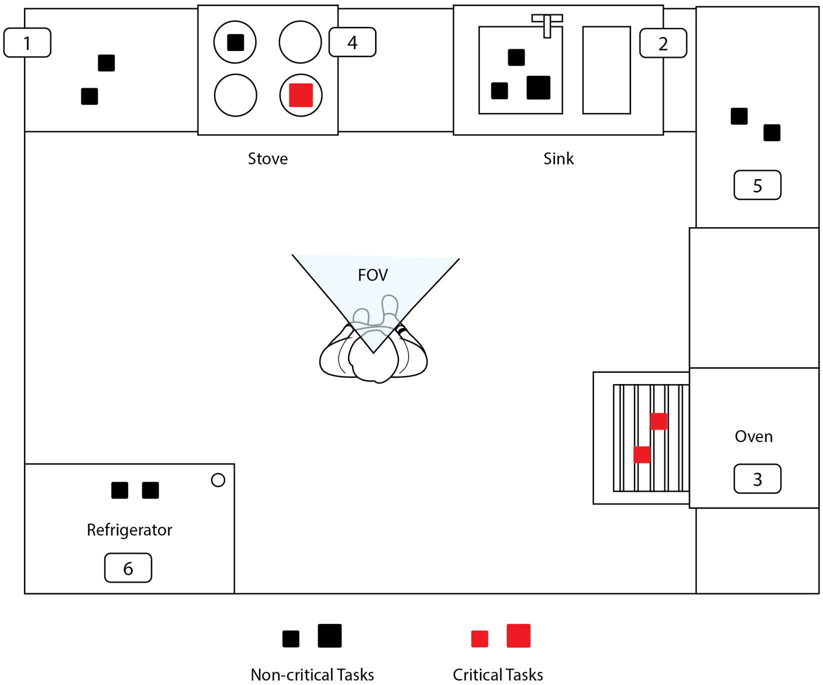


Figure 1.1: Simplified representation of a kitchen with spatially distributed tasks and different numbered workstations with a chef and his/her indicated FOV (own illustration).

Our goal is to reduce the stress factors of time-critical, parallel, and spatially distributed tasks in order to enable people in different work processes to better orient themselves in time and space. In this dissertation, we gradually approach different solutions and consider different challenges to simplify working life and reduce complexity by supporting such tasks (see Section 1.3). We examine how technical support can reduce the complexity of these tasks. As indicated in the previous section, we focus on an industrial use case that is representative of other application areas in order to identify specific challenges and requirements for support. On this basis, we develop research priorities and questions that contribute to overcoming the identified challenges.

1.2 Scientific Approach

Especially when designing support options for safety-critical work scenarios, where failure to perform time-critical tasks can have negative consequences, the specific needs and requirements of users must be taken into account. Due to other factors influencing task complexity, such as spatial distribution and parallel execution of multiple tasks, the design must be such that complexity is actually reduced and people are not faced with additional challenges. To make people and their needs the starting point and benchmark for our design, we use the Human-Centered Design (HCD) process according to ISO 9241-210 [ISO11]. As a participatory process involving users [Mul02; Bod+21], it aims not only to improve technologies and systems, but also to improve people's experiences when interacting with technology.

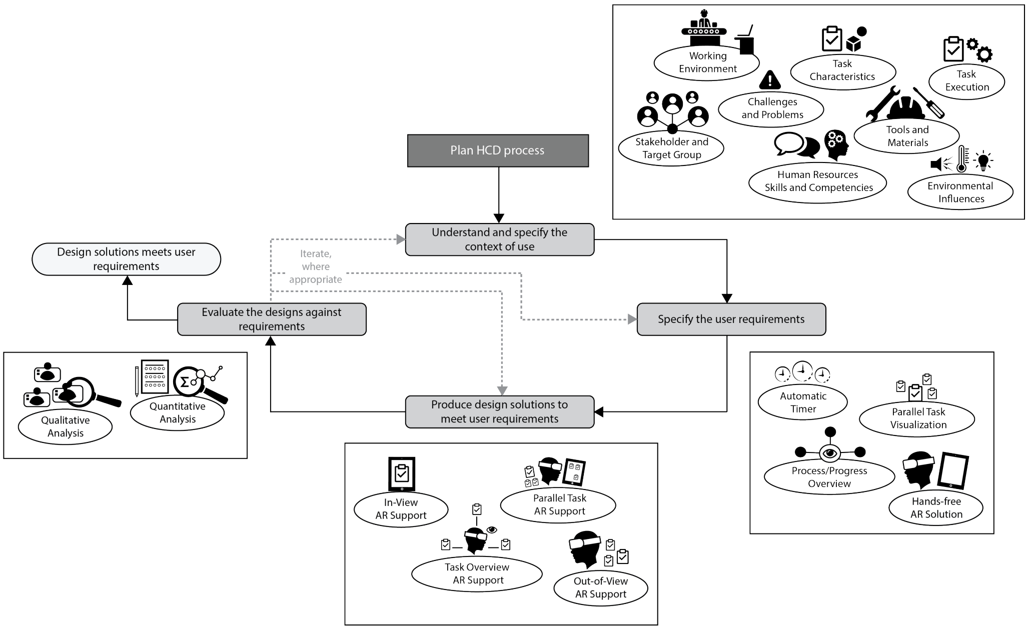


Figure 1.2: The Human-Centered Design Process (own illustration based on ISO 9241-210 [ISO11]).

The HCD process is designed as an iterative, abstract process and is divided into different phases (see Figure 1.2): (1) understand and specify the context of use, (2) specify the user requirements, (3) produce design solutions to meet user requirements, and (4) evaluate the designs against requirements. These phases are iterated to incrementally improve the design [Kru14]. As we conduct basic research by investigating research questions along prototypes, we focus on the design and usability of AR support solutions following the phases of the HCD process. We consider adhesive bonding processes[1] as sub-processes of manual manufacturing and use them as representatives of other work scenarios that have to cope with time-critical, parallel, and spatially distributed tasks (see Section 3.3.3). To ensure the safety of people performing tasks in safety-critical work scenarios, we would like to refer to basic research at this point – for this reason, our results are not evaluated in the field as part of this thesis.

Parts of the work presented in this chapter were published as a paper in the

[1] In the remainder of this thesis, the adhesive bonding process will be abbreviated as the bonding process for ease of reading, although both terms have the same meaning.

journal „Neues Archiv für Niedersachsen“, in 2024 [Alt+24].

Context of Use

The context of use analysis is an important part of the HCD process to better understand the context in which users find themselves. The context is defined based on the users, the tasks, and the organizational, technical, and physical environment [ISO11]. These insights can reveal needs, problems, and limitations that the future system must address. One method in the context of use analysis is to observe users in their natural (work) environment to identify their behaviors, needs, problems, and challenges. To analyze the context of a representative use case for dealing with time-critical, parallel, and spatially distributed tasks, we conducted an observation in a real training environment of a bonding process (see Chapter 2). Our goal was to identify the work processes, tools, protective clothing, materials, and equipment used. This allowed us to observe at which steps of the bonding process potential errors and uncertainties occur on the part of the trainees. The observation was followed by interviews with experts in the field of bonding technology, who gave us a real picture of the manufacturing and assembly processes and confirmed the common sources of error that we had observed.

User Requirements

Determining user requirements and defining functional and other requirements for a system is one of the main activities in most design projects. User requirements define the specific functionalities, properties, and performance characteristics that a system must have in order to provide a suitable solution in the previously analyzed usage context [LHB10]. The context analysis resulted in several requirements for our AR support system (see Chapter 2).

Design Solutions

In this phase of the HCD process, specific design solutions are developed to meet user requirements [ISO11]. In keeping with the process, we adopt an iterative approach to incrementally improve our AR support possibilities. In this context, design concepts improve our understanding of user needs and context, and enable us to explore and evaluate ideas and communicate design decisions [Nis15]. Design concepts can be realized through prototypes, which can vary in their level of detail and functionality. Depending on the level of detail, we can distinguish between low-fidelity and high-fidelity prototypes. The level of detail generally depends on the iteration of the process. Prototypes characterize a design before a final solution exists [Mog06]. Since the development of systems with high functionality is very time-consuming and expensive, we will not go beyond the prototype stage in this work. Our prototypes serve primarily to answer our underlying research questions, and would need to undergo further evaluation phases for use in a real working context. Each research question is addressed in a separate chapter describing the prototypes developed and the results of the study.

Evaluation

The evaluation of (interim) results is a necessary activity in the HCD process. Design and development concepts should be evaluated at an early stage to gain a better understanding of user needs. For this reason, the process includes an evaluation phase after each iteration step.

In the context of this work, the possibilities of our AR support are examined independently of the target group, which we identify in the context of use analysis and subsequent requirements specification. Since we will find out in our context of use analysis that in the real working context of small to medium-sized companies the bonding work is very often done by unskilled personnel, our non-specialized study participants are representative for the evaluation of our AR support possibilities for handling time-critical, parallel, and spatially distributed tasks. For this reason, we sought a broad age range when recruiting our study participants. This approach allowed us to explore our research questions at a fundamental level and to test whether the results could be generalized to other work contexts. Participants in our studies received no compensation and were informed that they could withdraw from the study at any time without negative consequences. All of our studies were conducted as laboratory studies, and our research has been approved by our institute's study board review.

We collected both quantitative and qualitative data for our studies.

Quantitative Data. In our user studies, we collected quantitative data using both subjective and objective measures. We used standardized questionnaires for our subjective measurements, as well as individual Likert items for specific statements that we developed. The standardized questionnaires we used include the System Usability Scale (SUS) questionnaire [Bro96] to assess usability and the NASA Raw TLX (Raw TLX) questionnaire [Har06] to measure subjective workload. The SUS was developed by John Brooke in 1996 and can be used independently of the object of investigation. The questionnaire consists of 10 statements to which participants indicate their agreement or disagreement on a scale of 1 to 5 (1=strongly disagree, 5=strongly agree). Once all statements have been answered, an overall usability score is calculated – the calculated score is between 0 and 100, with higher scores indicating better usability. The Raw TLX was developed by NASA in the 1980s and is a simplified version of the original NASA TLX that can be used to measure people's perceived workload when performing various tasks. In the simplified version, the dimensions are not weighted and participants are not required to rate the relative importance of each dimension. The overall score of the Raw TLX is therefore based solely on the direct ratings of the participants. For our individual Likert items, our participants had the opportunity to express their agreement with statements we created using 5-point Likert scales (1=strongly disagree, 5=strongly agree). The statements varied depending on the user study and research question. In our objective measures, we mainly measured task errors, time deviation, (head) movements, reaction times, precision, and process times. We report the median (Md) and interquartile range (IQR) for each of these measures. For descriptive data, such as the age of the participants, we report the mean (M) and standard deviation (SD). Our user studies have been designed as mixed, between-subjects, or within-subjects designs. In a within-subjects design, all participants participated in each condition. In a between-subjects design, each participant experienced only one condition. In a mixed design, one condition was changed between participants and another was changed within participants. All differences between groups were determined using statistical tests of variance. For the variance tests, we first determined which study design we were using. Then the type of data – ratio, interval, or ordinal – was determined. The significance level was set at < 0.05 for all tests. For our ratio or interval data, a Shapiro-Wilk test was then used to test whether the data were normally distributed. Ordinal data did not require a test for normal distribution. To test for significant differences, we needed to distinguish between between-subjects (unrelated groups) and within-subjects (related groups) when selecting the test, in addition to the normal distribution. Therefore, different statistical tests were used depending on the study design and number of groups (=2, >2).

Qualitative Data. In addition to collecting quantitative data, we also collected qualitative data. While quantitative data provides measurable and scalable information that lends itself well to statistical analysis, qualitative data captures the complexity of human experiences, opinions, motivations, and emotions behind the numbers. However, both the quantity and quality of the data are significantly influenced by the participants' personalities and willingness to communicate, which is why our work focuses on collecting quantitative data. To collect the qualitative data, we used the thinking-aloud protocol [BR00], where participants were asked to think aloud during the experiment to obtain qualitative feedback. The collected user feedback was then analyzed qualitatively using inductive categorization according to Mayring's qualitative content analysis [May14]. This is a structured, qualitative method for analyzing text-based data. We created categories from user statements and extracted key motifs and recurring statements. For predefined categories, such as whether a statement was positive or negative, we used the deductive approach and evaluated the participants' statements.

1.3 Thesis Outline

This thesis is divided into a total of eight chapters, the structure of which is shown in Figure 1.3. The first two chapters provide an introduction to the problem and a description of our application scenario by presenting the results of our context analysis. Chapter 3 gives an overview of the necessary background information relevant to understanding the possible contexts of this thesis. Chapter 4 then presents our conceptual design decisions developed to address our research questions. Chapters 5 to 7 present the related work and the user studies conducted to answer the derived research questions. The final chapter reflects on our findings and identifies potential avenues for future research.

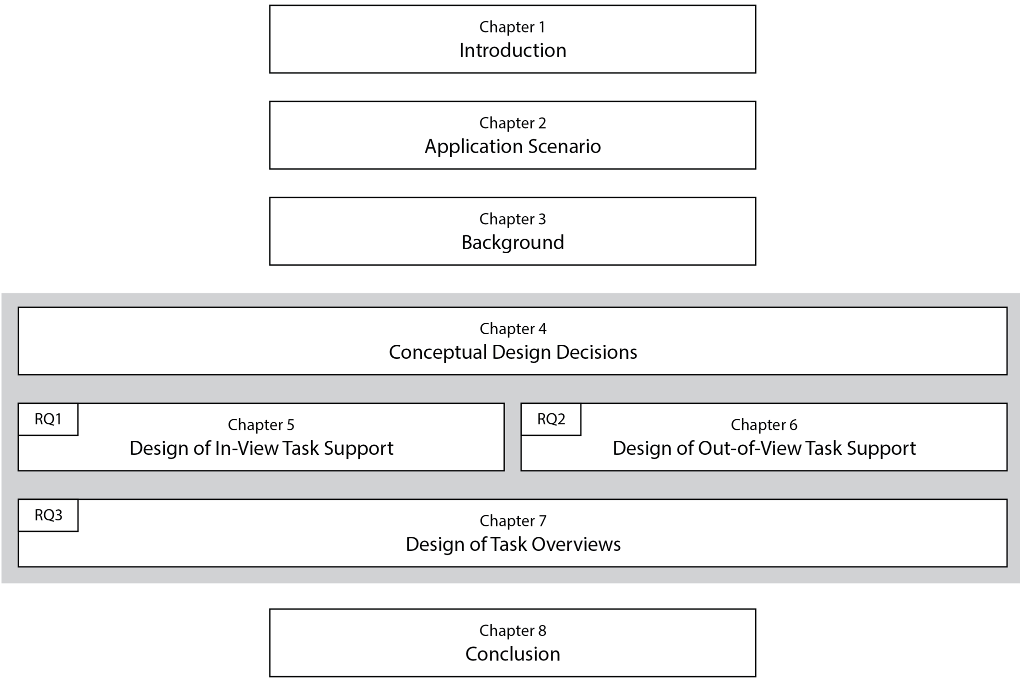


Figure 1.3: Outline of the thesis. Chapters 1 and 2 cover the introduction as well as the application scenario of the thesis. Chapter 3 presents the background of the thesis. Chapter 4 describes the conceptual design decisions that were developed. Chapters 5 to 7 present the user studies conducted to answer research questions RQ1 - RQ3. Chapter 8 provides a discussion of the results and contributions and highlights potential directions for future work (own illustration).

The chapters of this thesis are described in more detail below.

Chapter 2: Application Scenario

In the second chapter, we identify the specific challenges that need to be addressed in the context of this work. First, we present the results of our observation of an industrial use case as part of the context analysis of the HCD process. We then describe the subsequent expert interviews and explain the derived requirements for supporting time-critical, parallel, and spatially distributed tasks. Finally, we define the research questions and our contributions to address the identified challenges before concluding the chapter.

Chapter 3: Background

In the third chapter, we provide a detailed overview of the necessary background information for this research. First, we focus on our human perception capabilities, describing our visual perception, our multitasking capabilities, and our perception of time. We then describe the necessary basics of AR technology to explain how it works and how it differs from other technologies. Finally, we describe working environments and, in this context, present task characteristics, task execution, and task challenges, linking the cognitive psychological aspects of our described human perception capabilities. Finally, we summarize the chapter to illustrate the influence of the background chapter on the various aspects of this dissertation.

Chapter 4: Conceptual Design Decisions

The fourth chapter presents the conceptual design decisions that were developed as part of the thesis. These were derived from both our contextual analysis and previous work. In particular, we describe our concepts for representing time and first discuss the different manifestations of time that we defined to address the research questions. We then consider possible visual concepts for representing temporal information and decide on the necessary time segments (tenses) of tasks that are required for autonomous task planning. We explain why each segment is necessary and discuss the practical relevance of providing people with a comprehensive overview of their tasks. Afterwards, we describe the conceptual decisions that were made regarding our visual AR guidance. In this context, we first discuss the AR form factors we chose to address our research questions. We then differentiate the visualization techniques we used and, based on two focus groups, determine what specific temporal information is required for visual AR guidance based on the task characteristics described (see Section 3.3.1) and our observation (see Chapter 2). To this end, we have developed an information design from which we derive what information is needed to support time-critical and spatially distributed tasks.

Chapter 5: Design of In-View Task Support

In the fifth chapter, we explore possible solutions for visual AR instructions for individual workstations that support the execution of time-critical and parallel tasks within the FOV. We first present the related work that we identified as relevant in our literature review. We then show ways to enable hands-free working with AR devices and design part of a standardized bonding process as AR instructions using the manifestations of time from Chapter 4. In a user study, we compare AR instructions using a tablet and a head-mounted display (HMD) with traditional paper instructions and egg timers, highlighting the individual advantages of each technique. We then focus on the best technical solution and improve it based on the results of the first user study. In a second user study, we then adapt our AR guidance to different degrees of visualization parallelization and investigate how many parallel visualizations are useful in terms of execution time and error rate when providing assistance.

Chapter 6: Design of Out-of-View Task Support

In the sixth chapter, we investigate how to improve the execution of time-critical and parallel tasks when they are also spatially distributed, i.e., outside the FOV. To this end, we implement the results of our two focus groups that developed an information design for supporting time-critical and spatially distributed tasks (see Section 4.2.2). We then present related work that we have identified as relevant. Subsequently, we select four out-of-view visualization techniques used for HMDs and extend these techniques with our information design for out-of-view tasks. In a user study, we compare all four techniques and identify the individual benefits of each technique. In a second user study, we then select the two best techniques based on the results of the first user study and apply them to our specific use case, which we described in the context analysis. This approach allows us to verify whether the selected out-of-view visualization techniques improve user performance even under the most realistic conditions.

Chapter 7: Design of Task Overviews

In the seventh chapter, we investigate how to provide an overview of processes involving time-critical, parallel, and spatially distributed tasks so that people can quickly obtain all the necessary information. To this end, we first present related work that we identified as relevant in our literature review. We then derive the information we need to design potential overview techniques from our context analysis, previous work, and the results of RQ1 and RQ2. Based on this, we design three overview techniques with different degrees of spatial registration and with our defined time segments for the tasks (see Chapter 4), which we compare in a subsequent user study to verify whether our techniques improve user performance and information transfer.

Chapter 8: Conclusion

In the final chapter, we discuss the research conducted as part of this thesis. First, we briefly summarize all of the previous chapters and then discuss the contributions to each of the research questions. We then critically discuss our research in terms of appreciative technology design and point out limitations that we need to consider when designing future research. Based on this, we conclude this thesis with an outlook for future work.

1.4 Contributions

In this thesis, we make several important contributions to research and practice in the field of AR. Design concepts and recommendations for supporting time-critical, parallel, and spatially distributed tasks are developed for designers, developers, and researchers. Designers can use our concepts to create user-friendly and efficient AR applications and take our recommendations into account to design customized and individual user experiences. Developers can implement our prototypes and adapt them to specific use cases. They can also work to overcome the technical limitations we identify and improve AR devices for long-term use. Researchers can use our research results as a basis for further investigations to support time-critical, parallel, and spatially distributed tasks. This will validate the concepts and techniques developed in real-world work environments and advance the understanding of the cognitive requirements and potential of AR.

Excerpts of this work have been published in peer-reviewed scientific conferences and journals. In the following we list all core publications, ordered by their publication date in descending order.

- Jannike Illing et al. „Time is money! Evaluating Augmented Reality Instructions for Time-Critical Assembly Tasks“. In: *Proceedings of the 19th International Conference on Mobile and Ubiquitous Multimedia.* MUM '20. Essen, Germany: Association for Computing Machinery, 2020, 277—287. ISBN: 9781450388702. DOI: 10.1145/3428361.3428398
- Jannike Illing et al. „Less is More! Support of Parallel and Time-Critical Assembly Tasks with Augmented Reality“. In: *Proceedings of Mensch Und Computer.* MuC '21. Ingolstadt, Germany: Association for Computing Machinery, 2021, 215—226. ISBN: 9781450386456. DOI: 10.1145/3473856.3473861
- Jannike Illing, Uwe Gruenefeld, and Wilko Heuten. „Keep Track! Supporting Spatial Tasks with Augmented Reality Overviews“. In: *Proceedings of the Symposium on Spatial User Interaction.* SUI '24. Trier, Germany: Association for Computing Machinery, 2024. ISBN: 9798400710889. DOI: 10.1145/3677386.3682093

Further publications on related topics have been published, that also contributed to the idea and outcome of the thesis are listed below:

- Uwe Grünefeld et al. „Mind the ARm: Realtime Visualization of Robot Motion Intent in Head-Mounted Augmented Reality“. In: *Proceedings of Mensch Und Computer.* MuC '20. Magdeburg, Germany: Association for Computing Machinery, 2020, pp. 259–266. ISBN: 9781450375405. DOI: 10.1145/3404983.3405509

- Antonia Altendorf et al. „Von Nutzung zu Mitgestaltung: Wie Digitalisierung gelingt. Arbeitssoziologie, Informatik und Kommunikationswissenschaften im Dialog“. In: *Neues Archiv für Niedersachsen* 11.1 (2024), pp. 78–105. ISSN: 0342-1511. DOI: 10.5771/0342-1511-2024-1-78. URL: https://doi.org/10.5771/0342-1511-2024-1-78

- Melanie Malczok, Antonia Altendorf, and Jannike Illing. „Well-being at digitalized workplaces: An interdisciplinary perspective on technology design and the role of internal communication management“. In: *Book of Abstracts of the 31th International Public Relations Research Symposium BledCom*. Ed. by Dejan Verčič, Ana Tkalac Verčič, and Krishnamurthy Sriramesh. Lake Bled, Slovenia: University of Ljubljana, Faculty of Social Sciences, 2024. ISBN: 9789612950859

2 Application Scenario

This chapter describes the application scenario of the thesis. The use case of bonding processes is considered an exemplary case, since in this industrial application the handling of time-critical, parallel, and spatially distributed tasks is part of the routine work. First, the scenario is presented to get an idea of the functions and challenges of industrial bonding. The observation of a real training environment is then described to gain insight into the work context. Subsequently, expert interviews provide insight into the production and assembly sequences of bonding processes. Requirements for Augmented Reality (AR) support are derived from the results of the observations and interviews. Finally, we present our three central research questions that we investigate in this thesis.

Parts of the work presented in this chapter were published as a paper in the journal „Neues Archiv für Niedersachsen“ in 2024 [Alt+24].

2.1 Introduction to Industrial Bonding

Industrial bonding is a process in which adhesives are used to join a wide variety of materials such as metals, plastics, glass, wood, or ceramics [Hab06; IFA24; Wie18]. The adhesive, in liquid, paste, or solid form, is applied to the surfaces of the parts and cures (technical term for hardening) to form a strong bond. Unlike mechanical joining techniques such as screws or rivets and thermal processes such as welding, adhesive bonding allows materials to be joined without damaging their structure. Industrial use of adhesive bonding is growing in many industries, including automotive, aerospace, electronics, construction, and packaging. This technology ranges from simple applications in small workshops to highly complex processes in large original equipment manufacturers (OEMs). The benefits of bonding include the even distribution of mechanical stresses, the ability to join thin materials, and the ability to join dissimilar materials that would be difficult to join mechanically. At the same time, the technology places high demands on process control. Compliance with standards such as DIN 2304-1 [DIN20] and ISO 21368 [ISO24], or DIN 6701-2 [DIN15] and EN 17460 [EN22], is crucial, especially in safety-critical applications such as automotive, where bonds must withstand high loads and changing environmental conditions.

In industrial bonding, there are several steps that must be taken to achieve a quality bond [Hab12]. Choosing the right adhesive plays a key role, as each adhesive has different properties that are suitable for specific materials and applications. Using the wrong adhesive can result in a weak or unreliable bond [Hab03]. The physical and chemical properties of the adhesive, such as viscosity, setting time[1] and strength, must be compatible with the materials being bonded

[1] The setting time describes the time it takes for an adhesive to change from a liquid to a solid state (time to cure).

[Hab12; Hab06]. The preparation and mixing of the adhesive and subsequent processing are significantly influenced by factors such as pot life[2] and setting time. Equally important is the thorough preparation of the surfaces of the joining parts (parts to be joined). Methods such as grinding, pickling, or plasma treatment are often used. The parts must then be cleaned and treated to remove contaminants such as oils or oxidation. Preparation and cleaning of the joining parts is very important because even minor contaminants can affect adhesion and reduce the strength of the joint [Hab03]. After cleaning, a certain flash-off time[3] must be allowed to ensure that the surfaces are completely dry and free of solvent residue. After surface preparation, the adhesive is applied to the intended surfaces. Depending on the adhesive and setting time, this may need to be done quickly as some adhesives have a short pot life. Application can be manual or automated, depending on the production process [Wie18; IFA24] (see Figure 2.1). Curing can be accelerated by various methods such as heat, UV light, or pressure, depending on the specific requirements of the adhesive [Wie18; Hab12]. A long curing process can delay the production process, so choosing the right curing technique is crucial. After curing, the quality of the bonded joint is tested to ensure that it can withstand the required mechanical, chemical and thermal stresses. The entire process is determined by a number of time factors, including flash-off time, setting time, and pot life. These times must be adhered to precisely to ensure a quality bond. Failure to adhere to these times can result in incomplete cure, inadequate adhesion, or even failure of the bond, which can significantly affect the entire production process [Hab03]. Environmental factors such as temperature, humidity and UV radiation also pose a challenge because they can affect the long-term durability of the bonded joint. Particularly in safety-critical applications such as automotive and aerospace, bonded joints must withstand extreme conditions, requiring accurate testing of aging and environmental effects. Careful process monitoring is therefore essential to achieve consistent results and detect potential weaknesses in the bonded joint early on.

In summary, industrial bonding requires extremely precise process control, from the selection of the right adhesive to thorough surface preparation and careful monitoring of the entire manufacturing process. Each step must be precisely coordinated to ensure a reliable and durable bond. At the same time, the large number of process parameters – such as material properties, environmental influences, and time factors such as flash-off time, setting time, and pot life – pose a significant challenge. In particular, the workers who perform the bonding process face a cognitive load. They must continuously monitor a large number of variables and ensure that all steps are performed correctly in real time. The complexity of this process carries the risk of mental overload, which increases

[2] The pot life describes the workability or usage time of an adhesive after mixing a component adhesive.

[3] The flash-off time describes the period of time that must be waited when using cleaners, activators, or primers so that the solvent has completely evaporated and the adhesive can be applied.

Figure 2.1: Examples of industrial bonding in vehicle construction. Manual bonding in rail vehicle construction [Hau24] (top left), and in aircraft construction [Mat24] (top right). Automated, robot-controlled bonding in automotive construction [Hes18; Gmb20] (bottom left, bottom right).

the likelihood of errors and can affect the quality of the bonded joint. However, in order to achieve a stable and reliable bond over time, it is crucial that the many time-critical factors are adhered to. At the same time, automated systems or optimized processes should minimize the cognitive load on workers to ensure consistently high quality.

2.2 Observing an Industrial Use Case

As part of the context analysis of the Human-Centered Design process, we conducted a two-day observation of a real training environment for prospective bonding technicians to better understand the work context of bonding processes. This observation followed a systematic approach aimed at gaining insight into the work processes, identifying the tools and materials used, and identifying the challenges in industrial bonding technology. It was particularly important to understand the bonding process and its timing, the influence of environmental factors, and the interaction between the process steps and the trainees in order to identify potential challenges.

Our observation was conducted as a direct, non-participatory observation in which we did not influence the trainees' actions. This allowed us to capture the

Figure 2.2: Observation of the training environment for bonding processes [Ill+20].

environment and workflow without disrupting the natural flow. During the observation, we took notes on the trainees' activities, the individual process steps, the rooms, the tools and materials used, and the process-related influencing factors. In addition, we documented the execution of the process steps with photos and videos. The interactions between the trainees and the process also played an important role.

We used an observation guide to record the relevant aspects in a structured way. This included documentation of the process, such as the sequence, timing, and duration of the process steps, description of the work environment, list of tools and materials used, trainees' work characteristics, and documentation of other parameters that could affect the bonding process. We also conducted informal interviews with the instructors and some of the trainees to understand the specific challenges of the process. Upon completion of the observation, the collected data was analyzed, clustered, and summarized, allowing us to capture the observed process and how it was handled, as well as identify challenges and recurring issues in the data.

Below, we report the key findings from our two-day observation of the training environment. We present the identified challenges that arose during the observations, addressing the process-related influencing factors as well as the trainees' handling of the process steps.

A first striking observation of the workflow was that the trainees had to adhere to different times during the bonding process. There were also various parameters that could affect these (bonding) times, such as (room) temperature, humidity, or application quantity. These times were set using conventional egg timers and several timers that were difficult to distinguish from each other.

The trainees needed to know which clock belonged to which process step and whether it was a time-critical situation (e.g., the adhesive is now starting to dry after mixing the components and must be used immediately) or whether it was just an elapsed waiting time (e.g., the parts have now dried after cleaning). In addition to the time factor, the order in which the process steps were performed also played an important role. For example, certain steps depended on whether and how the previous steps were performed. Within the process, most steps were not interchangeable and the order had to be strictly followed (see Section 3.3.2). A simple example is when a part needs to be cleaned and dried before it can be coated with adhesive and assembled.

Another observation was that the trainees had to perform a process step on multiple parts in parallel at multiple locations (e.g., glue 4 parts at station A, glue 2 parts at station B). This was done to simulate real-world conditions, as in production operations, multiple parts are typically processed simultaneously and a process step is applied directly to multiple parts to increase productivity. In addition to the parallel processing of several parts per step, there was further parallel processing in the form of parallel processing of several steps, e.g., by using (bridged) waiting times.

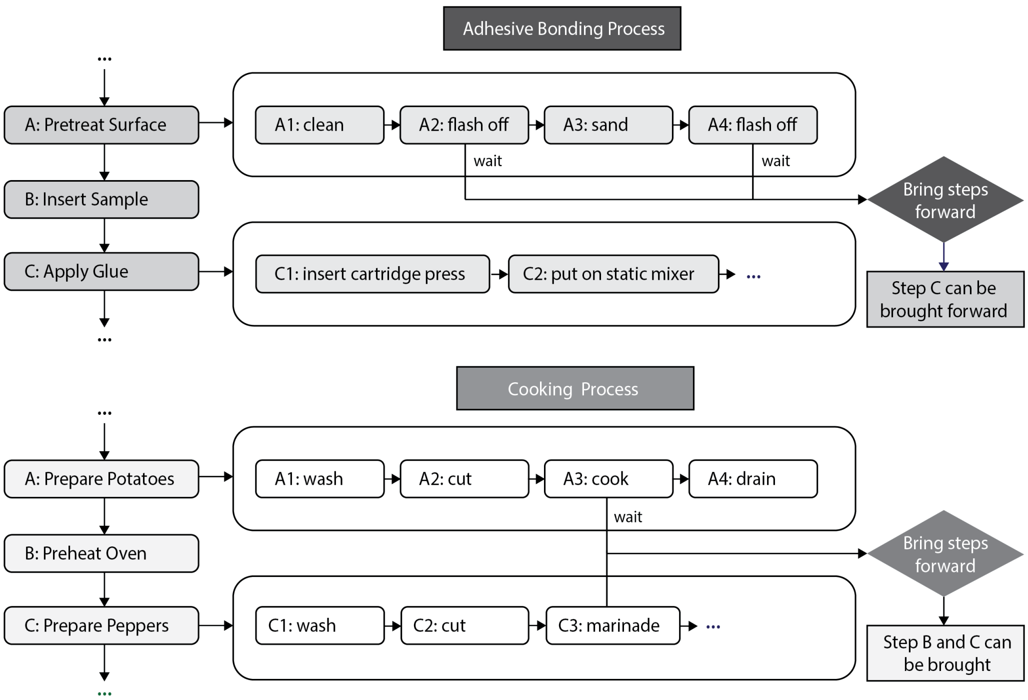


Figure 2.3: Abbreviated section of a simple bonding and cooking process to illustrate the similarity of these processes in terms of parallel execution of steps and time constraints (own illustration based on [Alt+24]).

Similar to cooking, there can be „waiting times“ during the process, such as when parts need to be „flashed off“ (see also Section 2.1). This means that after chemical pre-treatment, the parts must be placed under a fume hood to dry and remove toxic substances that should not be inhaled. In this way, several steps could be performed in parallel (see Figure 2.3).

In addition to performing the process, we noticed that there were several workstations where the trainees had to perform process steps, such as the glue/mix stations, sanding stations, machine stations, and the storage area with a cleaning station. For example, when all the parts were taken out of storage, the parts had to be sanded (sanding station) and then cleaned (cleaning station). The bonding process took place at a gluing and mixing station, where the components first had to be mixed. In addition, all steps and times, as well as environmental parameters such as temperature and humidity, had to be recorded in a handwritten log.

In addition to observing process execution and identifying various tools and materials, we observed trainees taking over tasks from others – either because it was their turn next or because a trainee needed to leave the workstation for a moment. A recurring problem was that the person taking over often had to find out where the workpiece for the subprocess was located. The person leaving the workstation would usually just point to the step he/she was working on. This meant that the next trainee knew what to do, but had no information about where the workpieces for the other tasks were located or which task was next in priority. Clear prioritization of tasks is crucial in such environments, especially since the trainees have to work under time constraints. For example, if a part was already glued, the counterpart had to be assembled very quickly before the glue dried.

Another important finding was that the trainees came from different companies that have integrated or are integrating the bonding sub-process. These were not companies that were exclusively specialized in bonding technology. Most of the trainees came from craft trades (e.g., metalworkers, welders) and wanted to educate themselves further in this context. In addition to the (work) processes, we noticed that the prospective bonding technicians have to follow strict hygiene regulations. They have to wear special shoes, goggles, protective suits, and gloves. This is partly because the bonding must be free of contamination to meet quality standards and partly because the adhesives are very toxic and the trainees must be protected from contact. For this reason, the technical support must allow hands-free working, as the equipment must not be touched.

This analysis led to key findings that highlighted the complexity of the bonding process and served as the basis for developing our research questions (see Section 2.5).

2.3 Interviews with Experts

The observation was followed by structured interviews with bonding technology experts (n=4), who gave us a real picture of the manufacturing and assembly processes and confirmed the common sources of error we observed. Due to strict privacy guidelines, no audio recordings were made during the interviews. Instead, notes were taken during the interviews based on a prepared interview guide to ensure that all relevant topics were systematically covered. Written informed consent was obtained from all experts prior to the interviews to ensure their agreement to participate and to the use of the data collected. The interviews were conducted with experts from different companies. The interviewees included a managing director, a deputy head of department, a trainer, and a head of a certification body, all of whom also worked as bonding engineers, process planners, or certifiers. These experts came from a variety of fields and companies, giving us a broad perspective on the challenges and requirements of adhesive bonding technology. Each interview lasted approximately 90 minutes.

The interview guide consisted of five thematic blocks aimed at gathering comprehensive information on different aspects of the bonding process. The first block, „assessment of the environment and general conditions“, asked about the general conditions in the interviewee's company, including the work environment, the technology used, and the skills of the employees. In the second block, „assessment of the current process flow situation“, the current flow of the bonding process was described in detail to gain a precise understanding of the operational processes. The third block, „assessment of the current process flow difficulties/problems“, focused on the most common challenges and problems encountered during the bonding process, including possible sources of errors and bottlenecks. The fourth block, „assessment of the technology support, needs, and capabilities“, focused on the potential use of technology tools, such as AR, and the experts' expectations for future technology support options. Finally, the fifth block, „assessment of the barriers, acceptance, and drawbacks to system adoption“, addressed potential barriers to the adoption of new technology systems, acceptance of such systems, and potential drawbacks from the respondents' perspective.

After the interviews were completed, the notes were analyzed and summarized. The results of the interviews were then compared with our observations of the training environment to create a valid database and draw informed conclusions.

The analysis of the interviews revealed that the employees work under a high cognitive load, which often leads to errors when adhering to different time constraints. In addition, the spatial accuracy of the parts is often underestimated and workpieces have to be re-bonded or reworked because, for example, the parts do not fit exactly on top of each other after bonding. The interviews also revealed that in most small and medium-sized enterprises (SMEs), such as workshops, the bonding work is very often carried out by unskilled personnel, which means that errors and accidents due to overloading are very common, especially in the handicraft sector. Bonding processes in these small enterprises are typically characterized by many manual steps that are presented to the employees on paper-based instruction sheets. The importance of providing clearly defined information during take-over processes, such as shift changes, was also highlighted, including which tasks need to be performed, where these tasks take place, and how quickly they need to be completed. This information is essential to ensure a smooth transition and efficient workflow. The lack of clear instructions often leads to delays and problems in production and assembly processes, especially under time pressure, as materials such as adhesives require quick and precise action. As employees are often exposed to a lot of noise from machines in the real work context, it became clear from the interviews that we should limit ourselves to a visual solution.

Through observation and interviews, we were able to identify the need for technical assistance in AR. AR makes it possible to change the perceived reality by superimposing digital information on the real environment [ZDB08; Azu97]. AR has already proven to be a helpful technology in the past, providing step-by-step instructions for manual assembly and manufacturing [Ren+13; SK08]. The superimposed virtual information allows for accurate and precise mapping of real objects in future positions with a virtual model. For example, parts of an assembly process can be positioned virtually in advance, and the user gets an accurate (spatial) impression of the desired assembly position before the actual assembly process begins [Alv+19; Pla+19; Hoo18]. This could, for example, reduce errors in the spatial accuracy of the parts.

2.4 Derivation of Requirements

Following the context analysis, we are able to derive several requirements for our AR support system (see Figure 2.4).

We need to allow users to work hands-free to avoid contamination. We also need to visualize the different times, especially the critical times, because in the past, mistakes were often made, and the set times could not be distinguished. In addition, the AR support should especially support beginners, because it is very often unskilled personnel who do the bonding. Due to the spatial distribution of the workstations, tasks that are not in the field of view (FOV) should also be supported. In addition, visualization of the spatial joining positions is important to ensure that the parts fit together accurately after bonding. Since the process steps for multiple tasks are performed simultaneously, it is necessary to adapt the AR visualization according to several parallel steps. In addition, an overview of the process is needed in case the steps need to be resumed after a break or when a colleague is absent. If the AR assistance system is to be used in practice, it must also visualize environmental information and generate a final report to reduce paperwork.

In addition to the requirements specification, we summarized the user requirements in the form of fictional personas (see Figure 2.5). Personas play an important role in our design process. They are derived from the target groups, with each persona acting as a representative of a specific target group and representing important characteristics of a group of people in a typified form. This approach helps us to better understand the needs and characteristics of users and integrate them into the development process.

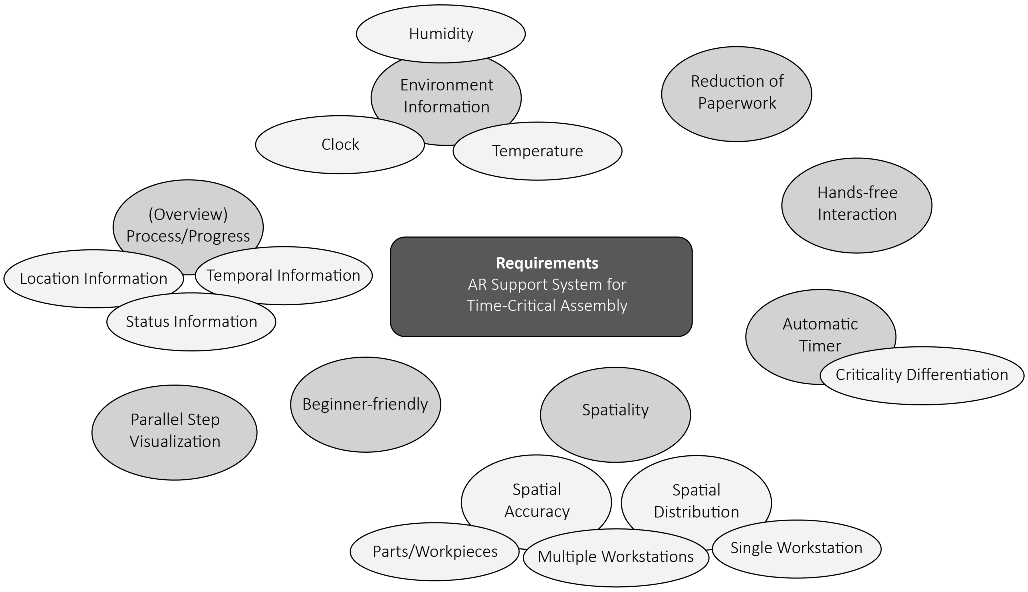


Figure 2.4: Simplified overview of key requirements [Alt+24].

2.5 Research Questions

The observations, interviews, and derived requirements described above lead us to three key research questions that we explore in this thesis.

*RQ*1 How can time-critical and parallel tasks be visualized within the field of view?

*RQ*2 How can time-critical, parallel, and spatially distributed tasks be guided outside the field of view?

*RQ*3 How can time-critical, parallel, and spatially distributed tasks be overviewed?

The following paragraphs describe the research questions addressed in this thesis in more detail and summarize our contribution to the research.

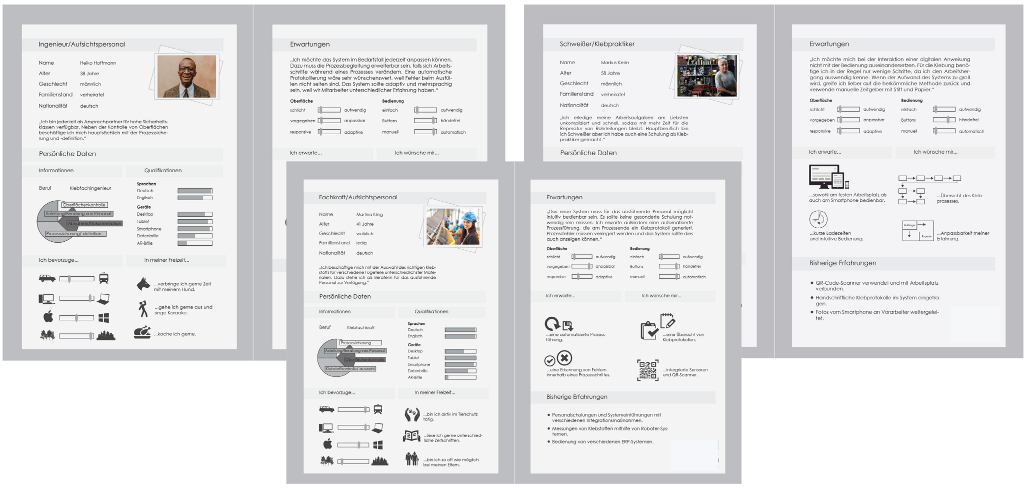


Figure 2.5: Developed personas as a basis for the design process [Alt+24].

RQ1: How can time-critical and parallel tasks be visualized within the field of view?

In the first research question, we investigate possible solutions for visual AR instructions that support the execution of time-critical and parallel tasks within the FOV. To this end, we first visualize the manifestations of time in AR that we have defined (see Chapter 4) and compare the visualizations with different AR devices that we adapt for possible hands-free work. Our contribution is to help people who are involved in time-critical processes where precise spatial assembly of parts is important and where high safety/hygiene requirements must also be met, making precision work even more difficult. In summary, we want to investigate the possibilities of AR to support and reduce possible errors, such as the non-observance of different times and the incorrect spatial positioning of (assembly) parts. In addition, we want to evaluate to what extent our AR instructions can be adapted to different degrees of parallelization of visualizations, since in practice process steps for several tasks are executed in parallel at the same time (see Chapter 2). In this context, our contribution is to show a possible quantitative characterization of a trade-off between error rate and process time and to determine an appropriate number of concurrent visualizations.

RQ2: How can time-critical, parallel, and spatially distributed tasks be guided outside the field of view?

When time-critical and parallel tasks are also spatially distributed, location-based (in-view) AR visualizations are not sufficient to display tasks outside the FOV. The second research question investigates how to support time-critical and parallel tasks that are spatially distributed. To this end, we first relied on the results of two focus groups of UX experts and users who developed an information design and then created several sketches. From this, we deduced that in addition to our location-based AR visualizations, we needed to display both the time criticality and the location of the distributed tasks. In a first study, we want to evaluate the extent to which existing out-of-view visualization techniques can be adapted to time-critical tasks. For this purpose, promising techniques will be extended by encoding time information. Subsequently, we compare these techniques to gain insight into user performance and to enable a selection of the best perceived techniques. In a second study, we apply the different temporally extended out-of-view visualization techniques to our specific use case to verify whether our techniques improve user performance. In summary, our contribution aims to identify ways to improve the spatio-temporal guidance of people who need to manage time-critical, parallel, and spatially distributed tasks.

RQ3: How can time-critical, parallel, and spatially distributed tasks be overviewed?

In a real work environment, time-critical, parallel, and spatially distributed tasks often need to be taken over by other people in the middle of the process. In such cases, the current status of the tasks and possible relationships are often unclear to the person taking over. It is therefore necessary to obtain information quickly in order to enable a rapid takeover. In our final research question, we therefore want to support take-over situations of time-critical, parallel, and spatially distributed tasks. To this end, we design different AR overview techniques with increasing levels of spatial registration and apply the necessary time segments (tenses) we defined for tasks (cf. Chapter 4) to these techniques. In this way, we determine the extent to which we can look into past and future tasks. Based on the results of the second research question, we know that to support distributed tasks we need both (a) time information and (b) the location information of the tasks. Therefore, we extend our AR overview techniques to encode this information. In a study, we compare our overview techniques to see if our techniques improve user performance and information transfer. Our contribution is to enable people to better orient themselves, reduce cognitive load, and capture task-specific challenges.

3 Background

This chapter reviews the background knowledge that is fundamental to developing ways to support work scenarios involving time-critical, parallel, and spatially distributed tasks (see Figure 3.1).

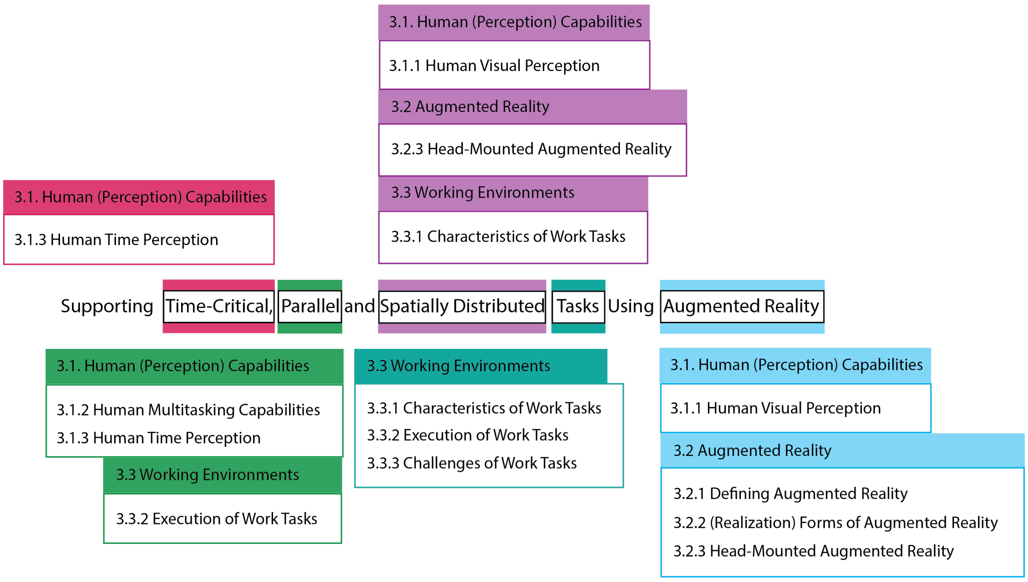


Figure 3.1: Necessary background chapters for understanding each aspect of the work (own illustration).

To understand time and time criticality, we need to look at our ability to perceive time (see Section 3.1.3). In addition, we know from our application scenario that tasks have to be processed in parallel and that several aspects have to be dealt with at the same time. Our ability to multitask therefore plays an important role (see Section 3.1.2). Another interesting question is whether our perception of time can also be influenced when we are working on several tasks at the same time. When it comes to spatial distribution of tasks or workstations, it is important to analyze the characteristics of the tasks to determine how to support spatial distribution (see Section 3.3.1). Here, it is of particular interest how Augmented Reality (AR) can support us and how our visual perception capabilities, especially peripheral perception, deal with it (see Section 3.1.1.3). We need to understand how AR solutions need to be designed to meet the specific requirements of our tasks. To address these challenges with AR, we need to take a closer look at the underlying technology (see Section 3.2). In this context, our visual perception plays a particularly important role (see Section 3.1.1). An understanding of our visual fields and color perception is necessary to understand and make the most of the technical limitations and functionality of AR. By understanding and addressing these factors, we can develop effective solutions to help people manage time-critical, parallel, and spatially distributed tasks.

3.1 Human (Perception) Capabilities

In this chapter, basic psychological principles are highlighted to provide a basis for a common understanding of possible design concepts and implications for study outcomes. We review our various perceptual abilities, including our visual perception, our perception of time, and our ability to multitask. Together, these aspects need to be considered during design to support time-critical, parallel, and spatially distributed tasks in AR. Visual perception allows us to respond quickly to visual stimuli and understand our environment without being overwhelmed by the abundance of stimuli [Fan+20]. Multitasking skills are important because they allow us to quickly switch between different tasks, which is especially useful when multiple tasks need to be completed at the same time [Cal14]. Time perception is also important because it allows us to make time-critical decisions and estimate the duration of events.

3.1.1 Human Visual Perception

We are primarily visual beings. Most of the information recorded in our central nervous system is visual. Through visual perception, we can quickly gain a great deal of information about our surroundings, such as the distance to objects, the spatial arrangement of our environment, and even the emotions of other people [Log20].

To explore the possibilities of assisting with time-critical tasks, we will take a closer look at color perception in the following chapters, as colors can be used to convey information (e.g., to signal a critical state). In addition, we need to look at our field of view (FOV), as current head-mounted AR solutions can only cover part of this FOV with visual information. For this reason, we are also interested in perception at the periphery of the visual field to gain insight into peripheral perception.

3.1.1.1 Color Perception

Our color perception describes the ability to perceive reflected light from surfaces differently depending on their spectrum. This requires different types of wavelength-sensitive receptors (photoreceptors) in the eye, each of which is sensitive to different wavelengths of light.

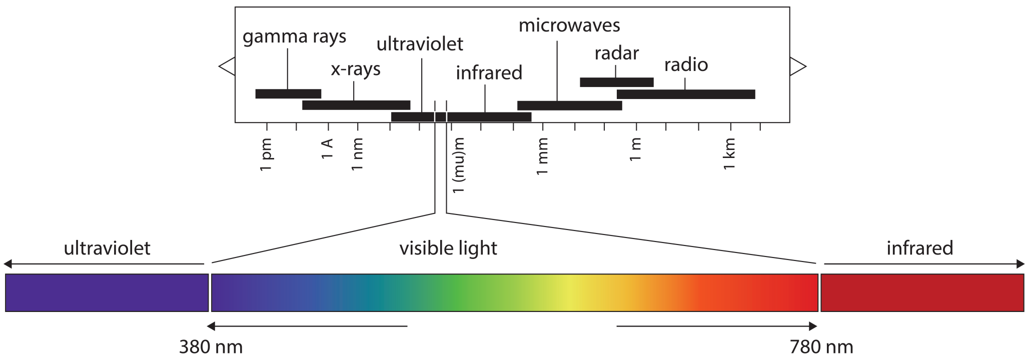


Figure 3.2: Visible wavelengths of light (own illustration based on [KC10; Ham08; Gou11]).

Wavelengths of Light

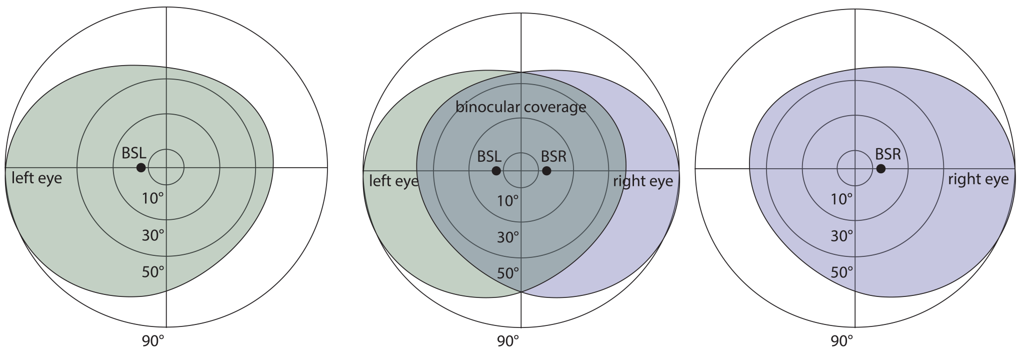
A crucial factor for our color perception is the wavelength composition of the light reflected from object surfaces. The distribution of wavelengths in the reflected light of a surface becomes the proximal stimulus[1] for color perception [Hag+11]. The different wavelengths of light are not fully visible to us, so only wavelengths in the range of 380 nm (blue-violet) to 780 nm (red) can be detected. Figure 3.2 clearly shows that only a very small range is visible to the human eye. Rays such as ultraviolet and infrared fall into the invisible (imperceptible) range [Ham08]. The physical properties of a surface then determine the distribution of wavelengths in the reflected or transmitted[2] light so that it becomes visible to our eyes. A blue object, for example, appears blue because it absorbs wavelengths outside the blue spectrum. In other words, the blue wavelengths are reflected [Gmb23].

Sensory Perception

A color impression is created through the interaction of the reflected light with the wavelength-sensitive receptors of the eye's retina and the subsequent signal processing [Hag+11]. There are different receptors (cones and rods) on our retina, and each receptor absorbs light according to its spectral sensitivity (degree of absorption). Rods primarily take over scotopic vision (dim conditions), while cones primarily take over photopic vision (bright conditions) [ANS08]. Three different functional cone types can be distinguished – S-cones (short wavelength receptor), M-cones (medium wavelength receptor), and L-cones (long wavelength receptor), where S-cones cover the blue range, M-cones the green range, and L-cones the red range [Gmb23; Hag+11]. The absorption curves of all three cone

[1] A proximal stimulus refers to the sensory image of reality that physically affects the respective sensory cells through a stimulus that is distant from the observer (distal stimulus).

[2] When light passes through a surface (transmission).



(a) Left monocular vision. (b) Binocular vision. (c) Right monocular vision.

Figure 3.3: Visual field of the left and right eye. Blind spot for the visual field of the left eye = BSL, for the right eye = BSR. Circles 10°, 30°, 50°, and 90° from the fixation point (own illustration based on [GGC80]).

types are relatively broad and overlap. One cone type alone does not provide sufficient information for color vision. This is only possible by neuronal processing of the excitation patterns of at least two different cone types [DMS12]. An exact delimitation of the cones is therefore not meaningful, since each cone type shows a different degree of activity for all wavelengths. The relative proportion in the different wavelength ranges ultimately determines which color is seen. In short, not only one type of cone is active at the corresponding wavelengths, so that the simultaneous excitation of two or three cone types results in different mixed colors. If all three cone types are activated at the same time, white is perceived, if they are not activated, black is perceived [Ham08]. The density of our cones is highest in the center of the retina, at the point of sharpest vision (fovea centralis) [GK03]. The density decreases outward, and there are many rods at the edge of the visual field. In the fovea centralis there are no rods. The fact that cones are responsible for color vision often leads to the erroneous conclusion that rods are responsible for brightness or black-and-white vision. However, rods only contribute to vision at low light levels [GK03].

3.1.1.2 Monocular and Binocular Fields-of-View

Each eye perceives only part of the environment (monocular vision). With both eyes, it is possible to perceive a larger visual space (binocular vision) and better estimate distances (stereoscopic vision) [Gon23]. The FOV represents the space visible to the motionless eye.

Monocular vision extends horizontally to an angle of about 150 degrees. Binocular vision refers to what both eyes see together at the same time and therefore describes the combined FOV of the two overlapping monocular fields of view. Here, the fields of view of the right and left eyes overlap in the center. This overlap is called binocular coverage and is approximately 120 degrees. Depth perception is only possible in this area (see Figure 3.3). In addition, this area ensures that the blind spot does not negatively affect our visual perception when we see with both eyes. The binocular FOV is about 180 degrees horizontally. It extends upward to about 60 degrees and downward to about 75 degrees [Ber17]. The distance between the two eyes causes the images to be positioned slightly differently on the two retinas, which is called binocular disparity. Binocular disparity refers to the difference in image position of an object seen by the left and right eyes that results from the horizontal separation of the eyes (parallax). The brain uses binocular disparity to extract depth information from the two-dimensional retinal images in stereopsis [Sie+16; Qia97]. Binocular disparity decreases with distance. Depth perception at six meters is similar to monocular vision. In this case, we use other visual properties such as relative size, shading, overlap, and perspective to estimate distances [Kal17].

3.1.1.3 Foveal and Peripheral Perception

Our visual field can be divided into five distinct areas with different perceptual characteristics: foveal, parafoveal, perifoveal, near peripheral, and far peripheral [Kal17] (see Figure 3.4).

Note that the foveal area covers a very small angle of vision. This is where the density of our cones is highest (cf. Section 3.1.1.1). Impressions in the parafovea are less clear because visual acuity, resolution, and color vision decrease with distance from the fixation point [Ros16]. The parafoveal area differs from the foveal area in that it has a lower density of cone and ganglion cells and a higher density of rods. Although spatial contrast sensitivity, visual acuity, and other visual characteristics are lower in this area than in the fovea, color perception is essentially the same [Sak20]. However, reading experiments on parafoveal information processing have shown that efficient reading requires simultaneous parallel processing of parafoveal and foveal information [SAR12]. In the perifovea, the proportion of rods in the photoreceptors continues to increase while the proportion of cones decreases. It is adjacent to retinal areas with the highest rod density (cf. Section 3.1.1.1).

In the periphery, stimuli are poorly resolved, but the movement of objects in the periphery greatly improves our ability to detect them. Peripheral vision is divided into near and far vision. In the near periphery, almost all colors can be perceived, but in the far periphery, there are areas that do not allow color perception at all. Simply put, everything our eye sees outside the fovea when it focuses on a particular point is in the peripheral vision area [IV+20]. Peripheral vision has not only reduced visual acuity and slightly distorted visual impressions, but also a greater crowding effect than foveal vision [Str20]. This perceptual phenomenon describes how the visual recognition of a particular shape is affected by the proximity of other shapes [SRJ11; Str20].

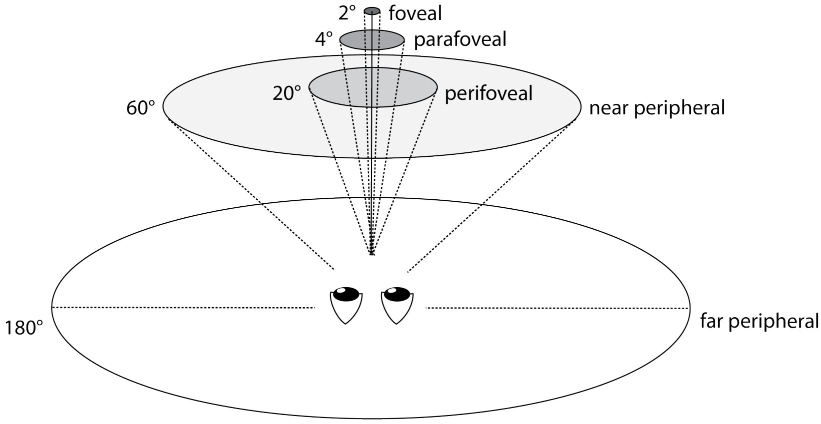


Figure 3.4: Visual field with different areas for foveal and peripheral vision (own illustration based on [IV+20; ANS08; Sak20]).

3.1.2 Human Multitasking Capabilities

The individual cognitive demands of tasks can be mastered relatively quickly on their own, as long as the task is performed in single steps and time pressure is kept to a minimum [BTC17]. However, although we are able to focus on task-relevant information and ignore distractions [ZG09; Ber+09], this neural capacity of working memory decreases with increasing information density because it is no longer possible to distinguish which information is important for the current goal at hand [Mil56]. From a cognitive psychology point of view, the parallel execution of tasks can lead to performance losses due to a so-called processing bottleneck. This bottleneck delays the preparation of a second task until the preparation of an earlier task has been completed [Pas99]. The optimization of so-called multitasking[3] processes is an important component to increase efficiency when processing multiple tasks simultaneously [FP15].

At first glance, our ability to perform multiple activities simultaneously seems self-evident and reliable [Pol+18; KMJ19]. This raises the question of whether cognitive processes associated with different tasks can occur only sequentially or also in parallel [FP15]. Many researchers describe that performing two or more tasks in parallel leads to performance degradation in the form of increased response latencies or error rates due to a cognitive processing bottleneck [Wel52; Kah73; Pas94; JSK04; PKB09; RM05; SD06]. This view, still accepted today, describes Pashler's [Pas94] highly influential Response-Selection Bottleneck (RSB) model (see Figure 3.5). According to the RSB model, the central processing phase for a second task (Task 2) cannot begin until the central processing for a first task (Task 1) has been completed, resulting in a cognitive delay [LSP03]. In simple terms, performing a task requires three stages. In the first stage, the

[3] Human multitasking refers to a state in which cognitive processes overlap in time. These cognitive processes can belong to two or more tasks [FP15; Koc+18].

perceptual attributes of a stimulus are analyzed. In the second stage, a decision is made about what the task requires. The actual response is made in the third stage. When the asynchrony of stimulus onset (SOA) is short and the tasks overlap, the first task delays the execution of the second. The difference in reaction time in Task 2 (RT2) between short and long SOA is called the Psychological Refractory Period (PRP) effect [Wel52]. The PRP paradigm refers to a time interval in which only one stimulus can be processed. When two different stimuli are presented in rapid succession (i.e., the SOA is short), each requiring a rapid response, the response to the second stimulus is delayed. Simply put, with a very short SOA, overlap of the two responses (to stimuli one and two) is very likely. However, such a conceptualization of multitasking would exclude the possibility of parallel cognitive processing of multiple task components [FP15]. Despite an assumed processing bottleneck, it was shown that parallel processing is possible in principle, e.g., through backward crosstalk [Hom98; Jan+14] or capacity sharing [TJ03; LH08].

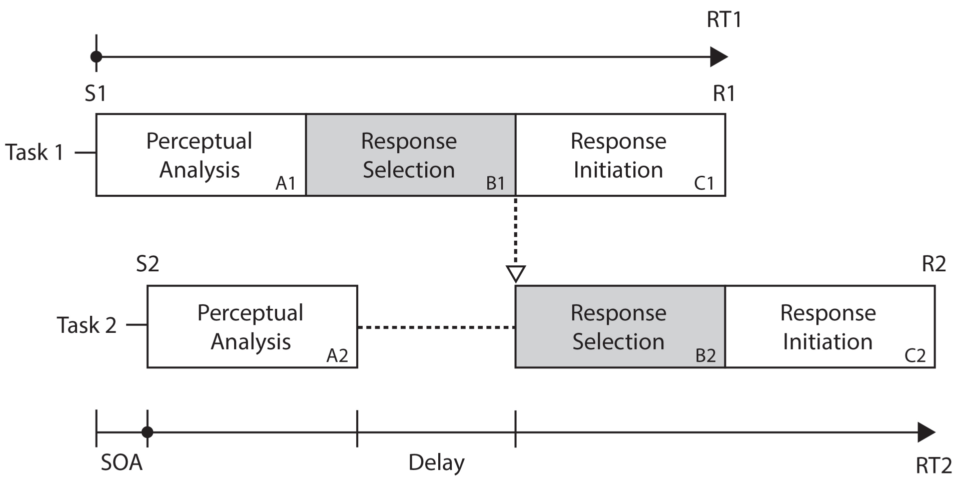


Figure 3.5: Pashler's response-selection bottleneck model for dual-task performance. S1, stimulus for Task 1; S2, stimulus for Task 2; R1, response for Task 1; R2, response for Task 2; RT1, response time for Task 1; RT2, response time for Task 2; SOA, stimulus onset asynchrony (own illustration based on [Pas94; LP02; LSP03; FP15]).

3.1.2.1 Backward Crosstalk

Backward crosstalk logic refers to the observation that the processing of a second task affects the processing of the first task, which is seen as evidence of parallel processing despite an assumed RSB [FP15]. Accordingly, the processing of a second task can increase or decrease the reaction time (RT) of the first task. With crosstalk logic, any influence on the first task is propagated back to the second task. This means that changes in RT1 can also be found in RT2. In contrast to the classical RSB model, the response selection phase in crosstalk logic is divided into two stages (see Figure 3.6). The first stage, „Response Activation“, still runs in parallel with the other stage and is where crosstalk effects can occur. The second stage, „Response Selection“, is again limited in capacity. Thus, the central processing of the second task affects the central processing of the first task before the bottleneck stage of the first task is completed. According to crosstalk logic, two tasks are rarely processed independently of each other [NM87]. Thus, the processing in the second task may even facilitate the activation of the response in the first task [Hom98]. The following holds: the greater the temporal proximity or high task similarity, the greater the likelihood of interaction between tasks [FP15; Dun79; NM87; NM02; Hom98; LS00; KP02; Mil05; FMS07].

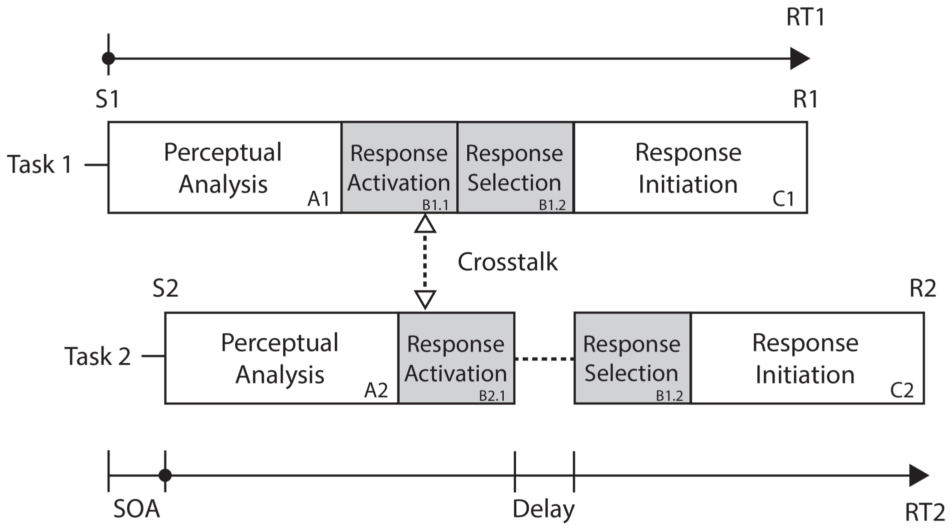


Figure 3.6: Backward crosstalk model for dual-task performance. S1, stimulus for Task 1; S2, stimulus for Task 2; R1, response for Task 1; R2, response for Task 2; RT1, response time for Task 1; RT2, response time for Task 2; SOA, stimulus onset asynchrony (own illustration based on [Jan+14; FP15]).

3.1.2.2 Capacity Sharing

Similar to crosstalk, resource models also assume a strict capacity limitation of central cognitive processing [FP15]. Two different resource models can be distinguished in the literature – models of a non-specific central resource [Kah73] and models of multiple specific resources [Wic84; Wic02].

Sharing Models of a Non-Specific Central Resource

Assuming a non-specific central resource, limited processing resources can be divided between two tasks in different proportions (see Figure 3.7). The more resources are shared, the greater the parallelism. Available resources are therefore scheduled for processing a specific task and can be allocated or shared [Kah73; NB75]. For example, in an extreme form of resource allocation, a processing bottleneck would occur if all resources were allocated to a first task and none to a second. These models can be used to explain the frequently observed findings of crosstalk between tasks in PRP-like paradigms [FP15].

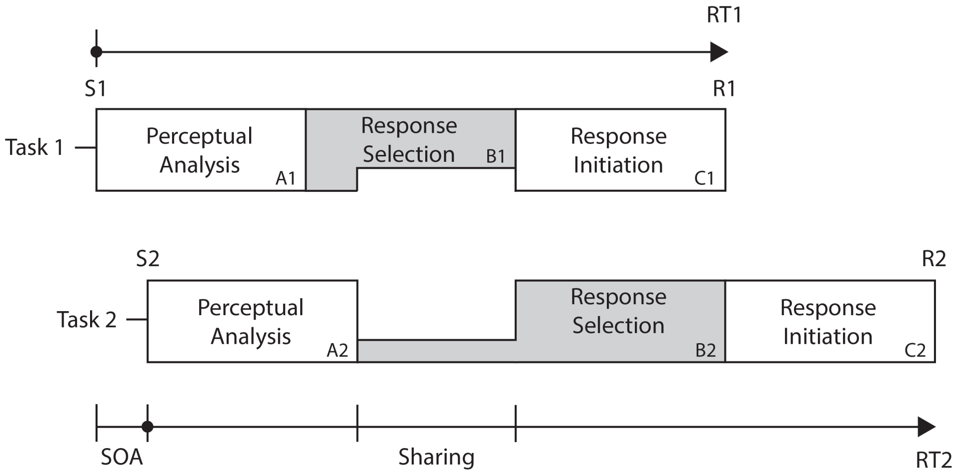


Figure 3.7: Capacity sharing model for dual-task performance. S1, stimulus for Task 1; S2, stimulus for Task 2; R1, response for Task 1; R2, response for Task 2; RT1, response time for Task 1; RT2, response time for Task 2; SOA, stimulus onset asynchrony (own illustration based on [FP15]).

Sharing Models of Multiple Specific Resources

Multiple specific resource models [Wic84] assume that the processing bottleneck is flexible and arises because two central processes require access to the same cognitive resources [FP15] – in other words, it does not necessarily assume that resources are generally limited. In flexible resource allocation, the allocation of attentional resources depends on instructions [LH08], task priority, and outcome value [Wic+03]. These models assume a strategic and flexible allocation of processing capacity through so-called cognitive control processes [FP15]. When two competing processes need the same access to local and task-specific resources, a bottleneck occurs. For example, several studies [AAR72; Wic84] have shown that when we process two very different tasks, we are able to demonstrate parallel processing of both tasks with a quality comparable to the processing of individual tasks [FP15]. At a concert, for example, we can enjoy this ability when a musician sings (Task 1) and plays a beautiful piano piece at the same time (Task 2). Not to mention that the musician sometimes has to read the sheet music (Task 3) (cf. [AAR72]).

3.1.3 Human Time Perception

Unlike other perceptual mechanisms, the human perception of time is not so easy to grasp because we lack a specific sensory organ for perceiving temporal sequences comparable to the eyes and ears that are responsible for perceiving light and sound. In other words, there is no separate receptor system responsible for perceiving time [Wit09]. However, psychological studies have shown that cognitive functions such as attention, working memory, and long-term memory affect our perception of time. Emotional states and personality factors also play a role. For example, time is also perceived subjectively, with pleasant events seeming to pass more quickly than boring ones. Our perception of time is thus the result of a complex interplay between specific cognitive functions and our current emotional states [Wit09].

3.1.3.1 Perspectives in Time Estimation

When estimating time, existing cognitive models make a fundamental distinction between two perspectives: prospective and retrospective estimation.

Prospective Time Estimation

We are able to correctly assess a time schedule prospectively in order to derive timed behaviors [RMH01; Gro10]. These behaviors depend on explicit prospective temporal judgments [RMH01], which in turn are known to be individually more or less good. With the help of this ability, we are able to perform several essential tasks [Gal90] such as rapid (re)planning or decision-making in the millisecond to minute range (e.g., [AOB21; Gro10; Gib+88; Mec03]). Moreover, in addition to estimating the time of a future task (e.g., [Gro10; RC08; RCM05; THN07]), the so-called prospective (time) memory allows, for example, to formulate promises in order to execute them in the appropriate context at a time (e.g., 8 pm) or in a period (between 2 pm and 4 pm) in the future [Gro10]. Most theoretical models describing prospective time perception are based on similar scientific approaches [Wea99; RMH01], including an internal timer, attention, and memory [GA84; MM00]. For example Gibbon and Allan [GA84], describe a well-known and often cited approach in terms of a clock metaphor [Mec96; GG00; RMH01]. In addition to the so-called clock as a timekeeper, a working and reference memory is used to temporarily or permanently store time measurements. In one study, the records of time intervals in the working and reference memory were compared using a binary decision process that specified whether to respond or not [GA84].

Retrospective Time Estimation

In retrospective perception, time judgments are based on past events. We are able to judge the duration of a past event, which in turn helps us to derive prospective time durations from our experience. Most theoretical approaches study retrospective time estimation by estimating the duration of a time interval that has already passed [Wit09; BGZ18; Bro85; Ünv23]. The estimate of duration must then be reconstructed from memory. Retrospective judgments can be based on time intervals ranging from a few seconds (short-term memory) to a lifetime (long-term memory) [Wit09]. The more contextual changes or changing experiences we have within a period of time, the longer the duration is subjectively experienced [Ünv23; Wit09; BR78], as these experiences are also stored in memory. In addition, time intervals for novel activities are perceived as longer than those for familiar, routine activities. When two identical stimuli are presented consecutively for the same duration, the first time interval is perceived as longer than the second. The perception of a longer duration of the first stimulus is explained by the presence of larger and more novel contextual changes during the first duration. Thus, the subjective evaluation of duration is dependent on activity and experience.

3.1.3.2 Time Perception Factors

In this section we will look at the possible factors that influence the perception of time. In doing so, we will consider factors that may be relevant in the context of this work due to the issue of supporting time-critical work scenarios. These include attention, task difficulty, and spatiality.

Attention-Dependent Time Perception

Based on the assumptions of the Attentional-Gate Model (AGM) of time perception, we perceive time through an internal clock [Blo90]. This internal clock is supported by a cognitive mechanism consisting of a pacemaker and an attentional gate. The pacemaker continuously sends out impulses that are registered by the attentional gate. We therefore perceive time by unconsciously comparing the number of received impulses with a so-called reference memory (cf. the clock metaphor of Gibbon and Allan [GA84]). When we pay more attention to certain temporal components, the attentional gate opens and allows more pacemaker impulses to pass through. The more attentional resources we devote to a temporal component, the longer its duration is perceived to be [BZ97]. The degree of attention is therefore closely related to human perception of time (e.g., [Bro85; RMH01; Fra84; Stu25; Jam90; Fra59]). For example, when we pay attention to time in everyday life, it sometimes seems to crawl by during a boring event such as sitting in a waiting room, while it seems to fly by during an evening of games and lively conversation. Situations of impatience, anticipation, or boredom require a heightened awareness of time. This, in turn, leads to a subjective slowing of time

[Bro85] and describes the well-known „watched pot“ effect [Fra63; BGR80; CE80; Zha+15], in which participants were asked to estimate when the water in a pot on the stove would begin to boil. One group of participants was given the task of observing the pot and giving a signal when the water began to boil. They were then asked to estimate the time in a given interval, while a control group without the observation task gave significantly shorter time estimates. The popular expression „a watched pot never boils“ is therefore derived from the psychological „watched pot“ effect and means that time seems to pass more slowly when you are impatiently waiting for something. In contrast to a „boring“ activity, temporal awareness is relatively minimized during a „captivating“ activity, and thus the perceived duration of time is shortened (cf. [Bro85]). In addition, there is a systematic shortening of the subjective perception of time when attention is distracted by something (cf. [RMH01]). Thus, the timekeeper’s impulses may also be lost during distraction [Bro85]. According to Zakay and Block [ZB96], attention can also mediate the flexible starting and stopping of the timekeeper impulses, which in turn enables the anticipation of predictable events and thus the prospective perception of time. In summary, the representation of the subjective perception of time is formed by the interaction of time measurement and so-called attention mechanisms (see [RMH01]).

Task-Dependent Time Perception

Several studies have found that prospective estimation of a given duration depends on the complexity of the task [Zak93; ZB96]. This, in turn, is closely related to attention, as complex tasks are generally more „engaging“ and thus require more attentional resources. Accordingly, for tasks that last the same amount of time, we make longer prospective estimates for simple tasks than for complex tasks, because they are presumed to require less processing effort and therefore less attentional resources [ZB96]. An important aspect of these studies is that in addition to the complexity of the task, the „mental“ allocation of the task also plays an important role. Is it my main task or is it just a secondary task that I have to do in addition? According to Wickens [Wic84], for example, differences in the resource demands of the primary task affect the performance of the secondary task (see Section 3.1.2). Time processing is negatively affected by the attentional demands or workload of a non-temporal (secondary) task [Bro97; Mio18]. Depending on whether the time estimation task is treated as primary or secondary, the prospective time estimates change. In this context, the prospective time estimate is increased when it is a primary time estimation task. This is explained by the fact that more resources are presumably allocated to the processing of a primary task [Mio18].

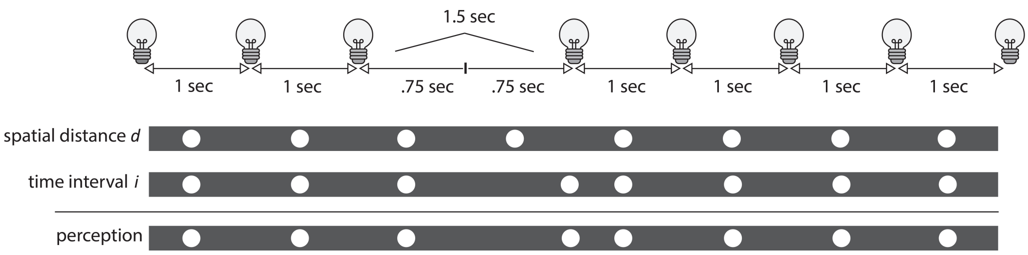


Figure 3.8: Influence of time information on a spatial distance (own illustration based on [SGP07]).

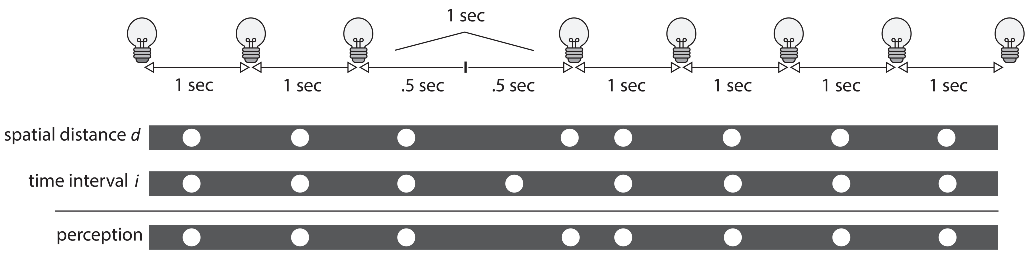


Figure 3.9: Influence of spatial information on time perception (own illustration based on [SGP07]).

Spatial-Dependent Time Perception

In addition to attention and task complexity, time perception can also be related to spatial perception. One example is the so-called tau effect, which describes the influence of temporal information on spatial distance [Gel14][4]. For example, several points of light are presented one after the other at the same spatial distance. If the time intervals between successive points of light are changed, the spatial perception also changes (see Figure 3.8). If the fourth light point follows the third light point at a greater time interval than the third light point follows the second light point ([i2+i3] < [i3+i4]), the third light point appears farther away from the fourth light point than it does from the second light point. If the time interval were smaller instead of larger, the third light point would appear closer to the fourth light point. Thus, temporal distance has the same effect on spatial perception. A similar interaction is described by the so-called kappa effect, in which spatial perception in turn influences the perception of time [CHS53]. Estimates of time are thus influenced by the spatial context of the stimulus arrangements (see Figure 3.9). For example, several light points are presented at the same temporal interval but at different spatial intervals. In the subsequent evaluation of the temporal intervals, the light points with a greater spatial distance are also assigned a greater temporal distance, although it remains constant. The example

[4] The tau effect was first mentioned by Benussi in his 1907 paper. However, Adhémar Gelb (1887-1936) is often credited with discovering the tau effect, although his paper was not published until 1914 (see [Eva08], p. 80f; [OTM05], p. 79f).

shows eight light points with the same temporal interval (i3 = i4) but different spatial distances (d3 ≠ d4). Here, the temporal interval (i4) is estimated to be longer, corresponding to the larger spatial distance (d4).

3.2 Augmented Reality

The fundamental idea of AR is to change the user's perceived reality by superimposing digital information on the real environment [ZDB08; Azu97]. This superimposed information allows real-world objects to be annotated by AR, which is useful for providing users with additional information [Ros+95]. In particular, AR allows the accurate and precise mapping of real objects to future positions with a virtual model. For example, parts of an assembly process can be positioned virtually in advance, and a user gets an accurate (spatial) impression of the required assembly position before the actual assembly process starts [Alv+19; Pla+19; Hoo18]. In the following chapters, we would like to provide an insight into current AR technologies in order to define specific technologies that are used to visualize support options for time-critical, parallel, and spatially distributed tasks for the user. First, the definition of AR is given. This is followed by an insight into how it works.

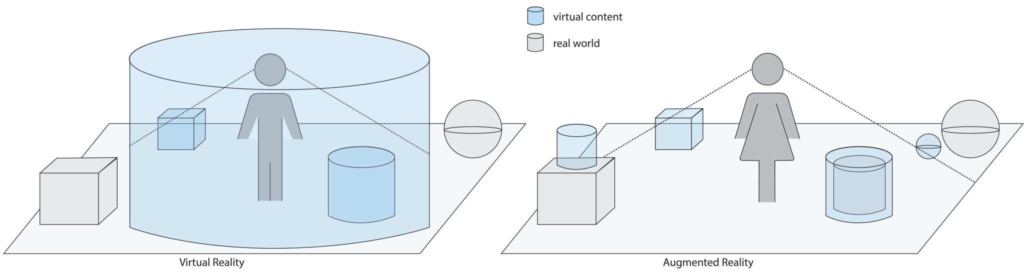


Figure 3.10: Interaction Models in VR and AR (own illustration based on [Dör+19]).

3.2.1 Defining Augmented Reality

To better understand AR, we first need to briefly introduce Virtual Reality (VR), which is necessary to better differentiate between the two technologies. Muhanna [Muh15] defines VR as a three-dimensional, fully computer-generated environment in which we are immersed through the use of appropriate hardware [Kin+19]. With this technology, we experience the simulated world „from the inside" in a perfectly immersive VR; we are completely cut off from the real world outside [Dör+19]. Unlike VR, in AR we can interact with both virtual content and the real environment. In addition, interaction between the real environment and the virtual content is possible – the virtual content and the real environment are not strictly separated but can overlap, superimpose, and penetrate each other

[Dör+19]. Figure 3.10 shows both technologies. In short, VR (left) replaces our perception of the real environment with a virtual environment. In contrast, AR (right) enriches the perception of the real environment with virtual content. Accordingly, there is no complete immersion with AR comparable to VR [Dör+19]. In addition to AR, the term Mixed Reality (MXR) is often used; unlike AR and VR, however, it is not a technology but a continuum [MK94]. Figure 3.11 shows the reality-virtuality continuum from Milgram and Kishino [MK94]. From left to right and away from reality, the virtual content increases. While VR fully immerses us in a digital environment, AR is a combination of our physical environment and virtual elements that together create a mixed reality in real time. AR complements our reality rather than replacing it [Azu97].

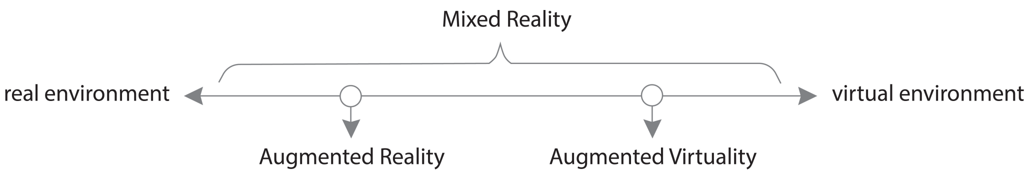


Figure 3.11: Reality-virtuality continuum (own illustration based on [MK94]).

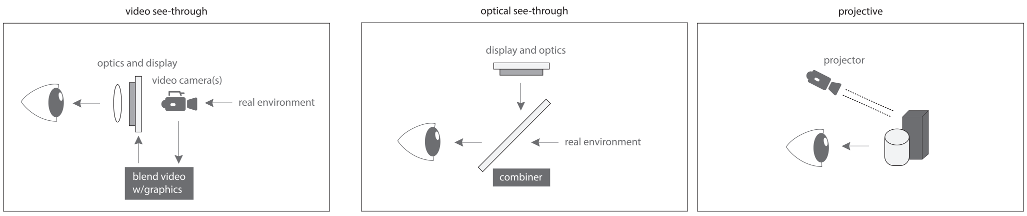
Simply put, the difference between AR and VR is the degree of immersion. Immersion, from the Latin „immersio“, is an indicator of the experience of an artificially created, realistic environment [Kin+19; DS19]. To create an authentic experience and a high degree of immersion, we are presented with illusory stimuli. These stimuli are primarily visual and auditory, but increasingly haptic, to create a perception of reality [Kin+19]. While AR applications generally have a low degree of immersion (reality does not need to be simulated, it is already there), VR applications strive for the highest possible degree of immersion.

3.2.2 (Realization) Forms of Augmented Reality

According to the definition of Azuma [Azu97], an AR system must fulfill three characteristics:

1) AR combines real and virtual elements (we can see both at the same time),
2) AR is interactive in real time (we can interact with virtual content), and
3) AR is registered in 3D (virtual objects have their fixed reference points in space).

AR merges reality with virtuality [MK94]. It is crucial that the extension of the real environment with virtual content is not static and one-time, but continuous and adapted to our current focus. Up to five steps are therefore necessary to implement an AR application: video recording (depending on the form of realization), tracking, registration, display, and output [Bro19]. More information about the technical realization of these steps can be found in Dörner et al. [Dör+19]. In the following, we will discuss the basic forms of AR and compare them in terms of their limitations and capabilities.



(a) Video see-through AR. (b) Optical see-through AR. (c) Projective AR.

Figure 3.12: Simplified representation of the (realization) forms of AR: a) video see-through AR combines virtual elements and recorded video of reality, b) optical see-through AR allows a direct view of the real environment through optical combiners, and c) projective AR projects virtual elements directly onto real objects (own illustration based on [Azu18]).

Video See-Through AR

Video see-through systems combine a synthetic image with an image of the real world captured by a camera (see Figure 3.12a). Reality is represented by a camera image and combined with virtual information. The digitized reality makes it easier to transfer or remove real objects. In addition, the digitized images allow motion tracking for better registration [KP10]. In such systems, dynamic and static capture problems can be solved. Dynamic problems can be solved by having the computer track the image being displayed. Static errors do not occur because there is no offset between the image and the position of the tracker. In addition, the brightness and opacity of the images can be adjusted. However, the quality of video see-through systems depends on bandwidth and resolution. Simultaneity is also limited due to delays in image transmission. There is also the problem of system crashes, in which case only a black screen is visible. Another disadvantage is the limited depth perception [Pfe+21], which makes it difficult to estimate distances.

Optical See-Through AR

Optical see-through systems combine computer-generated images with the real world through an inclined, semi-transparent mirror [KP10] (see Figure 3.12b). In contrast to video see-through systems, a video recording of the real environment is not absolutely necessary. We perceive the real environment directly by having virtual elements optically superimposed on reality by an output device. For this reason, a semi-transparent display is necessary so that the reality behind it and the additional virtual elements can be perceived. Our focus in relation to the display must be known so that the perspectives of the real environment and the virtual extension match. This requires that each eye has its own display. In the case of a stereoscopic display, which is viewed with both eyes, the perspective can be set correctly for each eye. In the case of monoscopic displays, which are viewed with both eyes, the perspective fits at most one eye and in the case of portable devices such as tablets or smartphones often neither eye [Bro19]. By looking through a semi-transparent display, the maximum perceived reality can be achieved. In addition, a head-mounted display (HMD) can be worn in off mode [KP10]. A particularly important feature is the depth perception of optical see-through displays, which makes it easier to estimate distances, for example.

Projective AR

Projection-based systems project virtual elements into the real environment using projection mapping techniques [LCZ22; Iwa24] (see Figure 3.12c). These systems are a form of so-called spatial AR and allow the visualization of virtual elements without external systems such as headsets or portable devices [Iwa24; BR05]. However, this also makes it clear that projective AR is generally used in a stationary context (see Section 4.2.2). Nevertheless, projection-based systems have the advantage that no additional systems need to be carried or held, and AR elements can be viewed simultaneously with others without a network connection. However, since projection-based systems cannot create new spatial structures, they are often limited to manipulating surface properties (such as color or texture) and displaying additional information on the surface (explanations, highlighting, symbols, etc.) [Bro19].

3.2.3 Head-Mounted Augmented Reality

In this chapter, we look at different technical solutions for head-mounted AR, assuming that freedom of movement, stereoscopic vision, hands-free use, and advanced augmentation will make it preferable to portable devices such as tablets or smartphones in the future. According to Azuma's [Azu97] three characteristics of an AR system, we can deduce that smart glasses such as Google Glass are not true AR devices, even though they are often referred to as such. There are two basic approaches to AR glasses: with optical see-through displays (OST displays), real and virtual images are optically superimposed. With video see-through displays (VST displays), the environment is captured by a camera and overlaid with the virtual content as part of the rendering process [Gri+19] (see Section 3.2.2). In the following subchapters, OST displays and their structure will be examined in more detail, before VST displays will be discussed further.

3.2.3.1 OST AR Displays

OST displays always provide a direct and immediate view of the real environment, while virtual elements are merely optically superimposed. This allows us to use them without any limitations in terms of quality and resolution. However, the background contrast of these displays is low in bright environments, and the virtual, superimposed elements are perceived as transparent compared to reality due to the low luminance of the display relative to the ambient light. For this reason, in bright environments, the overlay technique is adjusted using appropriate filters that reduce the transparency of the virtual objects in order to achieve the required background contrast for a given luminance. These various overlay techniques reduce the amount of incident light, making the surrounding reality appear darker. OST displays are therefore not suitable for use in sunlight, or only to a limited extent [Gri+19]. To get an impression of the design of the OST display used in this work, a more detailed description of waveguide-based displays is provided below.

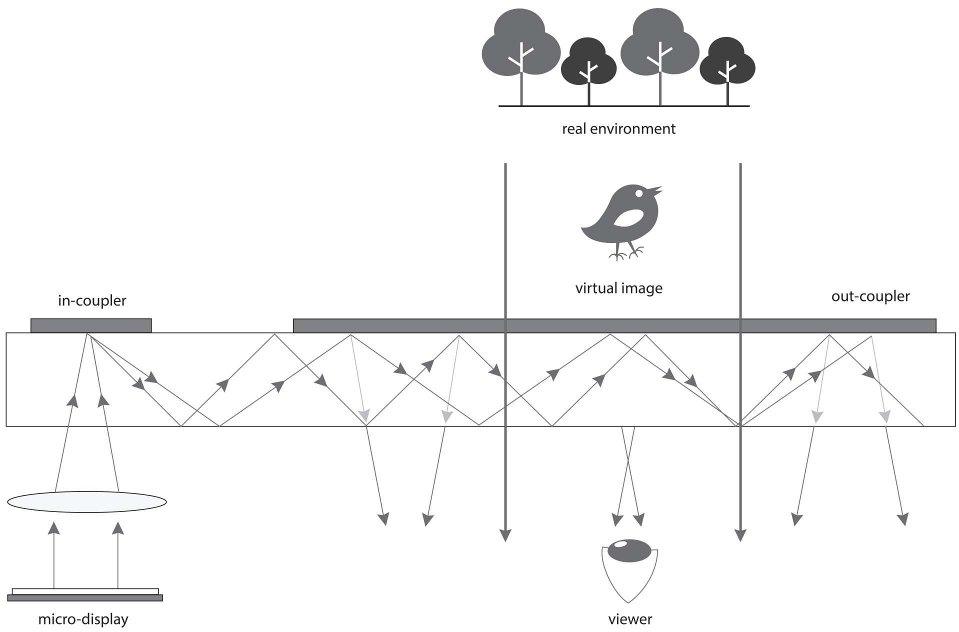


Figure 3.13: Waveguide-based AR displays with diffractive in- and out-couplers (own illustration based on [Sci23; Liu+20; Din+23]).

Waveguide-Based AR Displays

In waveguide-based approaches, light is coupled via a display into a waveguide, a largely flat glass body that serves as a light guide and propagates within it by internal reflections – it is reflected back into the waveguide at the outer sides and guides the light to the next structure. So-called coupling-in and coupling-out structures are applied to the glass body itself, allowing the light to enter (coupling-in) and leave (coupling-out) the waveguide (see Figure 3.13). The decoupling structures are arranged in such a way that the light leaves the waveguide at the corresponding point in the direction of our eye and becomes visible to us (as superimposed on the real environment). Since the waveguide is transparent, we can see both the real environment and the projected image at the same time. Waveguides are limited to reflecting one color of light. For a full-color display, three layers of waveguides must be placed on top of each other, as each color channel (RGB) is transmitted separately [Gri+19]. There are three basic types of waveguides (called combiners): diffractive, reflective, and holographic. They differ in how the light is guided through the waveguide and how it is combined with the view of the real environment. This allows us to see both the projected image and the real world at the same time. A more detailed description of the different combiners and their advantages and disadvantages can be found in Ding et al. [Din+23].

3.2.3.2 VST AR Displays

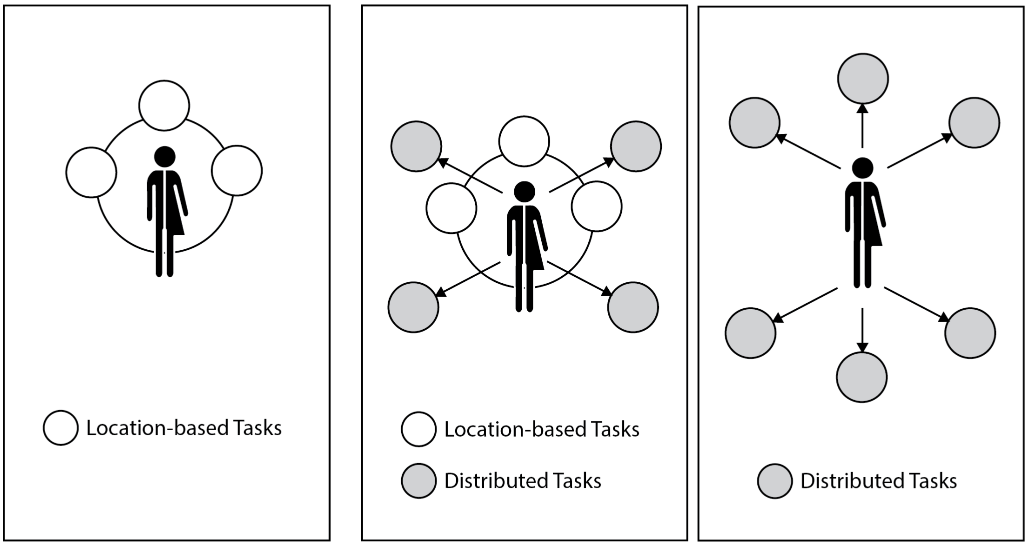
VST displays are basically HMDs that are also used in VR technology. In a completely enclosed design, we are initially completely shielded from our surroundings. VST displays almost completely encompass our natural FOV [Gri+19]. However, unlike VR, we do not want to immerse ourselves in a fully simulated artificial environment. To use VST displays for AR experiences, the real environment is captured in a video stream with calibrated cameras, giving us the impression that we are looking at our surroundings through the glasses [Bro19; Gri+19]. A simplified illustration is shown in Figure 3.12a from Section 3.2.2. For this purpose, video cameras are attached to or integrated into the display. Slightly different (offset) images are then displayed on two lenses to create a spatial impression (see Section 3.1.1.2). Our eyes perceive only the information projected by the display, i.e., all objects are on the same focal plane. In addition, the perception of our real environment is only possible with a reduced resolution and a limited dynamic range compared to the direct view with our eyes [Gri+19].

3.3 Working Environments

In this chapter, we focus on a detailed description of work environments in which the processing of time-critical tasks is an important component. To fully capture the dynamics of such environments, additional environmental variables must be considered. This view allows us to understand the process structures and human activities. A structured overview forms the basis for the design of subsequent support options. This overview is deliberately detached from a specific use case, as in Chapter 2, to ensure the applicability of our findings to a variety of work environments with time-critical challenges. A central aspect of our description is the characteristics of tasks – such as their criticality, their location, and the distinction between object-bound and object-unbound tasks. We further elaborate on the execution of tasks by highlighting sequential and parallel processing. We also consider the challenges, including the role of cognitive processes and extrinsic factors.

3.3.1 Characteristics of Work Tasks

When considering the different work scenarios (see Chapter 1), the inherent characteristics of the tasks, i.e., their complexity, their localization, and their criticality, are crucial. Understanding these characteristics helps to better grasp possible challenges and needs in work environments.



(a) Location-based. (b) Partially distributed. (c) Distibuted.

Figure 3.14: Different forms of task localization (own illustration).

3.3.1.1 Location

Task location determines where tasks are performed. There are tasks that are assigned to a fixed workstation and therefore have a fixed location and tasks that are distributed across multiple workstations [BSR15; Lat+18; IAO24]. An obvious example of task location is cooking [PKS15]. The preparation is distributed spatially in the kitchen (room). Locations in the kitchen can be the oven, the sink, or the cutting board. For example, all ingredients are cooked at the stove location, washed at the sink location, or baked at the oven location. Tasks are distributed spatially in the room and performed at different locations.

Location-Based Tasks

Location-based tasks are tasks that are tied to a specific location and are performed only at that location (see Figure 3.14a). It is not necessary to change locations to perform the tasks. An example is packaging workstations [Sto16; Qur16], where workers are tied to a workstation to package various products for dispatch. All necessary items such as labels, shipping boxes, stamps, and printers are also located at the assigned workstation so that all tasks can be performed at this specific location.

Distributed Tasks

Spatially distributed tasks describe tasks that are distributed across multiple locations and require coordination or interaction between these locations [Lat+18; IAO24]. There are two types of spatial distribution:

1) A person is assigned to a fixed location, but must leave the location (workstation) to perform (sub)tasks (see Figure 3.14b). For example, equipment, tools, parts, or supplies are located at another workstation or in other rooms, and the workstation must be left to complete subtasks, such as picking up needed supplies.

2) A person is not assigned to a fixed location and must change locations to perform tasks (see Figure 3.14c). For example, a work piece may need to be completed at different workstations, such as the paint station, the sanding station, etc. Another example is nursing tasks that are distributed to different wards. To care for a patient, medication must be picked up from the pharmacy, food must be picked up from the trolley, or bed linens must be taken to the laundry. All the necessary items are distributed to the different workstations, so most of the tasks have to be performed spatially distributed.

3.3.1.2 Object Binding

Looking at object binding provides insight into how tasks are structured and managed. There are tasks that are bound to a specific object [FJ18] and tasks that must be performed independently of an object. As with location, cooking is a tangible example of object binding. For example, chopping the ingredients for a salad is an object-bound task in which certain objects – in this case, the ingredients, such as tomatoes, cucumbers, and lettuce leaves – are processed using a tool, a knife.

Object-Bound Tasks

Object-bound tasks are tasks that are directly related to a specific object or person [DK18; FJ18; LW13]. This type of task requires direct interaction or manipulation of the object to bring it to the desired shape and size. An example of this type of task is a fixed fixture into which certain work pieces must be clamped (e.g., the gluing device in Section 5.2.1). Another example is the assembly and bolting of parts to a specific workpiece [FJ18]. Maintenance and repair tasks performed by technicians directly on machines are object-bound tasks as well. Similar to object-bound tasks are person-bound tasks – for example, applying bandages, administering medication, or handling probes and catheters are also object-bound (in this case, of course, person-bound) tasks [Cob21]. In all of these examples, the tasks are closely related to the objects to which they refer. The objects are central to the performance of the tasks, and the tasks themselves are designed to interact with, manipulate, or transform these objects.

Object-Unbound Tasks

Unlike object-bound tasks, object-unbound tasks are planning, organization, monitoring, and analysis tasks that can occur in different work environments [FJG18; YAHN07; Ant+21]. Examples are work planning and preparation tasks. For example, certain work processes must be planned, resources must be allocated, and schedules must be created before the actual assembly or patient care can take place [Hab07; FJG18; LW13]. This preparation phase includes tasks that have no direct contact with the parts to be assembled or the patient. Another example of object-unbound tasks is documentation, which is critical for quality, communication, and continuity of task completion.

3.3.1.3 Difficulty

The difficulty of work tasks has an impact on our physical and mental effort [GCM12; Ale+24; HSK02]. However, assessing task difficulty is very complex, even though there are tasks that are clearly physically or mentally demanding. Each work environment has its own level of task difficulty – whether it is assembly, cooking or caregiving – and each environment has its own challenges that are not always apparent at first glance [Her78]. In addition, difficulty often depends not only on the nature of the task itself, but is also strongly influenced by the individual skills, experience, and well-being of the person performing the task. Therefore, the perception of difficulty can vary from person to person. What is easy for one person may be challenging for another due to differences in ability or prior knowledge. These individual differences make it necessary to evaluate tasks not only according to their objective difficulty but also according to the subjective perception and abilities of the individual. According to our observations (see Chapter 2), the difficulty of a task is also influenced by other factors that may make it more difficult to complete. These include the prioritization between different tasks, the location where the tasks are performed, and the number of tasks. These factors can cause tasks that appear simple to be very complex (see Section 3.3.3). By taking into account individual skills and needs as well as the other factors that influence task difficulty, a work environment can be created that allows for efficient performance while being supportive.

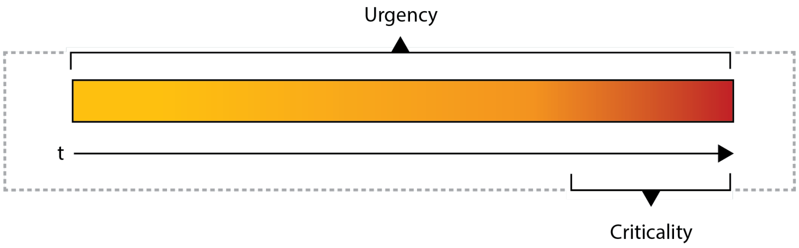


Figure 3.15: Distinction between urgency and criticality. The less time t there is to complete urgent tasks, the more critical they become (own illustration).

3.3.1.4 Prioritization

Prioritizing tasks allows for the optimal use of available (time) resources during a work process. Prioritization is therefore particularly important in work environments where time, accuracy, and resource optimization can make the difference between success and failure. Why and how tasks are prioritized depends on various factors such as availability, dependencies, and urgency of the tasks [FJG18; LW13]. For example, resource availability plays a role, and tasks for which all resources that are needed are available can be prioritized. Another factor is the dependency between tasks. In many cases, the start or completion of one task depends on the completion of another (see Section 3.3.2). Prioritization can ensure that all tasks are completed in the correct order and on time. Another important factor is the urgency of the task – urgent tasks usually cannot be postponed without negative consequences. For example, tasks with fixed or approaching deadlines are often given higher priority because failure to meet them can have negative consequences, such as economic damage. In this context, time is a key factor. The shorter the time to complete urgent tasks, the more critical they become. For this reason, we distinguish between urgency and criticality in this thesis (see Figure 3.15). An urgent task may not always be critical, a critical task, on the other hand, is also urgent. Critical tasks can not only not be postponed without negative consequences, but also require immediate attention. For this reason, time plays a key role in critical tasks.

Time Criticality

Time-critical tasks include all tasks that are subject to time constraints. Consideration of time criticality is crucial because it determines the urgency and priority of tasks. Representative time-critical tasks can be found in many work environments, such as patient care, assembly, or even everyday cooking. For example, when cooking, there are specific times that must be followed or the food may be undercooked, overcooked, or burned. In bonding processes, different times [Ras12; Hab03; Hab12] must be observed depending on the joint being glued, otherwise the joint may fail. In addition to the economic damage, this can lead to serious accidents in the worst case, for example, if a windshield comes off (to exaggerate). Finally, in order to preserve human dignity in patient care, situations such as changing bed linen after bedwetting must be carried out very quickly. In addition to strict time constraints [Han19; Kon+10; Cob21], such as time for examination and medication at specific times, adherence to time constraints in patient care can mean the difference between life and death in the worst case.

3.3.2 Execution of Work Tasks

Looking at task execution provides insight into the structure and performance of existing processes. This allows us to identify potential weaknesses such as bottlenecks, overworked staff, and other process deficiencies. Therefore, it is important to distinguish between single and multiple tasks in task execution.

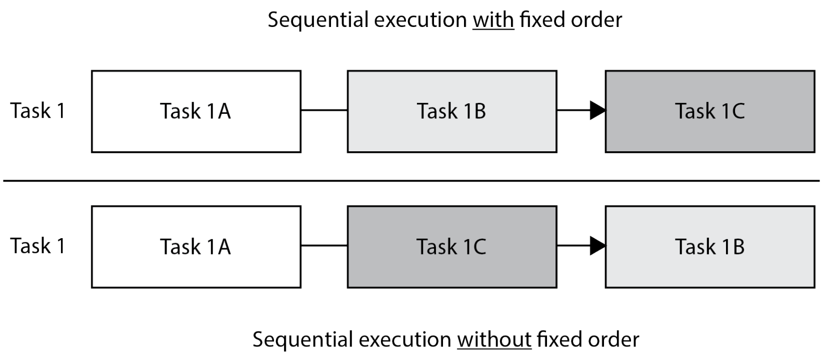


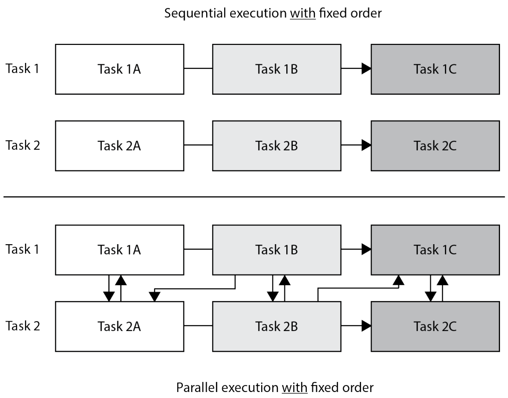
Figure 3.16: Sequential execution of single tasks with fixed and flexible step order (own illustration).

Single Tasks

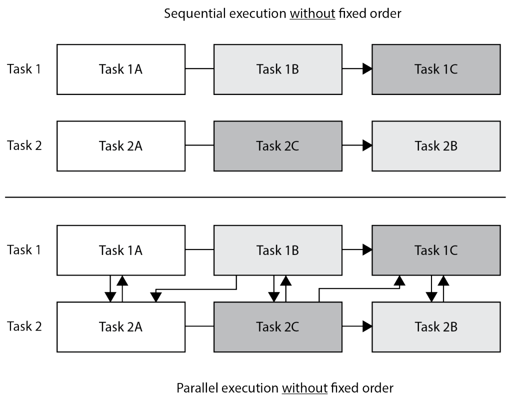
These tasks consist of a number of different steps and are therefore performed sequentially (see Figure 3.16). One step is often directly dependent on the previous one – for example, when making pasta, the water must be boiled before the pasta is added to the water. However, strict adherence to this order is not mandatory in every context, as some processes allow the order to be reversed, such as washing and chopping lettuce. In this case, it does not matter whether the lettuce is washed before or after chopping.

Multiple Tasks

Multiple tasks can be performed sequentially, just like single tasks, or in parallel (see Figure 3.17). Staying with the cooking example, a recipe usually consists of multiple tasks – for example, preparing a tomato sauce in addition to the pasta. In a sequential execution, we would cook the pasta first and then prepare the tomato sauce. This would be impractical, however, because 1) we would not have used the waiting time while cooking the pasta and 2) the pasta would be cold when the tomato sauce is ready. If we were doing this in parallel, we would probably start making the tomato sauce while the pasta was still cooking so that we could prepare both at the same time. For this reason, multiple tasks are often performed in parallel to bridge waiting times and increase efficiency. In many real-world work contexts, there are other factors to consider when performing tasks in parallel [Lap11], such as when task switching is required to ensure that all tasks are completed at the same time [Pik17; KA10; Chi+00]. Of course, task switching also causes an interruption of the current task [KTL17], meaning that it is important to know when an interruption is possible and how to resume a task.



(a) Sequential and parallel execution of multiple tasks with fixed step order.



(b) Sequential and parallel execution of multiple tasks with flexible step order.

Figure 3.17: Sequential and parallel execution of multiple tasks with fixed and flexible step order (own illustration).

3.3.3 Challenges of Work Tasks

By gaining insight into the task and execution characteristics, we can derive the inherent challenges of processes in different work environments. According to this, location, object binding, difficulty, prioritization, especially the consideration of criticality, as well as the sequential and parallel execution of work tasks play an important role. These challenges can also influence cognitive load by increasing task complexity. In this context, we were also able to identify some task and execution characteristics as potential factors influencing task complexity. For example, three key factors – namely, parallel execution (see Section 3.3.2), location (see Section 3.3.1.1), and task criticality (see Section 3.3.1.4) – can influence complexity.

Accordingly, the complexity of tasks may increase when they are performed in parallel and distributed across multiple locations. From a cognitive psychology perspective, the resulting increased mental load may be caused by our processing bottleneck, in which two competing cognitive processes require the same access to local and task-specific resources [FP15] (cf. Section 3.1.2). The more different the tasks are, the more likely we are to be able to multitask, because different task-specific resources are required for cognitive processing [Wic02] (cf. Section 3.1.2.2). If time pressure (cf. Section 3.3.1.4) is added to the parallel and spatially distributed execution of tasks, the complexity of execution increases significantly. The resulting stress can be explained by the fact that our perception of time is negatively influenced by the attentional demands or workload of a non-temporal (secondary) task [BGZ18] (see Section 3.1.3.2). Other stressors may include interrupting the current task to perform another critical task (see Section 3.3.2). In this context, a quick overview is required both when starting the new critical task and when resuming the interrupted task in order to reduce mental stress.

In addition to these challenges, there are domain-specific requirements to consider. For example, certain hygiene regulations play an important role in different work environments, and workers need to be equipped with gloves. Workers in a bonding process, for instance, need gloves because they handle hazardous chemicals, while caregivers need gloves to prevent infection and avoid cross-contamination. For this reason, hands-free working must be possible at all times to support the tasks.

While internal factors of the work environment are known in advance, such as the inherent time constraints of tasks, external factors can affect task performance. External factors tend to be unpredictable and more difficult to capture. Examples include changes in the work environment due to weather-related changes in lighting, or unexpected changes in noise levels due to a construction site. Sudden additional tasks can also be considered external factors because they can unexpectedly prevent us from completing our current work tasks – for example, a colleague suddenly needs help because they can no longer hold an object or position. We are all familiar with unexpected situations that require our immediate attention and interrupt our current task. Due to the complexity and multifaceted nature of external influencing factors, they are only included as a supplement in this work, such as adaptation to changing lighting conditions when designing AR support options. Our (main) goal is to reduce the complexity of the task by developing assistive technologies that provide people with better temporal and spatial orientation, reduce cognitive load, and minimize possible errors.

3.4 Summary

In this chapter, we have looked at human perceptual capabilities, AR technology, and task and execution characteristics in different work environments. These fundamentals help us to understand how we can provide people with better temporal and spatial orientation in different critical work environments (see Figure 3.18).

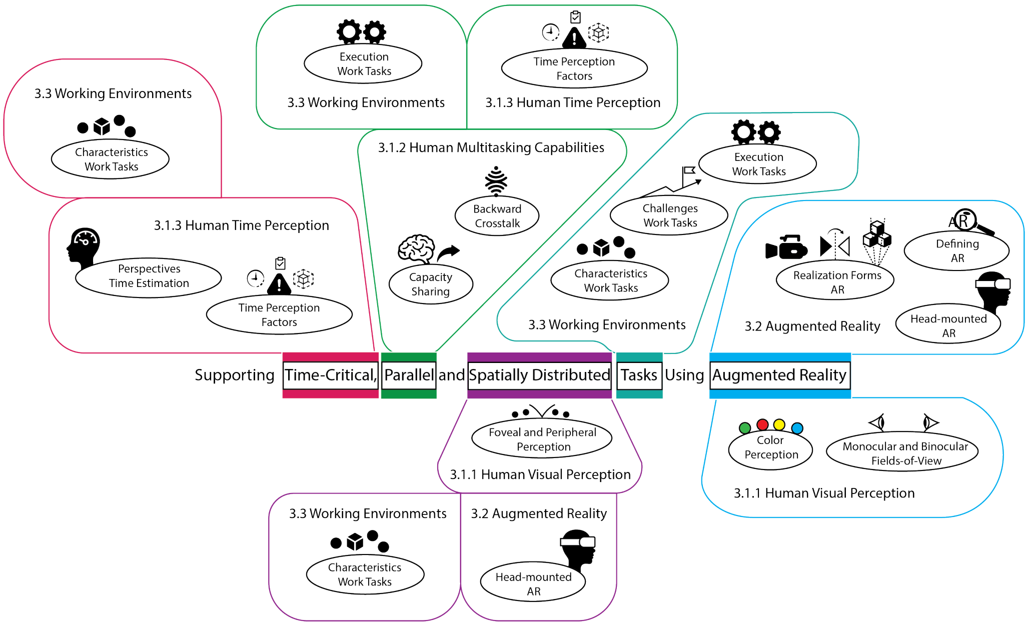


Figure 3.18: Background chapters and their influence on each aspect of the work (own illustration).

A basic understanding of visual perception helps us understand how we process visual information. When displaying temporal information, insight into human color perception is important to understand how and in what range colors are perceived. For example, we know that color is created by the interaction of reflected light with the wavelength-sensitive receptors of the retina. The reflected light depends on the structure and surface of the real environment, and we can design virtual objects in AR so that they are visible when superimposed on the real environment and create the appropriate color impression – for example, virtual AR elements with dark colors are better suited to bright surfaces to be clearly visible and create contrast. The virtual AR elements must therefore be adapted to the real environment. In addition, we know that our visual impressions in the parafovea are less clear due to a lower density of cone and ganglion cells – for example, there are areas in the far periphery that do not allow any color perception at all. Therefore, when supporting distributed tasks, we need to pay attention to the design of possible visual cues to support tasks in the periphery. Another important aspect of visual perception is that each eye perceives only part of the environment, and only when the visual fields of both eyes overlap can depth information be perceived. In this context, depth information is extracted from the two-dimensional retinal images by binocular disparity. This property is also simulated in the technology of head-mounted OST AR displays by overlapping two images, which enables stereoscopic vision and allows us to perceive depth information for visual AR elements through the overlap.

By looking at task and execution characteristics in different work environments, it has been shown that multiple tasks can be performed in parallel. In this context, a cognitive-psychological view of our multitasking abilities is helpful. We were able to show that the parallel execution of tasks can lead to performance losses due to a so-called processing bottleneck (RSB model) [Pas99]. For this reason, executing multiple tasks simultaneously can lead to performance degradation, such as increased response latencies or error rates. However, models such as backward crosstalk and capacity sharing have shown that parallel processing of multiple tasks is possible despite an assumed processing bottleneck. According to crosstalk logic, two tasks are rarely processed independently, and the greater the temporal proximity or task similarity, the greater the likelihood of interaction between the tasks. Capacity sharing models distinguish between the models of a non-specific central resource and multiple specific resources. Under the assumption of one non-specific central resource, limited processing resources can be shared between two tasks in different proportions. Under the assumption of multiple specific resources, the processing bottleneck is flexible and arises when two central processes require access to the same cognitive resources. In this context, Wickens [Wic84], for example, has shown that we are capable of multitasking when working on two very different tasks.

Looking at our perception of time shows that we are able to correctly estimate time prospectively. It is therefore likely that we also estimate task times correctly because we get a sense of them at some point. However, our perception of time depends on several factors, such as attention, task, and space. For example, we perceive a longer duration when we devote more attentional resources to a temporal component. Conversely, there is a systematic shortening of the subjective perception of time when attention is distracted. In this context, the timekeeper's impulses can be lost when distracted. Distractions can occur when multiple tasks are performed simultaneously. For example, the execution of one task must be interrupted when another task becomes critical and requires urgent attention. In such scenarios, the sense of time for these tasks can be lost due to the distraction of the interruption. Therefore, it seems reasonable to continue to show people the times of interrupted tasks so that they do not become critical as well. In addition, our perception of time is also task-dependent and can be negatively affected by processing a second task. This is closely related to the cognitive psychological view of multitasking, in that attentional resources are shared. Therefore, when supporting multiple, parallel tasks, we must keep in mind that not only the execution, but also our perception of time can be affected. Another interesting factor is the spatial dependence of time. For example, temporal information affects our spatial perception. Conversely, our spatial perception can also influence our perception of time. This effect has already been demonstrated in VR and can be used to modulate the subjective perception of time in VR [DP+23].

The insight into AR technology provided us with various approaches to support the described task and execution characteristics. For example, the realization forms of AR can be transferred to the location of tasks. If the tasks are location based, a stationary AR solution could be helpful. This could be realized, for example, with video see-through AR using a monoscopic screen or projective AR using projectors – even if the depth information cannot be displayed on monoscopic video see-through screens. For distributed tasks, we suspect that head-mounted AR may offer more flexible support options due to the freedom of movement and the ability to work hands-free. An insight into head-mounted AR showed us that OST AR displays are probably more suitable than VST AR displays in this context. In OST displays, real and virtual images are optically superimposed, whereas in VST displays, the environment is captured by a camera and superimposed on the virtual content as part of the rendering process. Therefore, with OST AR displays, the real environment is perceived without latency and the headset is not self-contained – when looking through „normal" glasses, OST displays allow for greater immersion and better perception of the environment. In addition, the optical overlay enables stereoscopic vision, which provides depth information for better distance estimation. While the FOV for displaying virtual AR content with OST displays is still very limited, the benefits of stereoscopic vision and instantaneous perception of the real world are crucial in critical work environments.

4 Conceptual Design Decisions

In this chapter, we describe the conceptual design considerations of this thesis that we have derived from our contextual analysis or from previous work. In the first section, we describe the concepts for representing time. First, we discuss the different manifestations of time and explain them in terms of the transferability of our specific use case to other work contexts. We then consider possible visual concepts for conveying temporal information and define the necessary time segments (tenses) of tasks that are required for autonomous task planning. In the second section, we explain the conceptual decisions we made regarding our visual Augmented Reality (AR) guidance. We first discuss the AR form factors we chose and then describe the visualization techniques we used, which we extracted from two focus groups and which were necessary based on the task characteristics described and our context analysis.

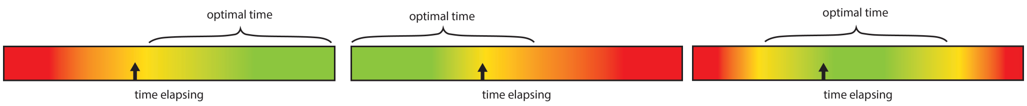
Parts of the work presented in this chapter were published as a full paper at the SUI conference in 2024 [IGH24].

4.1 Representation of Time

Temporal information plays an important role in the context of this thesis (keyword: time criticality). Therefore, we first need to define what manifestations of time can occur in different work contexts. Building on this, we will look at how we can visualize temporal information and look at previous concepts from previous work. In the last section, we define the necessary time segments (tenses) of tasks that we need for autonomous task planning and determine the extent to which we can look into past and future tasks. We explain why each segment is necessary and discuss the practical relevance of giving people a comprehensive view of their tasks.

4.1.1 Manifestations of Time

Our representative use case of the bonding process consists of several tasks with different requirements for their temporal execution. Therefore, we derived different manifestations of time in tasks from our context analysis to better understand the different manifestations that are ideally universally applicable. In this context, we also examined everyday examples of time-critical tasks, including everyday chores and professional applications. In our analysis, we identified three different manifestations: 1) a task has to be started after a specific period (*timer*), 2) a task has to be finished by a specific time (*countdown*), and 3) a task has to be started and finished within a specific time frame (*window*). All manifestations are visualized in Figure 4.1. These manifestations present a complete set, as two are opposite time restrictions (*timer* vs. *countdown*), while the third is simply the combination of the other two (*window*). In the following, we discuss them in more detail.



(a) Timer. (b) Countdown. (c) Window.

Figure 4.1: We consider three different manifestations of time: a) the beginning of the task is defined (timer), b) the ending of the task is defined (countdown), and c) both the beginning and the ending of the task are defined (window). Color encodes if a task should (green) or should not (red) be worked on. The black arrow indicates the same point in time across the three visualizations and runs from left to right (own illustration).

Timer

Time can manifest as waiting time, meaning a user has to wait a minimum amount of time before executing the task (see Figure 4.1a). For example, in a bonding process, a worker must wait a certain amount of time (e.g., flash-off time) before moving on to the next task [Ill+20]. In healthcare, an infusion must be passed before a patient can be discharged or treated. An everyday example outside the work context would be homemade ice cream, which takes a certain amount of time to freeze.

Countdown

Another manifestation of time criticality is a countdown, meaning a user has a maximum time in which the task must be executed (see Figure 4.1b). In bonding, this becomes relevant during the gluing stage, when workers have to hurry to join parts before the glue dries [DIN20]. In the medical field, such as in intensive care units, a countdown can take the form of an audible alarm [Cob21]. An everyday example outside the work context would be to bring in the laundry before it starts to rain.

Window

The last manifestation is a time window, which means that a user has both a minimum time before starting the task and a maximum time by which the task must be completed (see Figure 4.1c). In bonding, certain mixtures need to react chemically for a period of time. However, if one waits too long, they will dry out. An everyday example outside the work context would be cooking pasta, which requires a minimum amount of time, but becomes mushy if cooked too long.

4.1.2 Visualization of Time

To make the manifestations of time visible, we need to look at possible concepts that convey temporal information. Temporal information consists of both the state of time (current time) and the flow of time (progress of time) [SP10]. Research has been done on how to encode and represent temporal information. In this context, several works recommend the use of colors to convey temporal states [Rau+15; Mül+16; Cob21] because they are pre-attentive, making them quickly perceptible [WCF89]. Color also has an effect on reaction time [Bal+14; Hor+22]. For example, the use of traffic light colors (green, yellow, red) can affect reaction time [Hor+22] because traffic light colors are usually learned at an early age. In addition, the colors red and green show a significantly lower visual selection response [Bal+14].

In addition to the use of colors, shapes or sizes can be changed to represent a flow of time. For example, the perception of motion (e.g., changes in shape and size) is a strong stimulus for peripheral vision [GCC17; Lan+20]. The work of Aigner et al. [Aig+07] describes how dynamic representations [Wij02] are well suited for visualizing temporal processes, as long as they are not multivariate time series [TMB02; SR05]. Other work uses shape changes, such as the filling of a progress bar, to encode progress [Mye85].

Using a combination of different features to represent specific information (in our case, time) has proven effective [Grü+18b]. With this in mind, we decided to use multiple features to encode the temporal information, such as colors for the state of time and changes in size and shape for the flow of time (see Section 4.2.2).

4.1.3 Segments of Time

In various production processes, an overview of all ongoing tasks can be advantageous because it makes it easier for the user to take over and switch between tasks (c.f. Chapter 2). However, in practice, different processes can consist of a large number of complex tasks and steps that can be spatially distributed, so it is not possible to get an overview of all possible task steps at a glance due to the increasing information density [Kei+13; Jul+00; RHO15; RP17]. Information density determines the level of understanding of the task to be performed, where clarity can be lost if there is too much information.

Therefore, for scalability, we need to determine the extent to which we can dive into future and past process steps when creating process overviews in Chapter 7, and determine how to make these time segments visible to the user.

In our analysis, we identified three necessary segments for the steps of a process – previous step, current step, and future step. In order to distinguish the time segments more clearly and to allow differentiation between previous, current, and future steps, we recommend, for example, using a dashed arrow from the previous to the current step and a solid arrow from the current to the future step (see Figure 4.2). The selection of the three segments is explained in more detail below.

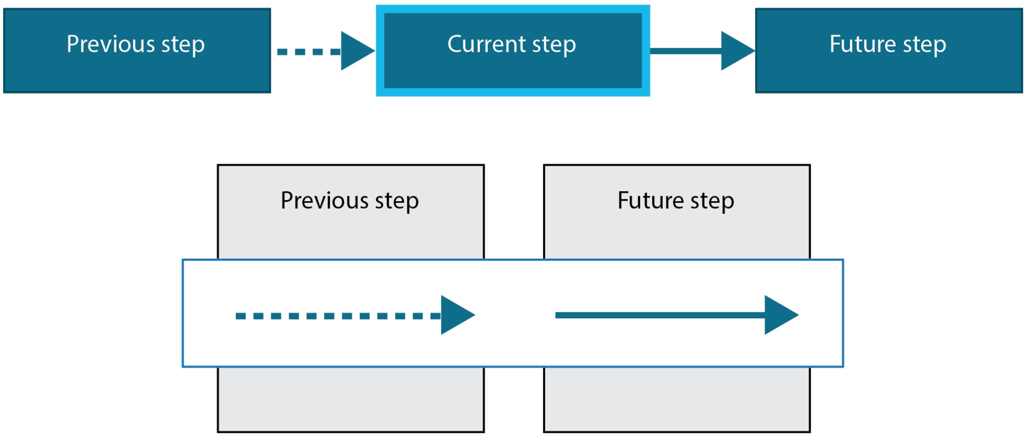


Figure 4.2: We consider (a) three different temporal states of steps in the assembly task overview: 1) previous step, 2) current step, and 3) future step. The current step is highlighted. The line structure (b) encodes whether the arrow points to the current or future step (own illustration).

Previous Step

Knowing the previous step is important for understanding the context of the current task. This helps the person taking over to know where parts might be located and to understand the workflow. For example, our context analysis revealed that one of the most common problems was a lack of knowledge about the completion status of previous tasks and the location of parts (see Chapter 2). Displaying the previous step in an overview ensures that users can quickly orient themselves and seamlessly continue the workflow, reducing cognitive load and potential errors.

Current Step

The current step should be highlighted in an overview to immediately inform the user about the task at hand. This is crucial for maintaining focus and ensuring that the current task is addressed promptly. Previous research has shown that clear, visually distinct indications of the current task significantly improve user performance and reduce the likelihood of errors (e.g., [Col+21; BC19]). Our design incorporates these findings to improve the efficiency of task management (see Chapter 7).

Future Step

Future steps provide essential information for planning and prioritization. Understanding what comes next allows the user to prepare accordingly, especially for critical tasks. This is especially important in production processes where certain steps must follow a strict timeline. For example, if a future step involves a process that must be completed within a specific time frame [Ill+20], the user can adjust their current actions to ensure readiness. By displaying future steps, users are better able to plan upcoming tasks, reduce the risk of delays, and ensure smoother transitions between tasks [SB03; Jou+23; VAS20].

4.2 Visual AR Guidance

There are a variety of ways to realize AR visualizations, both conceptually and technologically. In this section, we describe which AR form factors were selected in the context of this work in relation to our use case from the context analysis, and explain our decision based on previous work as well as the scalability of the technological possibilities for generating AR in the real work context. In the second section, based on the results of two focus groups, we explain the conceptual decisions we made regarding our visual AR guidance in order to meet the requirements of the task characteristics we described.

4.2.1 AR Form Factors

Previous work has explored different AR form factors to support assembly tasks, ranging from smartphones [Ser+17; Alv+19] and tablets [Syb+16; FKS16; Hoo18; Pla+19] to head-mounted [Syb+16; FKS16; Ser+17; Hoo18; Pla+19] and projected AR devices [FKS16; Alv+19]. AR is generated by portable devices such as tablets or smartphones by combining a synthetic image with a real image captured by a camera. Some head-mounted displays (HMDs), on the other hand, can generate AR by combining computer-generated images with the real world through an inclined, semi-transparent mirror. Our context analysis has shown that spatiality, e.g., through the precise spatial positioning of (assembly) parts, plays an important role. Since depth information cannot be displayed with monoscopic VST displays [Pfe+21] in this context, investigations into the use of such AR devices to support assembly tasks are of particular interest (see Section 3.2.2).

Projected AR was shown to be preferred by users for assembly tasks compared to VST AR on smartphones [Alv+19], tablets [FKS16], and HMDs [FKS16]. This is likely due to the fact that users did not have to use their hands to interact with the projected AR instructions, as Funk, Kosch, and Schmidt's [FKS16] tablet or paper instructions prevented participants from using both hands. In addition, task performance with projected AR was found to be significantly faster [Alv+19; FKS16] and error rates were lower than with head-mounted [FKS16] or smartphone [Alv+19] instructions. In this context, Funk, Kosch, and Schmidt [FKS16] also reported a higher cognitive load for the head-mounted instructions. However, it should be noted that the OST HMD used in this study was the Moverio BT-200, which is a relatively low performance solution compared to other OST HMDs [Ham+19; Qia+17]. It remains to be seen whether the results would have been different with a more powerful and comfortable OST HMD such as the Microsoft HoloLens [Qia+17].

It is also interesting to compare HMDs and tablets when performing assembly tasks [Hoo18] or when used in an industrial context [Syb+16] without the use of projected AR. In Hoover [Hoo18], user feedback favored the tablet application, with the HMD resulting in significantly faster assembly times. In Syberfeldt et al. [Syb+16], users responded positively to the OST HMD for hands-free operation. However, in both studies, users often reported that the HMD felt heavy after some time of use [Hoo18; Syb+16]. A possible explanation for the tablet preference in Hoover [Hoo18] is provided by Serubugo et al. [Ser+17], who compared wearable (smart glasses) and portable (smartphone) devices as platforms for an AR museum guide. Portable devices were found to be more intuitive and familiar to use than wearable devices. Another comparative study, but without an industrial context, was conducted by Plasson et al. [Pla+19] to evaluate the performance and usability of tablet-based and OST-HMD-based interaction techniques. Here, the HMD was perceived as faster and less physically demanding by the participants, with the direct touch technique being less affected by small targets and occlusions.

Summary

In order to select possible AR form factors for our studies, we first inferred applicability in a real-world work environment through internal discussion groups.

Although task processing was significantly faster with projected AR in several studies [FKS16; Alv+19] and participants preferred this form factor over other technological solutions, the problem remains that participants in these studies were only able to use their hands freely with projected AR. Although the OST HMD used by Funk, Kosch, and Schmidt [FKS16] enabled hands-free interaction in this context, it had a very small field of view (FOV) compared to current technological solutions, is comparatively low performance, and is uncomfortable [Ham+19; Qia+17].

In addition, projected AR presents a number of difficulties when it comes to establishing it in real-world work environments [BR05]. For example, virtual content can only be displayed within the projection area, making it less flexible to use. In addition, multi-projector configurations are required to prevent the projection from being obscured by shadows cast by physical objects or interacting users. Even with object-based visualizations, the display area is limited by the size, shape, and color of the physical object surfaces, and visualizations adjacent to the object surface are not possible without multi-projector configurations. In addition, the object can only be manipulated within the projection area, which makes it difficult to support spatially distributed workstations when, for example, an object needs to be further manipulated at another workstation. For this reason, the scalability of projected AR is also limited. When virtual objects are displayed with non-zero parallax, their use is limited to a single user without multiple projectors. In addition, three-dimensional projections depend on the viewing angle to be perceived correctly in terms of perspective. Another critical aspect of projected AR is its limited privacy, as the projected content is also visible to nearby people, even if it is irrelevant to them. For privacy reasons, the use of projected AR is therefore problematic in many areas.

Although mobile projectors [BSR15] now solve the stationary problem of limited projection area, we decided not to use projected AR in our studies because the complexity of consistent geometric alignment and color calibration increases with the number of projectors used, and we can also enable hands-free work with portable devices such as a tablet. In addition, issues such as data privacy protection need to be considered for the applicability of our studies to real-world use cases. Therefore, we use both tablets as portable VST displays and head-mounted AR as OST displays for our studies.

4.2.2 Visual AR Techniques

Based on the task characteristics we have described, we know that the location of tasks plays an important role (see Section 3.3.1). There are tasks that are assigned to a fixed workstation and are therefore fixed in location (location-based tasks) and tasks that are distributed across multiple workstations (distributed tasks).

On the basis of two focus groups, we created an information design that precisely takes into account the task characteristics described above. The first focus group consisted of five UX experts (2 female, 3 male) and the second focus group consisted of six potential users (3 female, 3 male). By using two focus groups, we were able to avoid the possibility of missing information. In order to introduce the participants to the topic, the cooking process was used as a reference (see Figure 2.3), as it seemed less abstract than the bonding process due to its familiarity and was more tangible for the participants (see Figure 4.3).

In addition, we also find comparable circumstances in cooking, such as the spatial distribution of tasks, the possibility of parallel execution, and the extracted manifestations of time from Section 4.1.1. Due to the Covid-19 regulations at the time, both focus groups took place online, with participants being provided with a video of a cooking scenario. After an introduction to the process, participants were asked to put themselves in the role of a chef and note what information they would need to execute a recipe. The information gathering and clustering process took 1 hour each. After creating the information design, participants were asked to create sketches for possible visual support in AR.

Figure 4.3: The cooking scenario as a starting point for the development of an information design and sketches to support time-critical and spatially distributed tasks (own illustration).

The results of the two focus groups show that due to the localization of the tasks, our context information must be available not only for the tasks in the FOV, but also for the tasks outside the FOV. In addition, we need to encode the temporal state for both variants to ensure criticality distinction (see Figure 4.4).

For this reason, our contextualized information needs to exist not only for in-view tasks, but also for tasks that happen out of view. To support tasks within the FOV, we can directly draw on the capabilities of AR by superimposing temporal information „on top“ of the tasks (see Chapter 5). To support tasks outside the FOV, we can extend existing visualization techniques that consist of proxies along the edges of the screen, pointing to relevant out-of-view content (see Chapter 6). We therefore distinguish between two types of visual guidance in AR: 1) in-view visualization techniques and 2) out-of-view visualization techniques. Depending on the research question, the in-view visualization technique is used to support location-based tasks, and both visualization techniques are combined to provide continuous visual guidance when supporting distributed tasks. To better illustrate the concepts of in-view and out-of-view visualization techniques, a simplified presentation method has been chosen. This simplification makes it easier to understand the basic differences and applications of the two techniques. In-view visualization techniques refer to the representation of tasks that are currently being processed and therefore directly relevant to the user. In contrast, out-of-view visualization techniques represent those tasks that are not currently the focus of processing. Hence, from a user's perspective, the two types represent opposite cases: „I am currently doing the task“ (in-view) and „I am currently NOT doing the task“ (out-of-view). The distinction between these two techniques is important and has led us to use different color schemes per technique to indicate time criticality (state of time) to ensure that both techniques have the same meaning. Therefore, we will discuss below how specific in-view and out-of-view visualizations can present time-critical information.

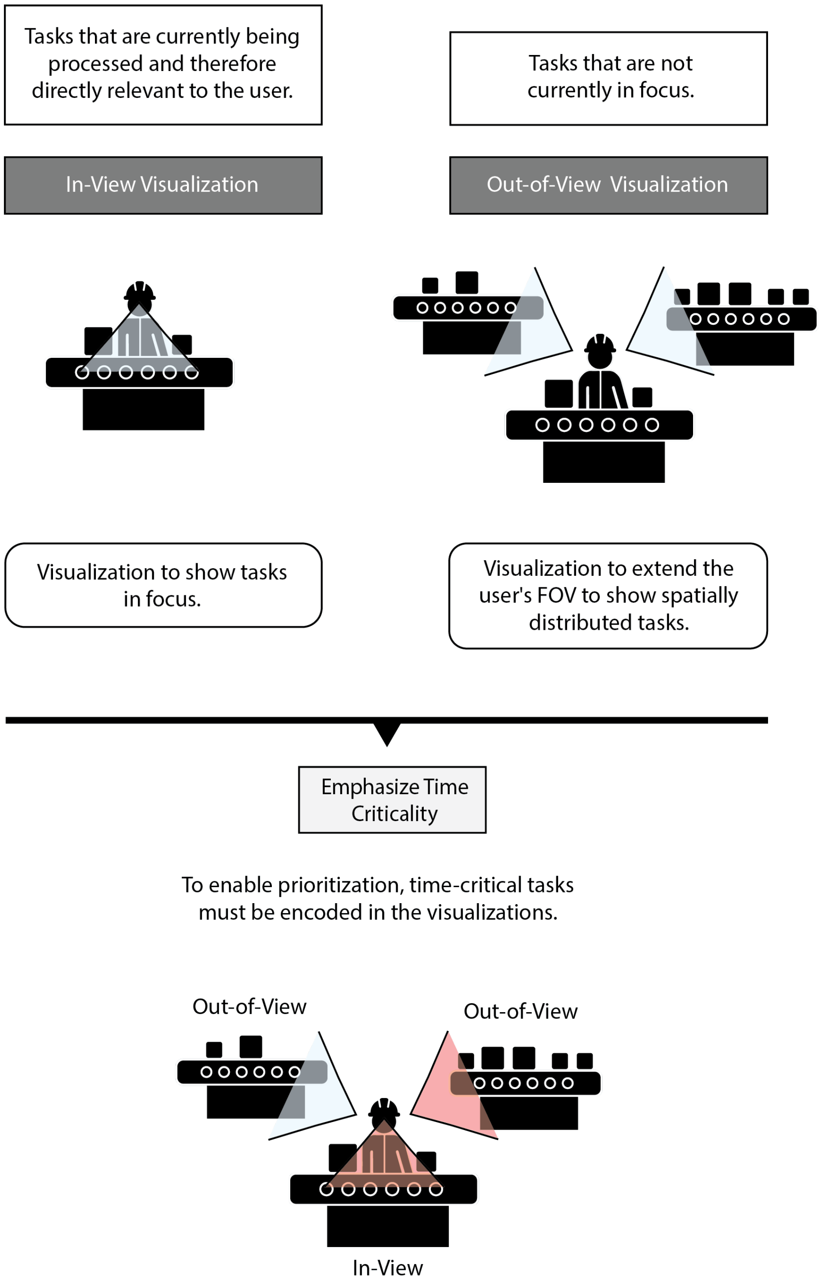


Figure 4.4: The resulting information design of the two focus groups to support time-critical and spatially distributed tasks. In-view and out-of-view visualizations are required to signal tasks within and outside the FOV (own illustration).

In-View Visualization Techniques

If a task takes place in view, it can be directly augmented with information about its time criticality. We use colors to convey time criticality, as they have been proposed in previous work to represent states of time and are pre-attentive, making them quickly perceptible (see Section 4.1.2). We apply the traffic light metaphor with a color gradient from red to yellow to green. Here, green stands for „perform task" and red for „stop". Since the color red is often associated with danger, it is a promising candidate for displaying a critical state [Pra+14; Ell+07]. We decided to use progress bars to visualize the flow of time, as they are a good way to inform the user about the current status [Mye85]. Depending on the manifestation of time criticality, the progress bar can take any of the three forms presented in Figure 4.1. A black arrow in the progress bar displays the current „progress" of the task.

Out-of-View Visualization Techniques

By understanding our visual perception, we know that our visual impressions in the parafovea are less clear due to a lower density of cone and ganglion cells and that there are areas in the far periphery that do not allow for color perception (cf. Section 3.1.1.3). When a task is at the edge of the FOV, it can be directly augmented with information about its time criticality, but this augmentation is not sufficient due to our limited color perception. In addition, a task may be completely outside our FOV, in which case we do not perceive the direct augmentation above the task. Therefore, to support tasks outside or at the edge of our FOV, we must rely on existing out-of-view visualization techniques in addition to direct augmentation. These techniques use visual proxies displayed at the edge of the screen to avoid visual clutter in the central FOV (see Chapter 6). To encode the temporal state of time criticality, we utilize color to maintain consistency between in-view and out-of-view information. However, there can be multiple out-of-view tasks, and too much detail could be overwhelming. Therefore, each proxy displays only one color at a time to encode its current state. We use a red-blue color scheme that follows the hot-cold metaphor used for heatmaps [Ho+14; Har00]. Here, blue indicates a „ready" state, while red indicates a „critical" state. We decided to use the opposite color scheme for out-of-view tasks, based on the „ready" and „critical" states. To encode „waiting", we used the color gray (i.e., „there is nothing you can do here right now"). Finally, when all steps of a task have been completed, the color „green" is used to inform the user that everything is now done[1].

Based on the perception of time described, we know that attention should be

[1] An alternative would have been to hide a completed task. However, our pilot study for the first study in Chapter 6 found that users preferred visual confirmation of their progress and the ability to easily review and track completed tasks. This helped to promote satisfaction and motivation through the visible sense of completion.

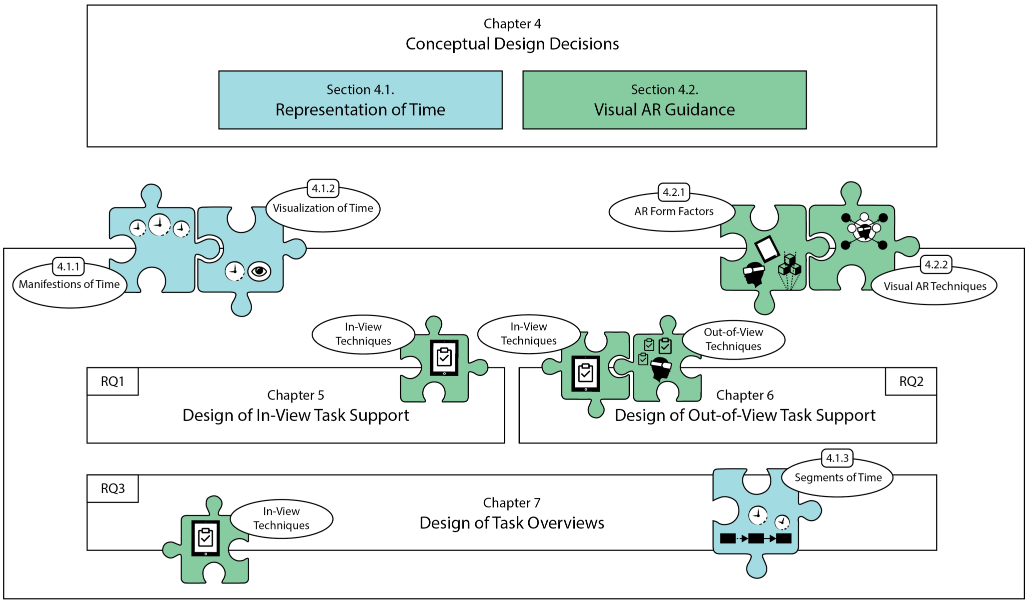


Figure 4.5: Chapter „Conceptual Design Decisions“ and the influence of each section on each subsequent chapter of the research questions (own illustration).

drawn to the temporal component only when necessary, so as not to increase the perceived duration of time [BZ97] (see Section 3.1.3.2). For this reason, we have decided not to draw the user's attention to tasks that are not time-critical. In this way, we can avoid interrupting an ongoing task. However, to ensure that critical tasks are not overlooked, we change the size to represent the time flow and the color to represent the time state of the visual proxies. As described in previous work [Mat+17; TA+21; RP17], our change in size may affect peripheral motion perception [Mat+17], contributing to more salient features and ensuring that users do not miss the stimuli [GCC17; Lan+20]. The more critical an out-of-view task becomes, the larger the visual cue becomes.

4.3 Summary

In this chapter, we have looked at the conceptual design decisions of this thesis that we have derived from our context analysis or from previous work. These decisions help us to understand the following chapters that deal with answering our research questions (see Figure 4.5).

First, we investigated different aspects of the representation of time (see Section 4.1). We identified three primary manifestations of time that allow us to understand different temporal constraints in task execution (see Section 4.1.1). Single or multiple time manifestations will play a role in all subsequent chapters. We also provide an insight into the visualization of temporal information through previous work (see Section 4.1.2) . In this context, we use a combination of features such as color for the state of time and changes in size and shape for the flow of time to design time in AR in the following chapters. At the end of this section, we discuss the necessary segmentation of time to determine the extent to which we can dive into future and past process steps for better planning and execution to enable transferability to real work contexts (see Section 4.1.3). This is particularly relevant for Chapter 7, where we explore different overview techniques in AR that are able to provide users with both spatial and temporal information.

In the next section, we describe the conceptual and technological possibilities for implementing visual AR guidance (see Section 4.2). First, we examine different (AR) form factors and their applicability in real-world work environments (see Section 4.2.1). Although projected AR is effective due to hands-free operation and faster task completion, it poses challenges in real-world work environments due to limitations such as projection surfaces and multi-projector configurations. Therefore, we have chosen to use either tablets as portable VST displays or head-mounted AR as OST displays in all subsequent chapters, depending on the research question. We then investigated AR visualization techniques based on the task characteristics and feedback from two focus groups, and developed an information system that supports both in-view and out-of-view visualization (see Section 4.2.2). In-view techniques supplement tasks directly in the FOV with time-critical information using colors and progress bars and play a role in all subsequent chapters on the research questions. Out-of-view techniques use visual proxies at the edge of the screen to represent tasks outside the FOV, with color and size changes indicating temporal state and flow, and are particularly relevant in Chapter 6. This dual approach ensures that users can effectively manage both current and upcoming tasks, maintaining awareness and readiness without overwhelming cognitive load.

5 Design of In-View Task Support

Our context analysis and background information on work environments have shown us the challenges that need to be overcome. For example, tasks can be location-based, i.e., performed at so-called individual workstations. These tasks are then primarily in the user's field of view (FOV) due to their location-based nature (see Section 4.2.2). In addition, tasks can be performed in parallel to bridge waiting times or increase productivity. The support of work tasks with Augmented Reality (AR) through instructions has been researched for several years [PAH24; BV19]. However, complexity factors such as hands-free work, inherent time criticality, and parallel execution have hardly been considered so far, which makes the transferability to contextual use cases difficult [PAH24]. Therefore, in this chapter, we want to investigate how we can support time-critical and parallel execution of location-based tasks within the FOV hands-free with AR and refer here to our first research question:

„RQ1: How can time-critical and parallel tasks be visualized within the field of view?“

To answer this research question, we use our use case of bonding and first review previous work on instructional design for manual tasks in AR. In this context, we provide an overview of previous AR instructions and extract possible design guidelines. We then visualize a section of a standardized bonding process [DIN20] with the time manifestations we defined as AR instructions and implement the instructions on two AR devices (tablet and head-mounted), each of which we adapt for possible hands-free work. We compare the two AR instructions with a paper instruction and with existing egg timers as a reference condition. Our two selected AR devices generate AR based on different technologies and have their own advantages and disadvantages (see Section 3.2.3). Our tablet as a video see-through system combines a synthetic image with a real image captured by a camera. Our head-mounted display (HMD) device as an optical see-through system uses a waveguide-based AR display that combines computer-generated images with the real world via an inclined, semi-transparent mirror. In a first study, we wanted to find out whether AR adds value to the existing solution of paper instructions and egg timers and which device is better suited to support location-based, time-critical tasks. We then select the best technique for location-based tasks from the first study and improve the AR instructions based on the results. Then, we adapt our AR instructions for different degrees of visualization parallelization and conduct a second user study to investigate how many parallel visualizations are useful for assistance in terms of execution time and error rate.

Parts of the work presented in this chapter were published as a full paper at the MUM conference in 2020 [Ill+20] and as a full paper at the MuC conference in 2021 [Ill+21].

5.1 In-View AR Instructions for Manual Tasks

In this section, we want to provide an overview of existing AR work instructions and derive design recommendations for their design. Therefore, in the following, we discuss related work on (1) AR work instructions in order to derive (2) AR visualization methods for the information design of work instructions. Our goal is to identify the advantages of AR instructions that have already been tested. To our knowledge, there is no work that explicitly addresses AR support for time-critical and parallel tasks in assembly.

5.1.1 AR Work Instructions

Several studies have been published on the topic of AR, quantifying the advantages of AR instructions over traditional instructions such as paper-based instructions [HWT15; Bla+17; Wie+03; Tan+03; Guo+14], video instructions [LQB16], digital 2D instructions [Tan+03], or expert tutorials [Wie+03]. In addition, Sanna et al. [San+15] reported that handheld AR devices contribute to error and time reduction as well as to a positive user experience.

A first concept for using AR to display work instructions was proposed by Caudell and Mizell [CM92] in 1992. They developed an early prototype of AR and postulated that a transparent and trackable HMD could be used to display work instructions, thus reducing the use of paper.

Using AR instructions to perform assembly tasks showed a reduction in mental workload [HWT15] and error rate [HWT15; Bla+17] compared to traditional isometric drawings [HWT15] or conventional pictorial instructions [Bla+17]. In terms of execution time, Hou, Wang, and Truijens [HWT15], Guo et al. [Guo+14], and Blattgerste et al. [Bla+17] report different results. Hou, Wang, and Truijens [HWT15] cut assembly time in half using AR instructions. Guo et al. [Guo+14] come to a similar conclusion, showing that picking using AR instructions is significantly faster than picking using traditional paper instructions, while Blattgerste et al. [Bla+17] found that paper instructions were the fastest way to complete the task.

In addition to paper instructions, Wiedenmaier et al. [Wie+03] also included an expert tutorial for comparison. They investigated the support of assembly processes by AR with tasks of varying difficulty. Their results show that assembly times varied. The AR support proved to be more suitable than the paper manual for difficult tasks, while the use of a paper manual for simpler tasks did not differ significantly from the AR support. Tasks performed under the guidance of an expert were completed the fastest.

A comparison between video and AR assistance in manual assembly was conducted by Loch, Quint, and Brishtel [LQB16]. Here, the AR assistance showed a significantly lower number of errors and a better rating in terms of time and mental effort.

Another interesting result is provided by Tang et al. [Tan+03], who compared AR with digital 2D instructions and paper instructions. Lower mental workload and error rates were reported when using the AR solution. The results confirm the findings of Hou, Wang, and Truijens [HWT15] and Loch, Quint, and Brishtel [LQB16] regarding lower mental workload and Hou, Wang, and Truijens [HWT15], Blattgerste et al. [Bla+17], and Loch, Quint, and Brishtel [LQB16] regarding lower error rate when using AR.

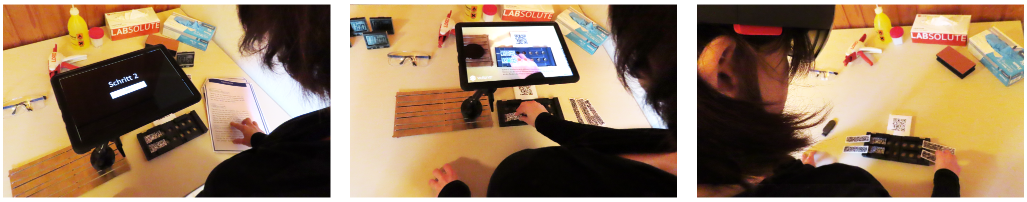
In addition to comparative studies, Pathomaree and Charoenseang [PC05] improve skill transfer in the assembly task using an AR training system. They used virtual objects and graphical instructions to guide the user through the assembly steps and target positions in the assembly task. Their results show that a training system in AR increases transferability and transfer effectiveness. In addition, their system reduced assembly completion time and the number of assembly steps. Users were very satisfied with this type of system.

5.1.2 AR Visualization Methods

In the process of AR guidance of assembly tasks, the visualization of information about the assembly process is the key factor for the effectiveness of the guidance [Li+19]. Therefore, it is important to present the information in an appropriate visual representation. In addition, the information density must be adapted to the task, as too much information can reduce the user's awareness of unexpected events [Dix+13]. In addition to information density, the use of complex visual elements to represent simple assembly tasks can increase the user's cognitive load [RHO15].

In order to investigate the AR visualization capabilities of specific process information, various studies have been conducted [Li+19; Kei+18; RHO15; Mac+17]. Among them, Li et al. [Li+19] proposed six AR visualization methods (image, static model, simulation animation, video, symbol, text) for expressing information in the assembly process, while Keil et al. [Kei+18] collected common AR visualization elements in terms of mediation and communication aspects and introduced three mediation principles (extend, emphasize, enrich).

A framing metamodel was also used to design a type of decision support regarding the mediation strength of a visualization element. Radkowski, Herrema, and Oliver [RHO15] investigated the relationship between commonly used assembly process information and the presentation of visual elements. They suggested that the complexity of a visual element should correspond to the complexity of the assembly task. In addition, MacAllister et al. [Mac+17] provide insight into how to construct an interface using occlusion and recommend the use of vivid outlines and large text as interface elements.



(a) Baseline. (b) Tablet. (c) Head-mounted.

Figure 5.1: Instructions evaluated on paper, tablet (Samsung Galaxy Tab S4), and head-mounted device (Microsoft HoloLens) [Ill+20].

In a study of two AR visualization methods for supporting assembly tasks with real-time assembly state detection, Khuong et al. [Khu+14] found that displaying information next to the physical target resulted in shorter processing times than superimposed displays. In addition to recommending different ways to display process information, existing work on specific AR assembly instructions provides insight into the most commonly used AR visualization elements [Bes+12; FKS16; Zhe+15; Bla+17; HWT15; Tan+03; PC05].

In this context, contour-based highlighting and coloring have been used to mark (real) elements [FKS16; Zhe+15; Bes+12]. In addition, 2D text or symbols are often used to describe the task [Zhe+15; PC05] or to mark objects [PC05; Bla+17; Tan+03]. Both simple [Bla+17; Khu+14] and detailed [HWT15; Tan+03; Bes+12; Khu+14] 3D virtual models (partially visualized as holograms) are used to represent specific assembly positions.

5.2 AR Modalities for Time-Critical Tasks

In this section, we compare paper instructions as *baseline*, *tablet* instructions, and *head-mounted* instructions in a laboratory study (see Figure 5.1). Both the *tablet* and *head-mounted* instructions are presented in AR, while the paper instructions represent the established analog approach and serve as a baseline condition. Our results contribute to assisting workers in location-based, time-critical processes where accurate spatial positioning/assembly of parts plays an important role. In addition, high safety/hygiene requirements must be met in bonding processes, making precise work even more difficult. In summary, we want to investigate the possibilities of AR support and reduce possible errors such as the non-observance of different times and the incorrect spatial positioning of spacers and joining parts. The specific contribution of this chapter is an evaluation of AR instructions in a laboratory user study compared to a paper-based baseline condition.

(a) Experiment setup. (b) Sitting execution. (c) Standing execution.

Figure 5.2: Apparatus of the experiment. The setup includes a 10.5" tablet on a fixed holder with a ball-and-socket joint for hands-free interaction that was moved away during the head-mounted instruction, a Microsoft HoloLens (not shown), a (gluing) device, four preset lab timers for the paper instruction (baseline), joining parts, and spacers (own illustration).

5.2.1 Design

Through our context of use analysis and our analysis of previous research and practice (see Section 5.1.1), we were able to identify relevant preliminary results and extract different human-technology interaction concepts for the performance of assembly tasks.

In this context, head-mounted AR, especially with the advanced Microsoft HoloLens device, proved to be the most suitable for visualizing contents of paper-based instructions and enabling hands-free interaction. To enable hands-free interaction with the tablet, we have attached it to a fixed mount with a ball-and-socket joint (see Figure 5.2). This allows the tablet to „move“ over the (gluing) device[1] (similar to a magnifying glass). In this way, it is possible to prevent the tablet from interfering with the performance of the task with both hands, as is the case with paper instructions [Zhe+15; FKS16].

Our selected process steps are derived from both the observations of the context analysis (see Chapter 2) and from the requirements for bonding processes defined in DIN 2304-1 [DIN20]. This made it possible to implement a standardized representation that contains all the information necessary to perform the individual work steps. For our study, we selected four work steps from an overall process that are particularly prone to errors (see Figure 5.3 and Figure 5.4).

The steps are used in training courses and are therefore particularly appropriate as our study was conducted with participants who had no bonding experience. For all AR instructions, we placed informational text [Zhe+15; PC05] about each step next to the physical target to optimize process times [Khu+14].

In this study, the use of color was initially omitted because the goal was to achieve direct comparability with paper instructions. In order to develop an

[1] A gluing device is a custom-made device into which spacers and joining parts can be inserted with a precise fit.

(a) Step 1 of the instructions.

(b) Step 2 of the instructions.

(c) Step 3 of the instructions.

(d) Step 4 of the instructions.

Figure 5.3: Step-by-step assembly instructions in AR [Ill+20].

AR variant that is as similar as possible to paper instructions, we symbolically represented the different time specifications as text, similar to a digital egg timer. In this way, we were able to implement the AR instructions in a way that was very close to the paper instructions without revealing any additional information [Kei+18]. To visualize the assembly positions, we displayed the corresponding parts as a holographic image [Li+19] at the respective positions.

Step 1 (preparation)

Two spacers must be positioned at the correct position of the (gluing) device (see Figure 5.3a). These keep the joining parts (metal plates) at a predefined distance from each other. Two positions[2] are shown on the left side of the (gluing) device in the AR view.

Step 2 (timer)

Four joining parts must be flashed off and positioned in the correct position (see Figure 5.3b). In bonding, the flash-off time describes the period of time that must be waited when using cleaners, activators, or primers so that the solvent

[2] All positions are represented in the AR view by holograms of the corresponding parts.

has completely evaporated and the adhesive can be applied (see Section 2.1). After positioning, one timer per joining part starts. A joining part cannot be machined until the timer has expired (cf. Figure 4.1a in Section 4.1.1). The AR view shows four possible positions. When a part is placed on one of these positions, a timer for that part starts.

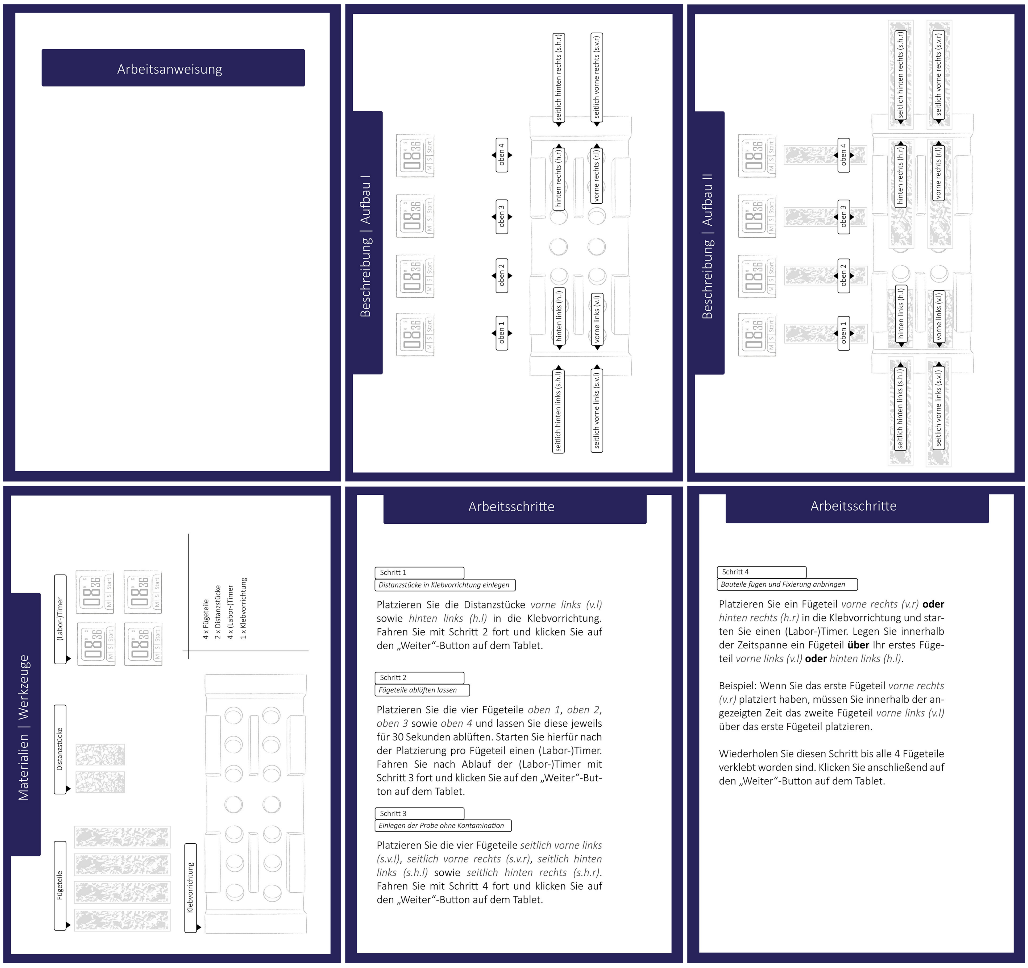


Figure 5.4: Step-by-step assembly paper instructions (baseline) (own illustration).

Step 3 (preparation)

Each joining part must be positioned laterally on the (gluing) device so that the next operation can be directly accessed (see Figure 5.3c). In the AR view, a total of 4 positions are displayed (2 positions each on the left and right side of the (gluing) device). The parts must be placed on these positions.

Step 4 (countdown)

A joining part must be glued[3] and placed in the correct position in the (gluing) device (see Figure 5.3d). A timer starts for each glued part. Another (non-glued) part must be placed on top of the (glued) part in the correct position before the timer runs out. In the AR view, two positions are shown on the right side of the (gluing) device. When a part is placed on one of the positions, a timer starts and the position of the counterpart is displayed on the left side of the (gluing) device. When the counterpart is placed on that position, the timer stops (cf. Figure 4.1b in Section 4.1.1). The timer simulates the short pot life (workability time or usage time of an adhesive) of the adhesive with a countdown because the adhesive must always be used at a specific time [Ras12; Hab03]. Example: if the first part is placed at the front right, the second part must be placed at the front left within the displayed time.

5.2.2 Experiment

The experiment was conducted as a two-group mixed design to rule out possible learning effects between the AR instructions. Both groups received paper instructions as the *baseline* condition. We examined the differences between the *baseline* and AR (*tablet* or *head-mounted*) instructions within a group. Between the two groups, we were able to test how the two AR instructions differed from each other. Participants were assigned to one of these groups. For example, the third participant was assigned to the head-mounted group and performed the *baseline* first and then the *head-mounted* instructions. Each group followed a complete counterbalanced design (see Table 5.1).

Table 5.1: Mixed design with counterbalancing [Ill+20].

Group	**Participant**	**Instructions**
Tablet group	1, 5, 9, 13, 17	Baseline + Tablet
	2, 6, 10, 14, 18	Tablet + Baseline
Head-mounted group	3, 7, 11, 15, 19	Baseline + Head-mounted
	4, 8, 12, 16, 20	Head-mounted + Baseline

We used quantitative methods to evaluate performance, using total duration, timer errors, spacer and joining part positions, usability, and task performance as dependent variables. To evaluate user performance with the different instruction variants, we conducted an independent controlled laboratory study using traditional paper instructions as *baseline* and AR (*tablet* and *head-mounted*) instructions.

For this study, we asked: **(RQ) To what extent can participants' performance in terms of work time, workload, and error rate be improved**

[3] For safety reasons, the part of the actual gluing is only fictitious.

by using AR for time- and space-dependent process steps?

H_1 We expect that *tablet*-based and *head-mounted* AR will improve the understanding and execution of each process step compared to *baseline*, because holograms directly indicate the placement of the joining parts at the correct position of the (gluing) device, and timers no longer need to be started manually.

H_2 We expect that the *tablet* solution will be preferred by the users over the *head-mounted* solution due to the assembly task at a fixed workstation, as no additional adjustment to the person (putting something on) is required.

5.2.3 Apparatus

We set up an empty office room with open windows and lights on to ensure that the AR devices could always identify the spacers and joining parts. Our AR instructions are displayed on the Microsoft HoloLens and Samsung Galaxy Tab S4. For the implementation, we used Unity (v.2018.4.5)[4], a 3D game development engine. Vuforia (v.8.3.8)[5] marker detection is used to detect the (gluing) device, the spacer, and joining parts.

Distance Measurement

To measure the distance, we placed a reference point `rf` (represented as green cubes on each spacer) (see Figure 5.5 or Figure 5.3). Then we placed the spacer in the correct position in the (gluing) device and placed another (optimal) reference point[6] `orf` (displayed as red cubes) on the (gluing) device in exactly the same position where `rf` was (after placing it in the device). The distance between `rf` and `orf` could then be determined using the Euclidean distance. When the cubes were almost on top of each other, the value of the distance was around 0, which would also mean that the spacer was placed close to the optimal position.

5.2.4 Procedure

The experiment took place in an empty office room, with the participants positioned in front of the (gluing) device. Each experiment began with a detailed explanation of the experimental procedure so that participants could try out the conditions, the workspace, and the task description in advance. Each condition consisted of four (working) steps of a bonding process that had to be performed one after the other (see Figure 5.3 and Figure 5.4). At the end of the last condition, a short questionnaire was administered to assess demographics, experience

[4] `https://unity.com`, last retrieved March 31, 2019
[5] `https://developer.vuforia.com`, last retrieved March 27, 2019
[6] The optimal reference points were invisible to the participants.

with instructions, experience with AR, and individual ratings. Each participant took approximately 25 minutes to complete the experiment.

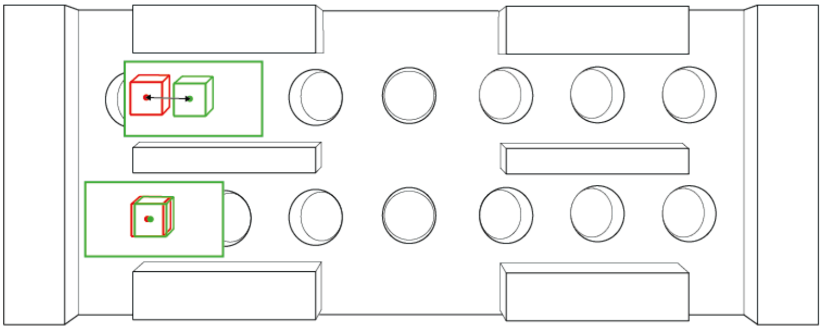


Figure 5.5: Distance measurement procedure [Ill+20].

Baseline (Figure 5.1a)

In addition to the paper instructions, participants were given four preset laboratory timers to correctly perform steps 2 (minimum timer) and 4 (maximum timer). The timers had to be started manually. In addition, a tablet was placed over the (gluing) device to record the experiment via log files. A black screen with the respective step and a button was displayed on the tablet. The decision whether a step was completed was made by the participants themselves. Participants tapped the button on the tablet after completing a step.

Tablet Instructions (Figure 5.1b)

Participants were given a tablet with AR instructions. The tablet was in a fixed holder with a ball-and-socket joint – so the tablet could be easily „moved“ over the work area. The required positioning of the spacer or joining parts was represented by holograms. The decision as to whether a step was completed was made by the participants themselves. After completing a step, the participant tapped the button on the tablet. The minimum and maximum time started automatically as soon as the part was correctly positioned.

Head-Mounted Instructions (Figure 5.1c)

The visualization and procedure did not differ from the instructions on the tablet. Instead of the tablet, participants were given a Microsoft HoloLens, which also displayed the AR instructions. However, a clicker was used instead of a button to confirm a completed step.

5.2.5 Participants

We recruited a total of 20 volunteer participants[7] through public and online advertisements.

Tablet Group

10 participants (6 male, 4 female, 0 diverse), aged between 21 and 62 years (M=34.70, SD=14.61). None had color vision impairment, five had corrected-to-normal vision, and five had normal vision.

Head-Mounted Group

10 participants (6 male, 4 female, 0 diverse), aged between 19 and 46 years (M=27.70, SD=10.13). One participant had color vision impairment, six had corrected-to-normal vision, and four had normal vision.

We asked participants to rate their experience with AR on a 5-point Likert scale. We also asked them to rate their experience with manual work instructions on a 5-point Likert scale. In both groups, participants indicated that they had limited to medium experience with AR (Md=2.00, IQR=1.00) and that they had medium to very high experience with work instructions (Md=3.50, IQR=1.00).

5.2.6 Results

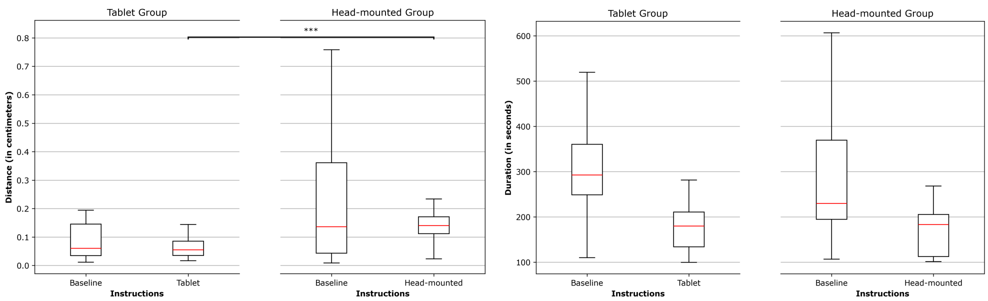
In this section, we present the results of the user study and highlight any significant differences.

Spacer Distance

To find out how the participants understood the different instructions, we compared the distance from the optimal position of the spacers in the (gluing) device with the (real) position. This allowed us to determine how the participants placed the spacers in the (gluing) device (see Section 5.2.3). Therefore, we recorded all positions of the spacers (including position and rotation) during the study. The median distance in centimeters per condition for the tablet group in ascending order are: *tablet* instructions (Md=0.05, IQR=0.05) and *baseline* (Md=0.06, IQR=0.11). The median distance per condition for the head-mounted group are: *baseline* (Md=0.14, IQR=0.32) and *head-mounted* instructions (Md=0.14, IQR=0.06). The distances are compared in Figure 5.6a. A Shapiro-Wilk-Test showed that our data are not normally distributed ($p<0.001$).

[7] For mean effect sizes of (d=0.60), at least 74 observations are needed, which requires testing at least 10 participants (for each condition we have 4 trials per participant). We calculated this value using G*Power under the Wilcoxon Mann-Whitney U-test for unmatched pairs (α=0.05 and 1-β=0.80).

We used a Wilcoxon Signed-rank test for not normally distributed data and non-parametric, related groups (within subjects). This showed neither a significant difference in the tablet group (W_{min}=87.0, z=0.672, p=0.502, r=0.150)[8] nor in the head-mounted group (W_{min}=74.0, z=1.157, p=0.247, r=0.259). For non-parametric, unrelated groups (between subjects) with not normally distributed data, we used a Mann-Withney U-test. This showed a significant difference between the *tablet* and *head-mounted* instructions (U_{min}=82.0, z=−3.178, p< 0.001, r=0.711) and no significant difference between the *baseline* of both groups (U_{min}=169.0, z=−0.825, p=0.409, r=0.184).



(a) Spacer distance. (b) Total duration.

Figure 5.6: The different quantitative measures taken in every condition. Statistically significant differences within and between groups are indicated by brackets and stars ($0 < {*}{*}{*} \leq 0.001 < {*}{*} \leq 0.01 < {*} \leq 0.05$) (based on [Ill+20]).

Joining Parts Distance

We compared the distance from the joining parts in the (gluing) device. The median distance in centimeters per condition for the tablet group in ascending order are: *baseline* (Md=0.04, IQR=0.07) and *tablet* instructions (Md=0.05, IQR=0.11). The median distance per condition for the head-mounted group are: *baseline* (Md=0.04, IQR=0.09) and *head-mounted* instructions (Md=0.04, IQR=0.10). A Shapiro-Wilk-Test showed that our data are not normally distributed (p<0.001). . A Wilcoxon Signed-rank test showed no significant difference in either the tablet group (W_{min}=380.0, z=−0.403, p=0.686, r=0.064) or head-mounted group (W_{min}=394.0, z=−0.215, p=0.831, r=0.034). A Mann-Whitney U-test also showed no significant difference between the *tablet* and *head-mounted* instructions (U_{min}=773.0, z=0.255, p=0.799, r=0.040) and between the *baseline* of both groups (U_{min}=753.0, z=−0.447, p=0.655, r=0.071).

[8] (r: > 0.1 small, > 0.3 medium, and > 0.5 large effect).

Total Duration

We consider the total duration of our four steps of the bonding process per condition. The median duration in seconds for the tablet group in ascending order are: *tablet* instructions (Md=179.79, IQR=76.84) and *baseline* (Md=292.33, IQR=111.79). The median duration in seconds for the head-mounted group are: *head-mounted* instructions (Md=183.11, IQR=93.13) and *baseline* (Md=229.62, IQR=174.94). The durations are compared in Figure 5.6b. A Shapiro-Wilk-Test showed that our data of the tablet group is normally distributed (p>0.10). Therefore, we used a two-tailed paired T-test for normally distributed data and parametric, related groups. This showed no significant difference in the tablet group for $p<0.05$ (M=112.83 s, S_M=51.39, t(9)=1.833, t=2.195, p=0.056, d_z=0.694). A Wilcoxon Signed-rank test showed no significant difference in the head-mounted group (W_{min}=13.0, z=1.478, p=0.139, r=0.467). A Mann-Whitney U-test also showed no significant difference between the *tablet* and *head-mounted* instructions (U_{min}=46.0, z=−0.265, p=0.791, r=0.084) and no significant difference between the *baseline* of both groups (U_{min}=43.0, z=0.491, p=0.623, r=0.155).

Timer Error

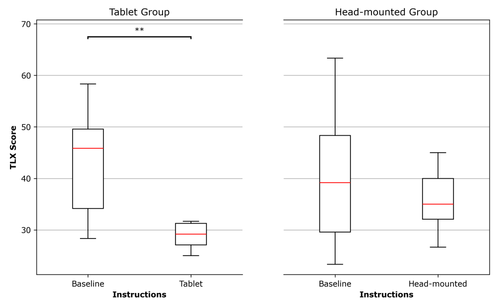
In order to check whether the participants understood the two different types of timers, we measured the number of correctly observed timers. The median number of correctly observed timers per condition for the tablet group in ascending order are: *baseline* (Md=5.00, IQR=1.00) and *tablet* instructions (Md=6.00, IQR=0.00). The median number for the head-mounted group are: *head-mounted* instructions (Md=6.00, IQR=0.75) and *baseline* (Md=6.00, IQR=1.75). A Shapiro-Wilk-Test showed that our data are not normally distributed (p<0.001). We used a Sign test for not normally distributed and non-parametric, related groups because the difference score of a subject was often zero under both conditions[9] for a Wilcoxon Signed-rank test. We found neither a significant difference in the tablet group (X=2.5, p=0.063) nor in the head-mounted group (X=0.5, p=1.0) for $p<0.05$. A Mann-Whitney U-test showed no significant difference between the *tablet* and *head-mounted* instructions (U_{min}=39.0, z=−1.136, p=0.256, r=0.359) and between the *baseline* of both groups (U_{min}=46.5, z=0.245, p=0.807, r=0.077).

Task Load

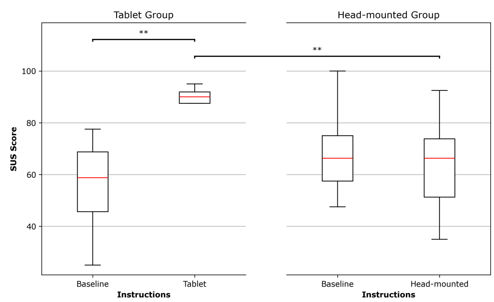
The resulting median (interquartile range) scores from lowest to highest task load for the tablet group are: *tablet* instructions (Md=26.17, IQR=4.17) and *baseline* (Md=45.83, IQR=15.42). The resulting median scores for the head-mounted group are: *head-mounted* instructions (Md=35.00, IQR=7.92) and *baseline* (Md=39.17 IQR=18.75). The scores for each group are compared in Fig-

[9] If the difference score is often zero, the sample size in the Wilcoxon Signed Rank test is reduced and undermines the reliability of this test. To be able to make a statement nevertheless, the Sign test was applied to non-normally distributed, related groups.

ure 5.7a. Since these are ordinal data, we directly used the Wilcoxon Signed-rank test and Mann-Whitney U-test. A Wilcoxon Signed-rank test showed a significant difference in the tablet group (W_{min}=0, z=2.807, p=0.005, r=0.888), and no significant difference in the head-mounted group (W_{min}=21.0, z=0.178, p=0.858, r=0.059). A Mann-Whitney U-test showed no significant difference between the *tablet* and *head-mounted* instructions (U_{min}=21.0, z=−1.926, p=0.054, r=0.642) and between the *baseline* of both groups (U_{min}=32.5, z=0.981, p=0.326, r=0.327).



(a) TLX score.



(b) Usability score.

Figure 5.7: Quantitative findings from questionnaires: a) median TLX score (Raw TLX) and b) median usability score (SUS). Statistically significant differences within and between groups are indicated by brackets and stars ($0 < *** \leq 0.001 < ** \leq 0.01 < * \leq 0.05$) (based on [Ill+20]).

For inferential statistics, we looked at the individual subscales. In the tablet group, we found a significant difference for the scales mental demand, performance, effort, and frustration. Since these are ordinal data, we directly used the Wilcoxon Signed-rank test (see Table 5.2). In the head-mounted group, between the *tablet* and *head-mounted* instructions and between the *baseline* of both groups, we found no significant difference for each scale.

Table 5.2: Significant differences for the scales of the Raw TLX in the tablet group (r: > 0.1 small, > 0.3 medium, and > 0.5 large effect) [Ill+20].

Scale	$\mathbf{W_{min}}$	**z**	**p**	**r**
Mental demand	28.0	2.414	0.016	0.763
Performance	1.5	-2.120	0.034	0.671
Effort	36.0	2.529	0.011	0.799
Frustration	27.0	2.209	0.027	0.698

System Usability Scale

With the help of the System Usability Scale (SUS) [Bro96], we were able to evaluate the usability of the different instructions. The usability was best rated for the *tablet* instructions, followed by the *head-mounted* instructions and the *baseline*. In contrast, the *head-mounted* instructions and *baseline* hardly differ. The median scores for the tablet group in ascending order are: *baseline* (Md=58.75, IQR=23.13) and *tablet* instructions (Md=90.00, IQR=4.38). The median scores for the head-mounted group in ascending order are: *baseline* (Md=66.25, IQR=17.50) and *head-mounted* instructions (Md=66.25, IQR=22.50). The scores for each group are compared in Figure 5.7b. Since these are ordinal data, we directly used the Wilcoxon Signed-rank test and Mann-Whitney U-test. A Wilcoxon Signed-rank test showed a significant difference in the tablet group (W_{min}=0, z=−2.803, p=0.005, r=0.886) and no significant difference in the head-mounted group (W_{min}=16.5, z=0.715, p=0.475, r=0.226). A Mann-Whitney U-test showed a significant difference between the *tablet* and *head-mounted* instructions (U_{min}=11.0, z=2.932, p=0.003, r=0.927) and no significant difference between the *baseline* of both groups (U_{min}=33.0, z=−1.251, p=0.211, r=0.396).

Individual Rating

After each condition, we asked participants to answer one questions with a 5-point Likert item (1=strongly disagree, 5=strongly agree). The results are shown in Figure 5.8. In the tablet group, participants were neutral for the *baseline* (Md=3.00, IQR=1.75), while almost all stated that the *tablet* instructions (Md=5.00, IQR=0.00) strongly supported them. In the head-mounted group, the participants stated that the *head-mounted* instructions (Md=4.00, IQR=1.00) and the *baseline* (Md=4.00, IQR=1.00) supported them equally. Because of the ordinal data, no test for normal distribution is necessary. A Wilcoxon Signed-rank test showed a significant difference in the tablet group (W_{min}=2.0, z=−2.257, p=0.024, r=0.714) and no significant difference in the head-mounted group (W_{min}=7.0, z=−1.265, p=0.206, r=0.422). A Mann-Whitney U-test showed no significant difference between the *tablet* and *head-mounted* instructions (U_{min}=26.0, z=1.701, p=0.089, r=0.567) and no significant difference between the *baseline* of both groups (U_{min}=32.0, z=−1.073, p=0.283, r=0.358).

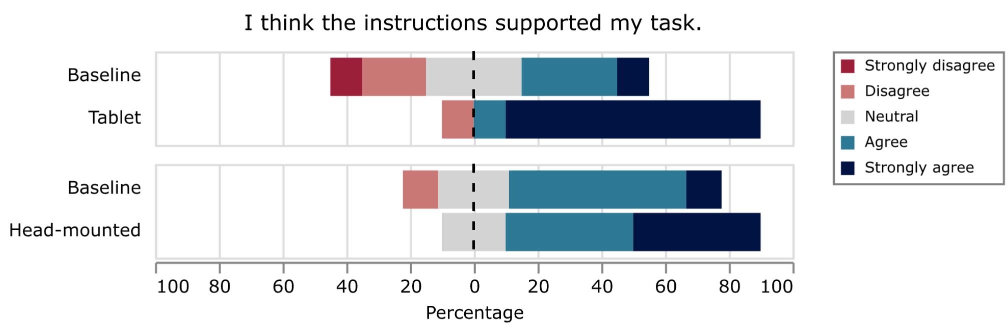


Figure 5.8: Results from Likert item questionnaire (based on [Ill+20]).

5.2.7 Discussion

In this section, we discuss the results of the user study and highlight the significance of each hypothesis.

Position Distance

We found that the AR instructions differed from the *baseline* in the correct positioning of the spacers and joining parts. In this regard, we found a significant difference between the *tablet* and *head-mounted* instructions in the positioning of the spacers. We believe that the participants had to get used to the *head-mounted* instructions in the first step. In this study, we cannot confirm our hypothesis H_1, since there was a positive but not significant difference between the AR instructions and the *baseline*.

Total Duration

There was a slight but not significant difference between the *tablet* instructions and the *baseline* for the duration. There was also no significant difference between the *head-mounted* instructions and the *baseline*, nor between the two AR instructions. In general, however, the duration was longer for the *baseline*. We suspect that reading and understanding the *baseline* and starting the manual timers resulted in increased durations.

Timer Measurement

For the minimum timer (step 2), we measured whether the four joining parts had flashed off for exactly 30 seconds. If the minimum time of 30 seconds per part was met, the timer was considered correct. With the maximum timer (step 4), we checked whether the joining parts were bonded within a maximum time span of 20 seconds. This measured how long each participant took to join the parts. If the value was $0 < t < 20$, the timer was considered correct. Otherwise, it can be assumed that the timer was misunderstood and the bonding would fail in reality. Based on our measurements, we could see that the timers were understood in all instructions. However, the *tablet* instructions caused the fewest errors, which confirms our hypothesis H_1 at least for the tablet group.

System Usability Scale

The usability score is highest for the *tablet* instructions, followed by the *head-mounted* instructions and the *baseline*. We found a significant difference in the tablet group, which supports our hypothesis H_2. We assume that the participants already had experience using mobile devices such as tablets and smartphones, so no learning effort was required [Ser+17]. The *head-mounted* instructions and *baseline* received the same median scores, with little difference between them.

Task Load

The results of the Raw TLX rating confirm the previous results. For inferential statistics, we looked at the individual subscales. The *tablet* instructions lead in all ratings. We also found that the *tablet* instructions resulted in significantly less mental demand, effort, and frustration, as well as higher performance compared to the *baseline*. Thus, the results confirm our hypothesis H_2. It is particularly interesting to note that the load is lower compared to both *head-mounted* instructions and the *baseline*, which is another indication that mobile devices such as tablets are accepted and even currently preferred over traditional paper instructions and futuristic solutions such as *head-mounted* instructions.

Individual Rating

The individual rating showed that all of our instructions helped participants understand their tasks. We found a significantly better rating for the *tablet* instructions compared to the *baseline*, confirming our hypothesis H_2. Overall, the *tablet* instructions received the best ratings from the participants. In the head-mounted group, the *head-mounted* instructions were rated identically to the *baseline*. Participants reported that the HMD felt uncomfortable. This is also reported by other studies [Hoo18; Syb+16; Bal+21], so we rule out a possible calibration error here. Specifically, spectacle wearers felt impaired. We believe that these are possible reasons for the identical ratings. In addition, this information tells us that the paper instructions were constructed fairly and are suitable as a *baseline* condition.

Distance Measurement

In order to measure the correct positioning of spacers and joining parts within the (gluing) device, we calculated the distance to the optimum position for each (see Section 5.2.3). This distance is an approximate value for us, which can vary by 0.2 cm after several previous measurements. This is due to the fact that the viewing angle of the device through the camera of the tablet, but especially the Microsoft HoloLens, causes a certain distortion. An exact measurement is therefore not possible due to the camera perspectives. However, since we are working with previously determined reference values, we can obtain a valid estimate of the positioning from the measurements.

Marker Detection

A challenge in our study was marker detection, which is highly dependent on environmental characteristics such as lighting conditions and camera focus. Therefore, the markers must meet certain requirements such as „rich in detail“, „good contrast“, and „no repetitive patterns“ in order to be well detected. Another characteristic is the size of the markers. Our markers were very small due to the spacers and joining parts, and we had to ensure recognition by placing boxes on the markers in the AR view (see Figure 5.3). These boxes were neon green to be clearly visible on the surface of the markers due to the contrast created. The color scheme was chosen based on human color perception, as the reflected light depends on the structure and surface of the real environment, and we wanted to make sure that it would be visible in varying lighting conditions (cf. Section 3.1.1.1). This way, the participants could always be sure that the measurement was performed correctly.

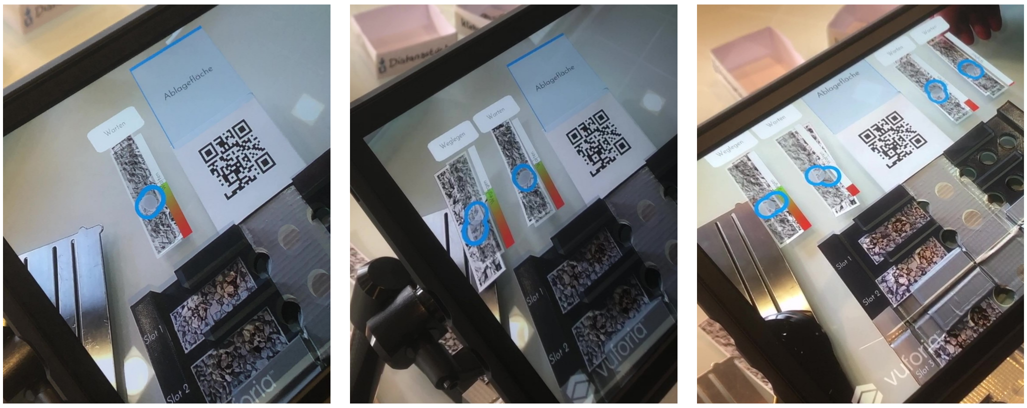
Limitations

One technical limitation was the limited FOV of the Microsoft HoloLens. This means that the potential of human vision cannot be optimally used to naturally enrich visual perception through AR. However, by using the Microsoft HoloLens with its limited FOV, we were able to measure the performance of what is currently possible for HMDs. For this purpose, we classified different temporal variables, such as time periods and points in time, and implemented different scenarios. A limitation of the study design was the low participation and selection of participants. The low participation may be the reason for the non-significant results. In addition, the participants are mainly students with no relation to bonding technology. A study with participants from a real training environment (as in Chapter 2) for bonding technology training courses might provide more meaningful results. Based on the evaluation, it was also determined that the *baseline* performed worse in the head-mounted group than in the tablet group. Since the selection of participants was random and without knowledge of the individuals, we cannot explain this phenomenon further.

5.2.8 Conclusion

When people are working in time-critical processes where precise spatial positioning of parts is also important, inexperienced workers in particular need clear and straightforward instructions. In this way, process-related safety factors can be better observed, error rates can be reduced, and motivation factors can be increased. With our study, we show ways to safely instruct novice workers in bonding processes. The training can be done faster and safer because the hands are „kept free“ and the time for comprehension is reduced by the AR display. In this work, we compared two different AR assembly instructions with a paper-based variant, while the worker could perform the various work steps without using their hands. We found that both the *tablet* and *head-mounted* instructions supported the participants in performing the process and resulted in reduced process durations. The *baseline* required more training, which increased the overall execution time. Participants reported feeling more comfortable with the AR instructions compared to the *baseline*. We explain this by the fact that AR made it possible to display the information directly in relation to the location (spatially registered), eliminating the need to switch between the instructions and the (gluing) device, as was the case with *paper* instructions. Our results also show that although a head-mounted AR device allows hands-free working, the technology still needs to be further developed in order to be accepted and used permanently. In particular, spectacle wearers complained about comfort issues.

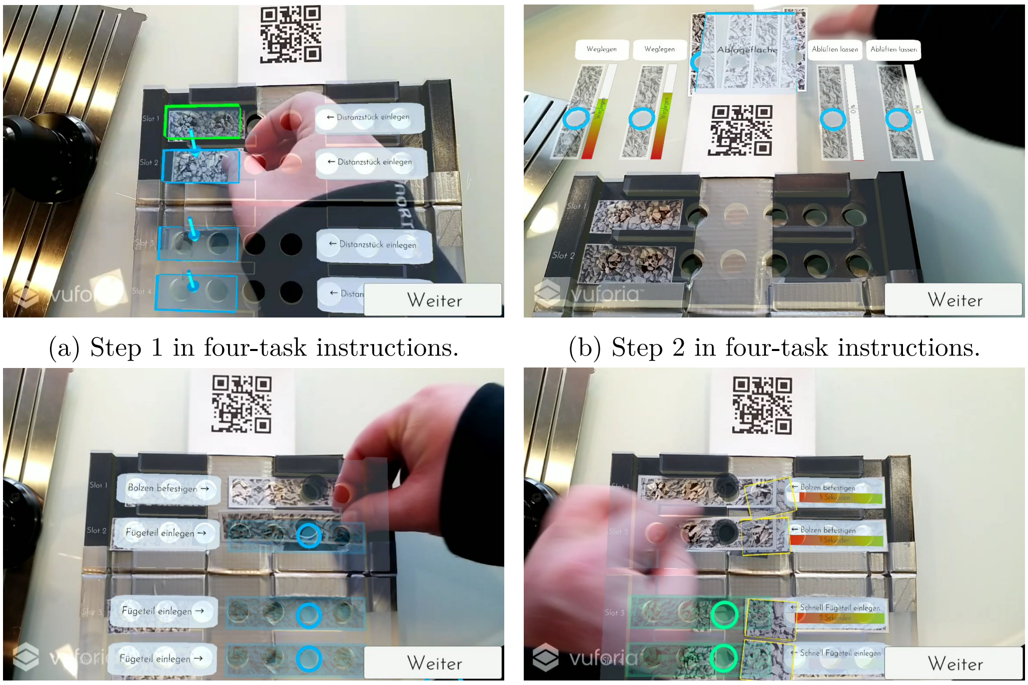
5.3 Parallel Visualizations of Time-Critical Tasks



(a) One-task instructions. (b) Two-task instructions. (c) Four-task instructions.

Figure 5.9: Instructions with one, two, or four tasks per step displayed simultaneously on a tablet (Samsung Galaxy Tab S4) [Ill+20].

In our first study, we showed that the AR instructions supported participants in performing the process and reduced process times and that participants felt more comfortable with the AR instructions than with the paper instructions. Therefore, in this section, we want to enrich our AR instructions with more information (see Section 5.3.1) and compare different levels of parallel task visualizations in a laboratory study (see Figure 5.9). We use a tablet to visualize AR instructions because handheld devices are more intuitive and familiar to use than wearable devices [Ser+17], and head-mounted solutions like Microsoft HoloLens still need to evolve to meet acceptance criteria (see Section 5.2.8). Our results contribute to assisting workers in location-based, time-critical processes where, in addition to precise spatial positioning/assembly of parts, parallel execution of tasks plays an important role. In summary, we want to show how time-critical, simultaneously presented assembly tasks can be designed with the support of AR, despite the inherent increased cognitive load of task execution, and whether this load can be reduced by AR. The specific contribution of this section is a quantitative characterization of the trade-off between error rate and process time for different degrees of visualization parallelization and the determination of the optimal number of parallel visualizations for time-critical assembly tasks with a balance between process time and error rate. We want to support the design of assistance systems for time-critical and parallel visualized assembly tasks.



(a) Step 1 in four-task instructions.

(b) Step 2 in four-task instructions.

(c) Step 3 in four-task instructions.

(d) Step 4 in four-task instructions.

Figure 5.10: Step-by-step assembly instructions with four tasks per step (own illustration based on [Ill+21])

5.3.1 Design

Our design process started as an iterative process model with an analysis of previous research to determine relevant previous results and to extract different (visualization) approaches for assembly work instructions. For all instructions, we used a color gradient from green to red to indicate how time-critical the tasks are. Here, red represents very critical and green represents not critical. In addition, the color red is commonly associated with danger [Pra+14; Ell+07]. We kept the complexity of the visual cues low to avoid overwhelming the user when performing parallel tasks [RHO15], since visualizing the possible parallelism requires sufficient attention. In addition, we placed textual information [Zhe+15; PC05] about the tasks next to the physical target to optimize processing times [Khu+14]. We used a detailed virtual 3D model to represent the (gluing) device, while we used contour-based highlighting and coloring to mark assembly positions [FKS16; Zhe+15; Bes+12]. We also made sure that all visualizations on the surface of the markers, the table, and the (gluing) device were clearly visible by creating contrasts on the surfaces (cf. Section 3.1.1.1).

All three instructions show the process steps derived from Section 5.2 to meet the requirements for bonding processes as defined in DIN 2304-1 [DIN20]. The instructions have been adapted in their visual presentation to allow parallel tasks per step (see Section 5.3.4). The procedure steps are described in more detail below:

Step 1 (position)

Four spacers must be placed in the correct position on the (gluing) device (see Figure 5.10a). As in the previous study (see Section 5.2), these spacers keep the joining parts (metal plates) at a certain distance from each other. For this purpose, one, two, or four positions[10] are displayed simultaneously on the left side of the (gluing) device in the AR view (see Figure 5.12). Step 1 contains a total of one task (positioning 4 spacers).

Step 2 (flash off and put away)

Four joining parts must be flashed off and positioned (see Figure 5.10b). After positioning, one time period per part begins. Unlike in the previous study (see Section 5.2), here we have added a time window (see Section 4.1.1) to the flash-off time function to increase complexity. A joining part must be flashed off for a minimum of 7 seconds and a maximum of 14 seconds (cf. Figure 4.1c in Section 4.1.1). Within a 5-second period, a part must be placed before the timer expires. Normally, the flash-off time describes the amount of time that must be waited for solvents to completely evaporate (see Section 2.1). The AR view displays one, two, or four positions simultaneously. As soon as a part is placed on one of these positions, the corresponding time period for that part starts. Step 2 contains a total of two tasks (flash off 4 parts and put away 4 parts).

Step 3 (position and fix)

Each joining part must be positioned on the (gluing) device so that the next step is immediately accessible (see Figure 5.10c). This is in preparation for the subsequent gluing process, as a counterpart will be glued to these parts in the fourth step, so that the pot life (workability time or usage time of an adhesive) is kept as short as possible [Ras12; Hab03]. In the AR view, a total of one, two, or four positions are displayed simultaneously on the left side of the (gluing) device. The parts must be placed on these positions and then fixed with bolts. Step 3 contains a total of two tasks (position 4 parts and fix 4 parts).

[10] All positions are displayed using AR with contour-based highlighting and coloring.

Step 4 (glue, position, and fix)

A joining part must be glued[11] and placed in the correct position in the (gluing) device (see Figure 5.10d). A timer starts for each glued part. Another (non-glued) part must be placed on top of the (glued) part in the correct position before the timer expires (cf. Figure 4.1b in Section 4.1.1). As in Section 5.2, the timer simulates the short pot life of the adhesive with a countdown. In the AR view, one, two, or four positions are displayed simultaneously on the previously placed parts (step 3) to mark the gluing position. When a glue piece is placed on a joining part, a timer starts and the position of the counterpart is displayed on the left side of the (gluing) device. When the counterpart is placed on this position, the timer stops. Then the counterpart has to be fixed with a bolt. Step 4 contains a total of three tasks (glue 4 parts, position 4 parts, and fix 4 parts).

5.3.2 Experiment

To investigate the possibilities of supporting parallel visualized tasks for assembly instructions in AR, we conducted a controlled, between-groups laboratory user study using a tablet. In this study, we revised the design of the selected steps of a bonding process in AR from the first study (see Section 5.3.1) and implemented them for three levels of instructional visualization, with one task, two tasks, and four tasks per step, and then compared the performance of the participants. Our independent variable was visualization with three levels (one task vs. two tasks vs. four tasks per step). We used quantitative methods to evaluate performance, taking total process time, error rate, usability, and task performance as dependent variables. The experiment was conducted with three groups to eliminate possible learning effects between the AR instructions. Since one instruction per participant was tested in our experiment, the order was repeated after the 3rd and 6th participant (see Table 5.3).

For this study we asked: **(RQ) To what extent does the number of parallel task visualizations affect participants' performance in terms of work time, workload, and error rate in time-critical process steps?**

H_1 We expect the completion time to be shorter and the error rate and workload to be higher when tasks are performed in parallel than when tasks are performed sequentially.

H_2 We expect the completion time to be longer and the error rate and workload to be higher when guiding four parallel tasks than when guiding two parallel tasks.

[11] For safety reasons, the part of the actual gluing is only fictitious.

Table 5.3: Order of the conditions with counterbalancing [Ill+21].

Instructions	**Participant**
One task	1, 4, 7, 10, 13, ...
Two tasks	2, 5, 8, 11, 14, ...
Four tasks	3, 6, 9, 12, 15, ...

5.3.3 Apparatus

We set up an empty meeting room and turned on the lights to make sure the AR device could always recognize the spacers and parts (see Figure 5.11). Our AR instructions are displayed on the Samsung Galaxy Tab S4. For the implementation we used Unity (v.2019.4.8)[12], a 3D game development engine. Vuforia (v.9.3.3)[13] marker detection is used to detect the (gluing) device, the spacers, and joining parts.

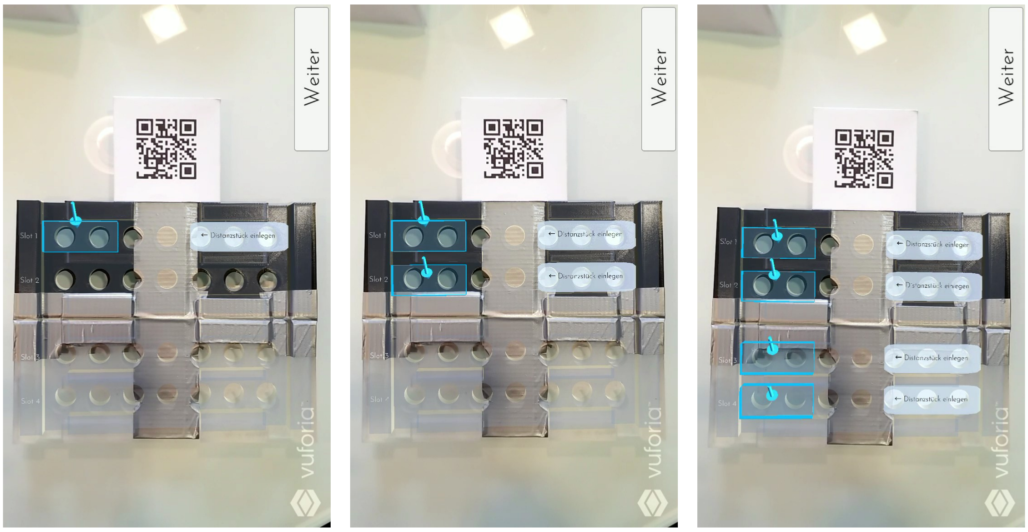
Figure 5.11: Apparatus of experiment[14]. Setup includes a 10.5" tablet, a tablet holder, a (gluing) device, and boxes with joining parts, spacers, glue pieces, and bolts (own illustration based on [Ill+21]).

5.3.4 Procedure

The experiment took place in an empty conference room with the participants standing in front of the (gluing) device. Each experiment began with a detailed explanation of the experimental procedure so that participants could try out the

[12] `https://unity.com`, last retrieved October 31, 2020
[13] `https://developer.vuforia.com`, last retrieved March 29, 2020
[14] The mask worn by the participant was not part of the study, but was required due to Covid-19 regulations in Germany in 2020.

conditions, the workspace, and the task description in advance. Each condition consisted of four (work) steps of a bonding process with four tasks per step, which could be performed in parallel or sequentially, depending on the condition (see Figure 5.12).



(a) Step 1 in one-task instructions. (b) Step 1 in two-task instructions. (c) Step 1 in four-task instructions.

Figure 5.12: Example of the first step (placing spacers) of the one-task, two-task, and four-task instructions (own illustration).

At the end of a condition, a short questionnaire was administered to assess demographics, experience with instructions, experience with AR, and individual ratings. Participants took approximately 20 minutes to complete the experiment. Participants were given a tablet with the AR instructions. As in our first study, the tablet was in a fixed holder with a ball-and-socket joint – so the tablet could be easily „moved“ over the work area (see Figure 5.11). The required positioning of the spacers or joining parts was represented by contour-based highlighting and coloring (see Figure 5.10). A step was finished when all displayed tasks were completed. The decision of whether a step was finished was made by the participants themselves. This was done by tapping a button on the tablet after completing a step. The timer started automatically as soon as the part was correctly positioned. The three instructions are described in more detail below:

One-Task Instructions (Figure 5.9a)

Displays only one task at a time per step. No parallelism was implemented. When a task was completed, the participant had to press a button to confirm. The next task for that step was then displayed. The participant had to complete 4 x 1 task per step in sequence.

Two-Task Instructions (Figure 5.9b)

Displays two tasks simultaneously per step. Some parallelism was implemented here. After two tasks were completed, the participant had to press a button to confirm. The next two tasks for that step were then displayed simultaneously. The participant had the option of completing 2 x 2 tasks simultaneously per step instead of sequentially.

Four-Task Instructions (Figure 5.9c)

Displays four tasks simultaneously per step. Parallelism was implemented here. After four tasks were completed, the participant had to press a button to confirm. The next step was then displayed with four tasks simultaneously. The participant had the option of completing 1 x 4 tasks simultaneously per step instead of sequentially. The more parallel the tasks, the higher the time criticality (see Figure 5.13). For example, if a participant placed a glue piece in step 4, a timer started and the participant had 15 seconds to place the counterpart. In the *two-task* and *four-task* instructions, time pressure increased when the displayed tasks were performed in parallel because the timer for each task also started in parallel. In the *two-task* instructions, a participant had only 15 seconds to place two counterparts when placing two glue pieces at the same time. In the *four-task* instructions, placing four glue pieces simultaneously left only 15 seconds for placing four counterparts. The same principle of increased time criticality is also possible in step 2, where the joining parts have to flash off within a certain period of time. It was up to the participants to perform the tasks in parallel for the *two-task* or *four-task* instructions. The simultaneous presentation of multiple tasks provided the opportunity to do so.

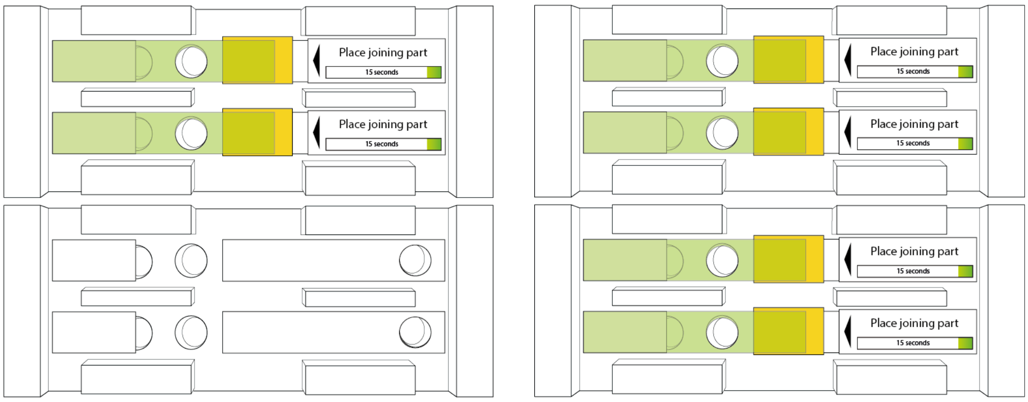
5.3.5 Participants

We recruited a total of 36 volunteer participants[15] (21 male, 15 female, 0 diverse) from the state of Lower Saxony in Germany through public and online advertisements. Participants received no compensation for their time, which was disclosed in the advertisement.

One-Task Instructions

12 participants (7 male, 5 female, 0 diverse), aged 20 to 63 years (M=35.17, SD=14.28). One had color vision impairment, five had corrected-to-normal vision, and seven had normal vision. We asked participants to rate their experience

[15] For mean effect sizes of (d=0.60), at least 86 observations are needed, which requires testing at least 11 participants (for each condition we have 8 trials per participant). We calculated this value with G*Power under the Wilcoxon Mann-Whitney U test for unmatched pairs (α=0.05 and 1-β=0.85).



(a) Two-task instructions time pressure. (b) Four-task instructions time pressure.

Figure 5.13: Increased time pressure with parallel execution using the example of step 4 in the two-task instructions (a) and four-task instructions (b) (own illustration).

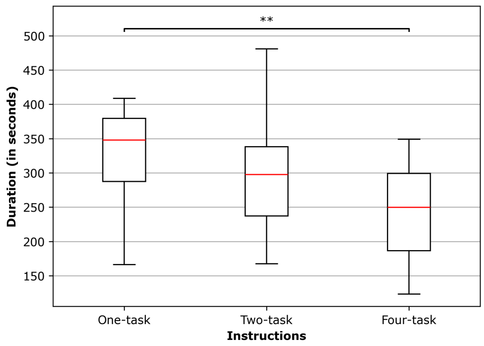
with AR on a 5-point Likert scale. We also asked them to rate their experience with manual work instructions and their experience with manual assembly processes on a 5-point Likert scale. The participants indicated that they had no to limited experience with AR (Md=1.00, IQR=1.25), limited to high experience with manual assembly processes (Md=2.00, IQR=2.00), and medium to high experience with work instructions (Md=3.50, IQR=1.00).

Two-Task Instructions

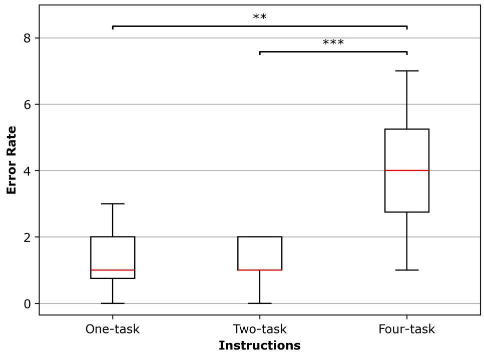
12 participants (8 male, 4 female, 0 diverse), aged 18 to 63 years (M=33.33, SD=11.78). None had color vision impairment, four had corrected-to-normal vision, and eight had normal vision. Participants reported having no to limited experience with AR (Md=1.00, IQR=1.00), medium to very high experience with manual assembly processes (Md=3.00, IQR=2.00), and high to very high experience with work instructions (Md=4.00, IQR=1.25).

Four-Task Instructions

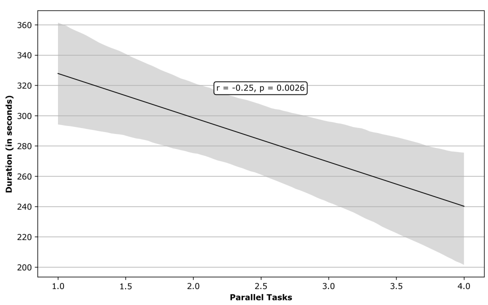
12 participants (6 male, 6 female, 0 diverse), aged 18 to 59 years (M=33.17, SD=13.05). One had color vision impairment, ten had corrected-to-normal vision, and two had normal vision. Participants reported having limited to medium experience with AR (Md=2.00, IQR=1.25), limited to medium experience with manual assembly processes (Md=2.00, IQR=1.25), and medium to high experience with work instructions (Md=3.00, IQR=1.25).



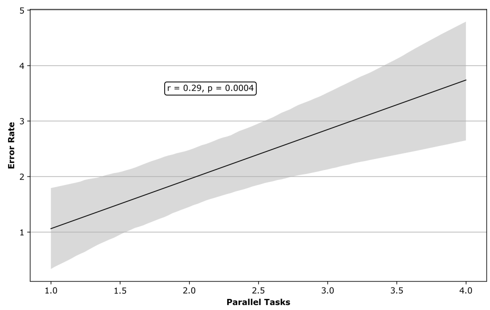
(a) Duration.



(b) Error rate.



(c) Correlation tasks and duration.



(d) Correlation tasks and errors.

Figure 5.14: The different quantitative measures taken in every condition. Statistically significant differences between groups are indicated by brackets and stars ($0 < {*}{*}{*} \leq 0.001 < {*}{*} \leq 0.01 < {*} \leq 0.05$) (based on [Ill+21]).

5.3.6 Results

In our experiment, we measured how the simultaneous presentation of multiple and time-critical tasks affected participants' performance. In the following sections, we present our results on the research questions.

Total Duration

We consider the total duration of our four steps of the bonding process per condition. The median duration in seconds, in descending order, is as follows: *one-task* (Md=348.04, IQR=91.94), *two-task* (Md=297.55, IQR=100.64), and *four-task* instructions (Md=249.73, IQR=112.81). The durations for each instruction are compared in Figure 5.14a. A Shapiro-Wilk test showed that our data were normally distributed. To compare our three groups with normally distributed data, we used a one-way ANOVA test[16] for parametric unrelated groups (between sub-

[16] A previous Levene test showed us equal variances between the different conditions (p>0.05), so the one-way ANOVA test was performed as well as the independent samples t-test with

jects). This showed a significant difference in duration between the three conditions ($F(2,33)=4.195$, $p=0.024$). A post-hoc test using a two-tailed unpaired t-test with Bonferroni correction for normally distributed data and parametric unrelated groups showed a significant difference between the *one-task* and *four-task* instructions (see Table 5.4). In addition, we found a negative correlation between the number of parallel task visualizations and the duration ($r=-0.25$, $p=0.003$). Therefore, we can conclude that the duration decreases with increasing parallelization (see Figure 5.14c).

Table 5.4: Pairwise comparisons of the duration with the two-sided unpaired t-test for the different conditions [Ill+21].

Duration	**T**	**df**	**p**	**95%-CI[l,u]**
One-task vs. two-task	1.00	22	0.327	-27.62, 90.71
One-task vs. four-task	-3.03	22	0.006	-149.36, -26.83
Two-task vs. four-task	-1.77	22	0.090	-117.82, 4.72

Error Rate

To check whether the different (simultaneous) visualizations contributed to understanding, we measured the overall error rate (see Figure 5.14b). In the first step, an error was counted for each spacer that was not correctly placed in the (gluing) device. In the second step, an error was counted each time a part was not flashed off or the time window for flashing off was not met. In the third step, an error was counted each time a part was not correctly placed in the (gluing) device. In the fourth step, an error was counted if either no glue piece was placed on the joining part or if the countdown of the corresponding part had expired. The median error rate for the instructions in ascending order are: *one-task* (Md=1.00, IQR=1.25), *two-task* (Md=1.00, IQR=1.00), and *four-task* (Md=4.00, IQR=2.50) instructions. A Shapiro-Wilk test indicated that our data were not normally distributed ($p<0.001$). To compare our three groups with non-normally distributed data, we used a Kruskal-Wallis test for non-parametric, unrelated groups (between subjects). This showed a significant difference for the error rate between the three instructions ($H=14.87$, $p<0.001$, $df=2$). A post-hoc test using a Mann-Withney U test with Bonferroni correction for non-parametric, unrelated groups (between subjects) with non-normally distributed data showed a significant difference between the *one-task* and *four-task* instructions as well as between the *two-task* and *four-task* instructions (see Table 5.5). Between the *one-task* and *two-task* instructions, we found no significant differences between the instructions. Furthermore, we found a positive correlation between the number of parallel task visualizations and the error rate ($r=0.29$, $p<0.001$). Therefore, we can conclude that the error rate increases with increasing parallelization (see Figure 5.14d).

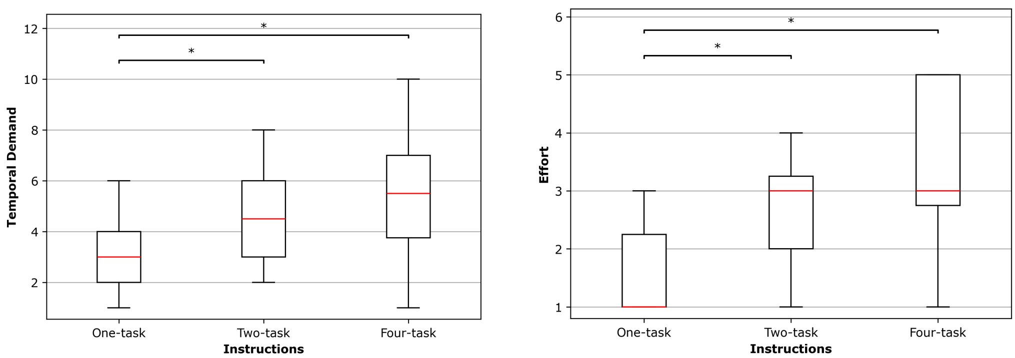
homogeneity of variance.

Table 5.5: Pairwise comparisons of the error rate with the Mann-Whitney U test for the instructions (r: > 0.1 small, > 0.3 medium, and > 0.5 large effect) [Ill+21].

Error Rate	$\mathbf{U_{min}}$	**z**	**p**	**r**
One-task vs. two-task	67.0	-0.275	0.784	0.079
One-task vs. four-task	21.5	-2.921	0.003	0.843
Two-task vs. four-task	11.0	-3.579	<0.001	1.03

Task Load

The resulting median (interquartile range) scores from lowest to highest task load are: *one-task* (Md=33.33, IQR=10.42), *two-task* (Md=35.83, IQR=17.08), and *four-task* (Md=41.67, IQR=12.08) instructions. Since these are ordinal data, we directly used the Kruskal-Wallis test, which showed no significant differences between the conditions (H=4.509, p=0.105, df=2).



(a) Temporal demand. (b) Effort.

Figure 5.15: The median scales per condition (Raw TLX). Statistically significant differences between groups are indicated by brackets and stars ($0 < *** \leq 0.001 < ** \leq 0.01 < * \leq 0.05$) (based on [Ill+21]).

For inferential statistics, we looked at the individual subscales. The *one-task* instructions induced the least mental, physical, and temporal demands as well as the best perceived performance and the least effort and frustration compared to all other instructions. The *four-task* instructions, on the other hand, induced the highest temporal demand, the worst perceived performance, and the highest effort and frustration compared to the *one-task* and *two-task* instructions. The highest mental and physical demands were induced by the *two-task* instructions. The Kruskal-Wallis test showed a significant difference for the temporal demand (H=7.181, p=0.028, df=2) and effort (H=7.868, p=0.020, df=2) scales. The median temporal demand and effort scales for each condition are shown in Figure 5.15. Using the post-hoc Mann-Whitney U test with Bonferroni correction, we found significant differences between the *one-task* and *four-task* instructions for the temporal demand and effort scales (see Table 5.6). For all other scales, we found no significant differences between the instructions.

Table 5.6: Pairwise comparisons of the TLX scales „temporal demand“ and „effort“ using the Mann-Whitney U test for the different instructions (r: > 0.1 small, > 0.3 medium, and > 0.5 large effect) [Ill+21].

Temporal Demand	$\mathbf{U_{min}}$	**z**	**p**	**r**
One-task vs. two-task	38.0	-1.959	0.050	0.566
One-task vs. four-task	30.0	-2.419	0.016	0.698
Two-task vs. four-task	57.0	-0.845	0.398	0.244
Effort	$\mathbf{U_{min}}$	**z**	**p**	**r**
One-task vs. two-task	36.5	-2.108	0.035	0.609
One-task vs. four-task	28.5	-2.558	0.011	0.738
Two-task vs. four-task	59.5	-0.715	0.475	0.206

System Usability Scale

Using the System Usability Scale (SUS) [Bro96], we were able to evaluate the usability of the different conditions. Usability was rated best for the *two-task* (Md=83.75, IQR=12.50) instructions, followed by the *one-task* (Md=80.00, IQR= 12.50) and *four-task* (Md=72.50, IQR=11.88) instructions. However, there is little difference between the *one-task* and *two-task* instructions. The median scores for the instructions in descending order are: *two-task*, *one-task*, and *four-task* instructions. Since these are ordinal data, we directly used the Kruskal-Wallis test, which showed no significant differences for the scores between instructions (H=5.689, p=0.058, df=2).

Individual Rating

After each condition, we asked participants to answer a 5-point Likert item question (1=strongly disagree, 5=strongly agree). The results are shown in Figure 5.16.

For the *one-task* (Md=5.00, IQR=1.00) and *two-task* (Md=4.50, IQR=1.00) instructions, almost all participants reported that they felt strongly supported by the instructions. For the *four-task* (Md=3.50, IQR=1.00) instructions, participants reported feeling medium to strongly supported. Due to the ordinal data, no test for normal distribution is required. A Kruskal-Wallis test showed a significant difference between the conditions (H=11.096, p=0.004, df=2). A post-hoc Mann-Whitney U test with Bonferroni correction showed a significant difference between the *one-task* and *four-task* instructions as well as between the *two-task* and *four-task* instructions. No significant differences were found between the *one-task* and *two-task* instructions (see Table 5.7).

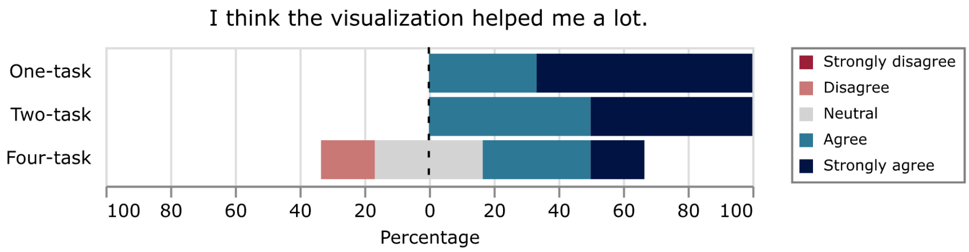


Figure 5.16: Results from Likert item questionnaire. Statistically significant differences between groups are indicated by brackets and stars ($0 < *** \leq 0.001 < ** \leq 0.01 < * \leq 0.05$) (based on [Ill+21]).

Table 5.7: Pairwise comparisons of the individual rating with the Mann-Whitney U test for the different conditions (r: > 0.1 small, > 0.3 medium, and > 0.5 large effect) [Ill+21].

Individual Rating	$\mathbf{U_{min}}$	**z**	**p**	**r**
One-task vs. two-task	60.0	0.777	0.437	0.224
One-task vs. four-task	24.0	2.912	0.004	0.841
Two-task vs. four-task	30.0	2.544	0.011	0.734

5.3.7 Discussion

In the following, we discuss our findings and the methodological and technical implications of our user study.

Total Duration

Duration differed significantly between the *one-task* and *four-task* instructions. There was no significant difference between the *one-task* and *two-task* instructions nor between the *two-task* and *four-task* instructions. In general, however, process time was highest for the *one-task* instructions and decreased with the number of tasks per step. The results confirmed our hypothesis H_1 that duration is shorter when tasks can be performed simultaneously. However, the duration for four tasks is not higher than for two tasks, so we have to reject our hypothesis H_2 here.

Error Rate

The error rate initially showed us an unexpected result. While the *one-task* and *two-task* instructions did not differ significantly, both differed greatly from the *four-task* instructions. This may be related to the fact that the distraction caused by the display was very high due to the many visualizations. Another reason could be that the tasks became more demanding when they were actually performed in parallel (e.g., when multiple parts were placed and more difficult time limits were set). This explains the finding from the individual ratings that participants felt uncomfortable with this density of information as novices. This result confirms our hypothesis H_2. An interesting observation is that the instructions with four tasks simultaneously have the highest error rate, even though the participants could learn directly from a display. For example, if a participant did not insert the first spacer correctly in the first step, the outline did not turn green. However, if the participant inserted the second, third, or fourth spacer correctly, the green outline became visible, and the other „incorrectly inserted“ spacers could be corrected just before the step was confirmed with a button. This form of learning was not possible with the *one-task* instructions because the button had to be tapped to get the next visualization for that step.

Task Load

The results of the TLX rating supported our previous findings that the *one-task* instructions induce the lowest perceived workload because corresponding tasks are presented sequentially per step, making distraction from overload less of an issue. We found significant differences between the *one-task* and *four-task* instructions on the temporal demand and effort scales. The *one-task* instructions scored higher on all measures, confirming our hypothesis H_1. Furthermore, the higher perceived frustration and temporal demand as well as the lower perceived performance in the *four-task* instructions can be explained by the fact that participants were more likely to miss some of the provided visualizations due to the information density [RHO15]. This also explains that the higher error rate was perceived by participants and thus influenced workload, supporting our hypothesis H_2 (see Section 5.3.6).

System Usability Scale

The usability is best for the *two-task* instructions, followed by the *one-task* and *four-task* instructions. We found no significant differences between the instructions for the usability score.

Individual Ratings

The individual ratings showed that the *one-task* and *two-task* instructions helped participants understand their tasks. We found a significantly better rating for the *one-task* instructions compared to the *four-task* instructions, confirming our hypothesis H_1. We also found a significantly better rating for the *two-task* instructions compared to the *four-task* instructions, again confirming our hypothesis H_2. For the *four-task* instructions, participants stated that they did not understand exactly what to do due to the density of information. They first had to „figure out" the instructions, which led to an increased task load (cf. Section 5.3.7). In addition, this information shows us that the density of information influences the subjective impression.

Marker Detection

A challenge in our study was marker detection, which is highly dependent on environmental characteristics such as lighting conditions and camera focus. Therefore, the markers must meet certain requirements such as „rich in detail", „good contrast", and „no repetitive patterns" in order to be well detected. Another characteristic is the size of the markers. Our markers were very small due to the spacers and parts, and we had to ensure recognition by placing colored outlines on the markers in the AR view. This way, the participants could always be sure that the parts were correctly identified and the correct parts were selected.

Procedure

We observed that some participants performed the four displayed tasks per step in single steps, despite the possibility of faster and parallel execution, so that the display had a rather „distracting" effect and the possibility of performing the steps „in parallel" was not used. This observation supports the explanation that performing two or more tasks in parallel leads to performance degradation in the form of increased response latencies or error rates due to a cognitive processing bottleneck (see Section 3.1.2).

Limitations

One technical limitation was the small display size of the tablet. In the *four-task* group, participants reported that the small display size was inconvenient because they could not see all of the visualizations and had to move the tablet with the holder. This means that the potential of the AR display is not fully exploited because the tablet had to be moved over the gluing device with the help of the holder in order to see the corresponding AR display in certain positions. A limitation of the study design was the low participation and selection of participants. The low participation may be the reason for the non-significant results. In addition, the participants mainly represent people who have no relation to bonding technology. A study with participants from a real training environment for bonding technology training courses may provide more meaningful results. Another limitation in the selection of participants was that two participants had color vision problems. It was not determined what type of color vision impairment the participants had. The urgency color scale of the timers in the second step ranges from green to red, which is inaccessible to people with red-green color vision deficiency. However, the participants were able to identify the filling of the bars as well as the percentage display and the textual instructions. Therefore, no special measures, such as extended explanation, were taken during the experiment to avoid providing an advantage.

5.3.8 Conclusion

Manual assembly tasks are often performed in parallel steps to increase revenue per unit of time. However, when working in time-critical processes, where parallel execution plays an important role in addition to the exact spatial positioning of parts, inexperienced workers need the ability to limit the simultaneous display of process steps.

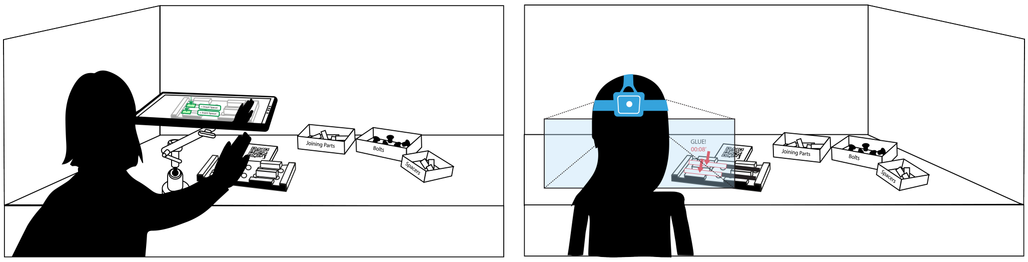
In this way, process-related safety factors can be better observed, quality standards can be maintained, error rates can be significantly reduced, and motivation factors can be increased. With our study, we show possibilities to design assistance systems for time-critical and simultaneously displayed assembly tasks despite an increased cognitive load. However, the degree of parallelism of the displayed tasks must always be considered. In addition, the AR display allows inexperienced workers to perform an unfamiliar process more safely by keeping their hands „free“ and reducing the time needed for comprehension. We found that both the *one-task* and *two-task* instructions helped participants perform the process and resulted in lower error rates. The *four-task* instructions required less overall execution time, but also required more cognitive load, which increased task load and error rate. Participants reported feeling more comfortable with the *one-task* and *two-task* instructions compared to the *four-task* instructions. We explain this by the fact that we had inexperienced participants who were exposed to the bonding technique for the first time. For this reason, the simultaneous display of more than two tasks was overwhelming for comprehension. Experienced workers could probably manage multiple tasks simultaneously and would be underchallenged by *one-task* or *two-task* instructions. Thus, we suggest that people are capable of processing multiple tasks despite a presumed processing bottleneck due to specific or non-specific cognitive resources (cf. Section 3.1.2.2). For this reason, an adaptive system that adapts the number of possible tasks to the level of experience might be advantageous compared to a fixed design solution for parallel processing. Our results can be applied to various application domains where time-critical and parallel tasks are executed and can help in the design and development of assistance systems to minimize process times, error rates, and task load.

5.4 Summary

Both studies focused on improving the safety and efficiency of time-critical assembly processes, especially for inexperienced workers. The use of AR instructions for in-view tasks was explored to provide clear guidance while keeping hands free and reducing comprehension time.

In the first study, AR instructions via tablets or headsets were compared to traditional paper instructions. Both AR methods showed advantages, including faster familiarization and shorter processing times. However, spectacle wearers in particular reported comfort issues with the HMD. It is important to note that with the Microsoft HoloLens 2, these problems can be solved by using a flip-up visor. The study used the first Microsoft HoloLens, which also had a smaller FOV than its successor. Overall, AR was shown to improve performance and understanding of temporal and spatial factors. This finding is consistent with previous work examining AR work instructions (cf. Section 5.1.1). The tablet instructions showed the best subjective results for the participants. The second study examined the impact of parallel task displays on process efficiency and error rates. It was found that limiting the number of tasks displayed simultaneously improved performance and reduced error rates, especially for inexperienced workers.

Overall, both studies highlight the potential of AR instructions and adaptive task displays to improve safety, efficiency, and comfort in time-critical assembly processes, with implications for various application domains. The results can be used to derive possible design proposals for supporting tasks in different work environments (see Figure 5.17).



(a) AR support for location-based tasks. (b) AR support for distributed tasks.

Figure 5.17: Derived AR concepts for the visualization of instructions to support time-critical workflows in (a) location-based and (b) location-distributed work environments (own illustration).

In this context, for example, a tablet is suitable for in-view tasks that are performed location-based, i.e., at a single workstation (see Figure 5.17a). The location does not need to be changed during the execution time (cf. Section 3.3.1). In this case, the tablet should allow for hands-free use, e.g., with a fixed holder with a ball-and-socket joint, so that freedom of movement is not restricted. In many work environments, assistance systems must be able to be operated without the use of hands, for example, in medical or assembly environments where workers wear gloves to protect themselves from potential contamination (cf. Chapter 1). But working hands-free is also useful for cooking. Many of us know how annoying it is to have to wash your hands every time you want to use your smartphone or tablet as a recipe display. Even though head-mounted AR in our study allows stereoscopic vision through optical superimposition, which makes it much easier to estimate distances through depth information (see Section 3.2.2), distance estimation did not seem to be that important due to the location-based nature of the tasks (to put it casually, the tasks were in front of your nose anyway). Another approach to support location-based, in-view tasks could be the use of projected AR. However, this option requires significantly more effort than a tablet and is limited in scalability (see Section 4.2.1).

In the case of distributed, out-of-view tasks, all locations would need to be equipped with the stationary AR solution, such as a tablet, and set up for the respective users. In this case, it would be much more time-consuming if a user had to log in again at each location (e.g., if a colleague had previously worked at that location) and the task status had to be saved from location to location for each user. This requires additional scheduling and distribution algorithms. In addition, similar to projected AR, we suspect a scalability limitation if, for example, another user is working on a task at the same location and the tablet is already „in use“. This problem could be solved by providing multiple tablet holders at each location and allowing users to bring their own device and „dock“ it at the appropriate locations. However, this solution would be limited by the need to avoid contact with external equipment during certain phases of a process (e.g., bonding) and the need to ensure that toxic substances do not come into contact with the assistive systems. For distributed tasks, head-mounted AR will therefore offer more flexible support options due to freedom of movement and the ability to work hands-free. In addition, stereoscopic vision, and thus better distance estimation based on depth information, becomes important when performing multiple spatially distributed tasks, such as estimating whether a location is worth walking to. However, a HMD that allows users to wear glasses without compromising comfort may be a preferable option, depending on individual needs and use case requirements.

Our second study showed that increasing the number of simultaneously visualized tasks reduced processing time, but also increased error rates. Thus, participants without a bonding background felt more comfortable with one or two tasks simultaneously than with four tasks. This observation supports the explanation that performing two or more tasks in parallel leads to performance degradation in the form of increased reaction latencies or error rates due to a cognitive processing bottleneck. The task load rating also shows that perceived time pressure increased as the number of tasks increased. This was due to the fact that the more tasks were actually performed in parallel, the more time-critical they became (see Section 5.3.4). One possible explanation for the perceived time pressure is our insight into human time perception (see Section 3.1.3.2) – there is a systematic shortening of the subjective perception of time when our attention is distracted [RMH01], caused by the division of attention when performing multiple tasks. In addition, our perception of time is negatively affected by the task load of a secondary task [Bro97; Mio18].

However, as the description of our multitasking capabilities in Section 3.1.2.2

shows, experienced users are likely to be able to perform multiple tasks simultaneously compared to novices, because as experience with multitasking increases, the distractions caused by multitasking decrease, which is likely to reduce perceived time pressure. Therefore, an adaptive system that adjusts the number of possible tasks based on experience may be beneficial compared to a fixed design solution for parallel processing. With this chapter, we have been able to extend previous research on supporting work tasks with AR through instructions by adding complexity factors such as hands-free work, inherent time criticality, and parallel execution, which facilitates transferability to contextual use cases.

To conclude this chapter, we would like to briefly present our demonstrator, which is based on the results of the two studies (see Figure 5.18). This demonstrator is characterized by its flexibility, as the number of visualized tasks is variable and can thus be adapted to the user's level of experience. Lessons learned from the studies were directly incorporated into the design of the demonstrator to demonstrate its ability to improve efficiency and reduce errors in time-critical assembly processes. The demonstrator visualizes AR assistance for processing different assembly tasks of the introduced bonding process. The AR assistance is displayed dynamically by adapting the displayed AR information to the respective tasks of the assembly process, thus guiding the user step-by-step through the process. The demonstrator has already been presented at several events and shows the potential of AR systems to optimize work processes.

Figure 5.18: Developed demonstrator for tablets and head-mounted devices based on the results of the two presented studies. The demonstrator guides the user step-by-step through the assembly process using AR (own illustration).

6 Design of Out-of-View Task Support

In addition to the challenge of time criticality and parallel execution of tasks, when investigating Augmented Reality (AR) support options, we need to extend the work environment from location-based single workstations to multiple distributed workstations to ensure transferability to real-world environments. In this context, our focus groups have shown that in addition to our in-view visualization technique, we need to use out-of-view visualization techniques to account for spatial distribution (see Figure 4.4 in Section 4.2.2). The support of out-of-view tasks with AR using visualization techniques has been researched for several years. However, complexity factors such as inherent time criticality have not yet been taken into account, making the transferability to contextual use cases difficult. Therefore, in this chapter, we want to investigate how we can support time-critical, parallel, and spatially distributed tasks with AR in a hands-free manner, which is related to our second research question:

„RQ2: How can time-critical, parallel, and spatially distributed tasks be guided outside the field of view?“

To answer this research question, we first analyze different guidance techniques that focus on spatial factors in AR. We will identify out-of-view visualization methods that are suitable for helping users identify surrounding locations (via direction and distance). We already learned in Section 4.1.2 that there is previous research that suggests how to encode temporal information. However, we can also identify research gaps. In particular, there is no research on how to combine spatial and temporal encoding in AR to support users in tasks that are both spatially distributed and time-critical. Because of this research gap, in Section 4.2.2 we first developed a better understanding of temporal information and the necessary temporal cues for spatially distributed tasks. In the following two user studies, we investigate how spatial and temporal information should be encoded in AR to support users in completing spatially distributed and time-critical tasks. In the first study, we will compare a set of out-of-view visualization techniques enhanced with temporal information in order to identify techniques that enable users to perceive spatial and temporal properties while still conducting tasks. For this study, we implement a game and conduct it in a laboratory setting to be able to control context and stimulation while being strongly bound to a particular application process. In the second study, we investigate the most promising time-extended out-of-view visualization techniques from the first study in a more realistic environment and apply them to the specific application domain.

6.1 Guidance Techniques for Multiple Distributed Tasks

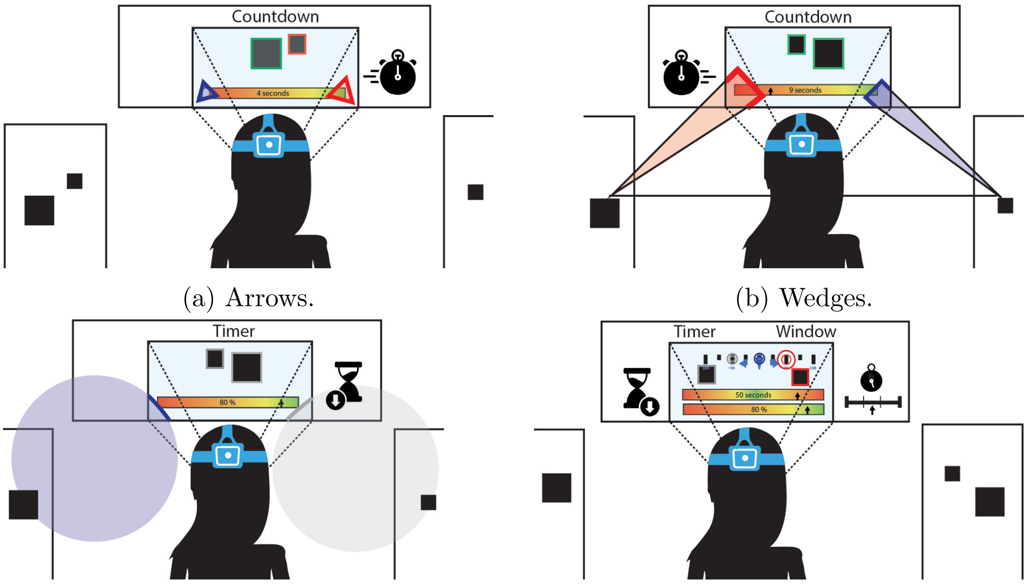
In various manual workflows, cognitive demands can be mastered relatively quickly as long as the task is performed in single steps and time pressure is kept low

[BTC17]. However, coordination of sequential and simultaneous tasks is often required, such as in manual assembly, where tasks are often performed in parallel to increase production or bridge waiting times (see Chapter 5). Since we aim to coordinate multiple tasks that are distributed over different locations, we explore different visual AR guidance techniques to support these scenarios.

In this context, many guidance techniques for locating objects have already been tested in previous work. Here, we can distinguish between in-view (e.g., [Bio+06; RP17]) and out-of-view (e.g., [Grü+17c; Lin+21]) guidance techniques. Both guidance techniques are important for supporting workflow in AR and displaying information about specific tasks. The focus of this work is to support multiple spatially distributed, time-critical tasks that must be coordinated simultaneously. Due to the spatial distribution, most tasks are out of view. In this context, researchers have proposed a plethora of visual out-of-view guidance techniques [Grü+17c; Grü+17b; Grü+17a; Grü+18a; GBH18; Bor+18; Eva+21; TA+21; RP17; Mat+17; Lin+21; MV+20]. These involve placing visual proxies (e.g., arrows [Grü+17c]) at the edge of the user's field of view (FOV) that point in the directions of out-of-view objects. The position of the proxy in the periphery naturally directs attention [GCC17]. Thus, the perception of motion in the periphery is also used for guidance techniques. The work of Matsuzoe et al. [Mat+17] involves circular, vibrating icons at the edge of the screen. In contrast, Truong-Allié et al. [TA+21] use a flashing 3D arrow based on neural network detection of user activity that appears only when current user behavior requires it. Other works, such as that of Renner and Pfeiffer [RP17], use something called spherical wave-based guidance (SWAVE) to direct visual attention to the next relevant action. To guide attention at specific times, we also use motion perception and resize our out-of-view visualizations when the related and spatially distributed task becomes time-critical (see Section 6.2). When selecting out-of-view guidance techniques, there are several options. For example, Grünefeld et al. [Grü+17b; Grü+17a] introduced a radar-like guidance technique (EyeSee360). Here, an ellipse extends over the entire screen, and a rectangle centered in the middle marks the focus area. The area between the rectangle and the ellipse encodes the environment around the user. Other horizontal lines and ellipses also serve as guides. A similar visualization is presented by Bork et al. [Bor+18] with their 3D radar, though they report reduced FOV coverage and greater information encoding potential than EyeSee360. In our work, a radar-like approach would limit the FOV too much because the goal is not to search for multiple out-of-view objects but to display the individual task states of the different workstations. For this reason, we use an alternative solution from Evangelista et al. [Eva+21], who proposed an AR compass. This is inspired by a so-called minimap solution from the computer game series „The Elder Scrolls".[1] Here, the compass is only fixed in the upper part of the FOV and does not restrict

[1] The Elder Scrolls, `https://elderscrolls.bethesda.net/de`, last retrieved December 12, 2022

the FOV as much as the radar-like guidance. Other work compares well-known 2D off-screen visualization techniques, such as Grünefeld et al. [Grü+17c]. In their work, they compared arrows, halos, and wedges, finding that wedges were subjectively preferred by participants, but halos resulted in the fewest errors in direction estimation. In our work, we want to rely on the visualizations because the small space in the FOV prevents distraction and because Grünefeld et al. [Grü+18a] have shown in another work that both halos and wedges are usable under the constraints of the respective technology (VR or AR).



(a) Arrows. (b) Wedges. (c) Halos. (d) Compass.

Figure 6.1: Four different out-of-view visualization techniques: a) arrows, b) wedges, c) halos, and d) compass, showing our identified manifestations of time (cf. Section 4.1.1). The different colors indicate the current state of a task out of view: red for a critical state, gray for a waiting state, and blue for a ready state. Moreover, the presented techniques are rendered larger when a task urgently requires attention (critical state) (own illustration).

6.2 Comparing Different Guidance Techniques

In this section, we compare four selected visualization techniques from previous work to point to locations out of view: *arrows* [Grü+17c], *wedges* [Grü+18a], *halos* [Grü+18a], and *compass* [Eva+21] (see Section 6.1). Each out-of-view location is represented in these techniques by a proxy, which is either an arrow pointing to the location, a wedge or halo spanning between the screen and the location (only partially visible, based on amodal completion [MTC91]), or an icon shown on a compass bar at the top of the screen (see Figure 6.1). By using visual proxies at the edge of the screen, visual clutter in the central FOV is avoided. These out-of-view visualization techniques are useful for helping users identify surrounding locations (via direction and distance). Instead of encoding distance, we have enriched the visualization techniques with temporal information (see Section 4.2.2). In this way, people working on spatially distributed time-critical tasks can be informed about the temporal status of the tasks.

The goal of this study is to compare the different time-extended out-of-view visualization techniques presented in the previous section, gathering insights into users' performances, and enabling a selection of the best perceived ones. Therefore, we implemented an AR game that playfully integrated the three manifestations of time (see Section 4.1.1) by presenting different tasks to the user (see Figure 6.2).

6.2.1 Study Design

To investigate our previously designed visualization techniques, we performed a comparative within-subjects user study in AR using a head-worn device. For the study, we combined our in-view visualization technique with each out-of-view visualization technique, resulting in the independent variable technique with four levels (*arrows* vs. *wedges* vs. *halos* vs. *compass*) (see Figure 6.2).

We varied only the out-of-view visualization technique for the following reasons: the out-of-view visualization technique needs to convey the spatial as well as the temporal properties while having only the screen edges to show information to the user (contextual cues). Moreover, there are oftentimes more tasks taking place out of view than in view. While we focus on qualitative feedback, we collected a few quantitative items, including task duration, error rate, usability with the System Usability Scale (SUS) [Bro96], task load with the NASA Raw TLX (Raw TLX) [Har06], and individual Likert items.

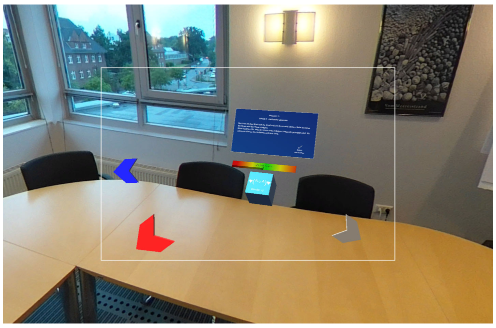
For this study, we asked: **(RQ) How do users perceive the different time-extended out-of-view visualization techniques?** We posit hypotheses for the quantitative data.

H_1 We expect a longer task duration for *arrows*, compared to *wedges*, *halos*, and *compass*.

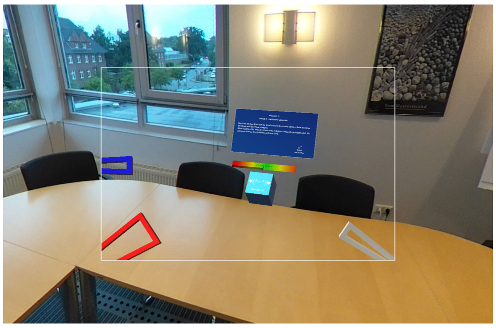
H_2 We expect that *arrows* results in higher usability than *wedges*, *halos*, and *compass*.

H_3 We expect that *compass* will lead to a lower task load compared to *arrows*, *wedges*, and *halos*.

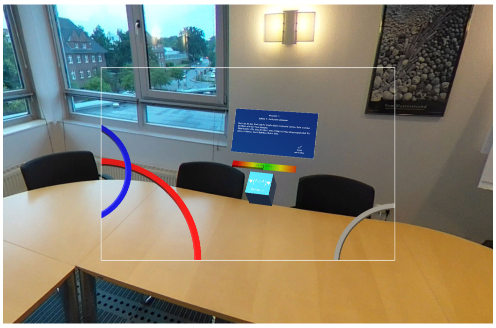
H_4 We expect that *arrows*, *wedges*, and *halos* will be subjectively rated better than *compass*.



(a) Arrows.



(b) Wedges.



(c) Halos.

(d) Compass.

Figure 6.2: Four selected out-of-view visualization techniques: a) arrows, b) wedges, c) halos, and d) compass taken from previous work and enriched with temporal information. The different colors indicate the current state of the task out of view: red for a critical state, gray for a waiting state, blue for a ready state, and green for a finished state. Moreover, the presented visualizations are larger when a task urgently requires attention (critical state) (own illustration) (see Section 4.2.2).

We assume a longer task duration for *arrows* because the other visualization techniques directly communicate the direction to the out-of-view location as well, while *arrows* only indicate the direction in which to search (H_1). However, unlike *wedges*, *halos*, and *compass*, the visualization technique *arrows* relies entirely on a well-known symbol that is used for guidance in various contexts (e.g., navigation). For this reason, the arrow symbol is a familiar concept, for which we expect higher usability due to the familiarity (H_2). Furthermore, we assume that not only the familiar concept but also the type of visualization plays a role. Therefore, we believe that *compass* leads to a lower task load compared to *arrows*, *wedges*, and *halos* because it uses only one instead of four edges and induces less visual clutter (H_3). In contrast, we hypothesize that *compass* will be subjectively rated lower than the other visualization techniques because the other techniques are contextual cues that are designed to point in the direction of the relevant out-of-view location, thereby extending the human attention mechanism naturally

(H_4).

6.2.2 Procedure

In the beginning, we obtained informed consent from each participant. Participants were then briefly informed about the procedure and asked to put on a headset. Then, each condition was tested in a block. The order of the blocks was counterbalanced using a complete counterbalanced design. Within each block, participants could try out the visualization technique and get familiar with the workspace and task. Each condition consisted of four spatially distributed tasks. Within each task, participants had to complete several steps. During the experiment, we instructed participants to think aloud to gather qualitative feedback. After a condition was completed, we asked for subjective ratings regarding SUS, Raw TLX, and individual Likert items. At the end of the last block, participants were asked to fill out a short questionnaire regarding demographics, eyesight, experience with AR, and their favorite condition. Each participant needed about 60 minutes on average to complete the experiment.

6.2.3 Tasks

The study contained four spatially distributed tasks around the user. For all tasks except the first one, participants had to perform five steps. We designed three steps to integrate all manifestations of time: timer, countdown, and window (see Figure 4.1 in Section 4.1.1). In addition, we integrated two distractor steps. Each step had a dialog attached that would inform participants of its goal. The step in the first task was running in parallel to the other three tasks (with five steps each), simulating parallel task execution. We asked participants to be as quick as possible.

Step 0

This step was only implemented in the first task and running in parallel to the other three tasks. In this step, we implemented a timer. Participants had to repeatedly touch a cube to earn points. One touch resulted in one point added to their score. However, if the cube was ignored for ten seconds (timer), points were deducted again, one for each second without interaction. During this time, the task was shown as critical (i.e., highlighted in red and increased in size). The task was automatically completed when all other tasks were completed.

Step 1

In the first step, we implemented a time window. After an initial touch of a specific cube, time would start running, and participants had to wait for 40 seconds before they could stop the time, thereby finishing the task. Additionally, they only had a window of 50 seconds (90 seconds overall) in which they could stop the time and successfully finish the task. During this window, the task was shown as critical. If the task was finished outside the time window, an error was counted.

Step 2

In the second step, we implemented a countdown. The countdown started as soon as the participants touched a specific cube. Eight more small cubes appeared around a task and a countdown was displayed. Participants had a maximum of 30 seconds to "catch" the eight cubes. An error was counted if the time expired.

Step 3

In the third step, we implemented a timer. As soon as a participant touched the cube, a timer appeared that started at that moment. The participant then had to wait for it to expire before touching the cube again. If the cube was touched again after the specified time period, the corresponding task was completed.

Distractor Steps

In addition to the steps with time criticality, we implemented two distractor steps. In the first one, participants were asked to rotate a specific cube several times around its y-axis until it turned green. If participants continued to rotate the cube, it would turn red. In the second one, participants had to touch a cube several times until the cube turned green. If the cube was touched > 18 times, it turned red. An error was counted if the cube was rotated or touched too little or too much.

6.2.4 Apparatus and Implementation

The experiment took place in an empty meeting room (see Figure 6.2). We turned on the lights to have good tracking conditions for the AR headset (Microsoft HoloLens 2). We implemented the different visualization techniques in Unity3D[2], a 3D game development engine. For *halos* and *wedges*, we extended the implementation of Grünefeld et al. [Grü+17c][3]. For the initial localization of the different spatially distributed tasks, we used marker detection based on Vuforia[4].

[2] Unity3D (v.2020.3.36f1), `https://unity.com`, last retrieved January 25, 2023
[3] Out-of-View Techniques, `https://github.com/UweGruenefeld/OutOfView`, last retrieved January 25, 2023
[4] Vuforia (v.9.3.3), `https://developer.vuforia.com`, last retrieved January 25, 2023

6.2.5 Participants

We recruited a total of 24 volunteer participants (10 male, 14 female, 0 diverse), aged between 18 and 65 years (M=33.66, SD=12.95) through public and online advertisements. Participants received no compensation for their time, which was communicated in the advertisement. None of the participants suffered from color vision impairments, 14 had normal vision, and 10 had corrected-to-normal vision. We asked the participants to rate their experience with AR, their experience with time-critical processes (e.g., cooking), and their experience with AR work instructions on a 5-point Likert scale (1=no experience, 5=very high experience). The participants indicated that they had little prior experience with AR (Md=2.00, IQR=3.00), little to high experience with time-critical processes (Md=3.00, IQR=2.00), and no experience with AR work instructions (Md=1.00, IQR=2.00). Participants were informed that they could end the experiment at any time without any negative consequences. Clearance for this research was obtained from our institute's study board review.

6.2.6 Results

In our experiment, we compared out-of-view visualization techniques to enable a selection of the best perceived techniques. First, we report the quantitative findings and then the qualitative findings.

Total Duration

We consider the total duration of our four tasks per condition. The median duration in seconds for the total task duration in ascending order are: *compass* (Md=363.32, IQR=247.56), *arrows* (Md=367.33, IQR=280.70), *halos* (Md= 378.35, IQR=319.79), and *wedges* (Md=417.58, IQR=315.09). A Shapiro-Wilk-Test showed that our data are not normally distributed ($p<0.001$), and thereafter we ran a Friedman test that revealed no significant differences for the indicators ($\chi^2(3)=0.2$, $p=0.978$, $N=24$).

Error Rate

In order to check whether the different indicators contributed to understanding, we measured the overall error rate. The median error rate for the indicators in ascending order are: *wedges* (Md=1.00, IQR=2.00), *compass* (Md=1.00, IQR=2.00), *arrows* (Md=1.00, IQR=2.25), and *halos* (Md=1.00, IQR=3.00). A Shapiro-Wilk-Test showed that our data are not normally distributed ($p<0.001$), and thereafter we ran a Friedman test that revealed no significant differences for the indicators ($\chi^2(3)=0.104$, $p=0.991$, $N=24$).

System Usability Scale

We asked participants to rate the usability of each condition using the SUS questionnaire [Bro96]. The resulting median (interquartile range) scores from highest to lowest usability are: *arrows* (Md=90.0, IQR=10.63), *wedges* (Md=82.5, IQR=18.75), *compass* (Md=82.5, IQR=15.63), and *halos* (Md=67.5, IQR=32.5). The scores are compared in Figure 6.3.

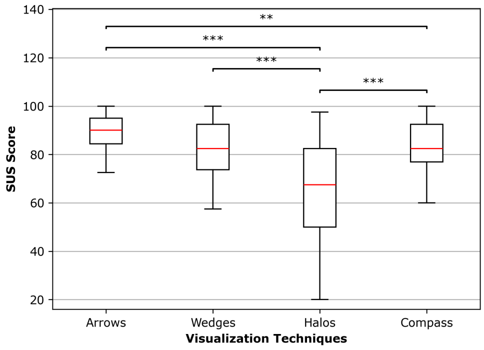


Figure 6.3: Median usability score. Statistically significant differences between groups are indicated by brackets and stars ($0 < {***} \leq 0.001 < {**} \leq 0.01 < {*} \leq 0.05$) (own illustration).

A Friedman test revealed significant differences ($\chi^2(3)$=26.00, p<0.001, N=24). A post-hoc test using Wilcoxon Signed-rank with Bonferroni-Holm correction showed significant differences between *arrows* and *halos* (W=16, Z=3.712, r= 0.758, p<0.001), between *arrows* and *compass* (W=47.5, Z=2.573, r=0.525, p= 0.01), between *wedges* and *halos* (W=38.5, Z=3.189, r=0.651, p<0.001), and between *halos* and *compass* (W=24.5, Z=−3.314, r=0.676, p<0.001). For the median score, we can conclude *arrows*, *wedges*, *compass* > *halos* and *arrows* > *compass*.

Task Load

To assess task load, we used the Raw TLX questionnaire [Har06]. The resulting median (interquartile range) scores from lowest to highest task load are: *arrows* (Md=36.67, IQR=11.25), *wedges* (Md=39.16, IQR=13.33), *halos* (Md= 40.0, IQR=12.08), and *compass* (Md=40.0, IQR=21.67). For inferential statistics, we looked at the individual subscales. A Friedman test for each scale of the Raw TLX revealed significant differences for two scales: effort ($\chi^2(3)$=9.313, p=0.025, N=24) and frustration ($\chi^2(3)$=10.711, p=0.013, N=24). A post-hoc test using Wilcoxon Signed-rank with Bonferroni-Holm correction showed significant differences between *arrows* and *halos* (W=28.5, Z=−2.075, r=0.423, p=0.038) and between *halos* and *wedges* (W=19.5, Z=2.346, r=0.479, p=0.019) for the scale effort. We also found significant differences between *arrows* and *wedges*

(W=6.0, Z=−2.222, r=0.454, p=0.026), between *arrows* and *halos* (W=20.5, Z=−2.464, r=0.503, p=0.014), between *arrows* and *compass* (W=4.5, Z=−2.144, r=0.438, p=0.032), and between *wedges* and *halos* (W=19.5, Z=−2.082, r=0.425, p=0.037) for the scale frustration. For the median effort, we can conclude *arrows*, *wedges* < *halos*. For the median frustration, we can conclude *arrows* < *wedges* < *compass* < *halos* and *wedges* < *halos*.

Individual Likert Item

After each condition, we asked participants to rate the statement „the shown technique helped me a lot“ with a 5-point Likert item (1=strongly disagree, 5=strongly agree). The median (interquartile range) ratings in descending order are: *arrows* (Md=5.00, IQR=1.00), *wedges* (Md=4.50, IQR=2.00), *compass* (Md=4.00, IQR=1.00), and *halos* (Md=3.00, IQR=2.00). All ratings are shown in Figure 6.4.

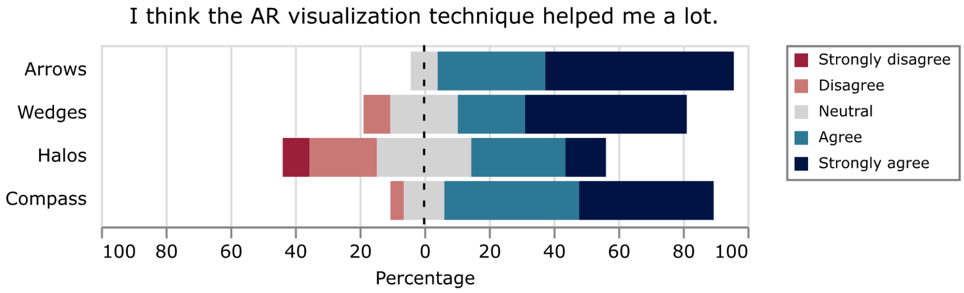


Figure 6.4: Results from Likert item questionnaire (own illustration).

We performed a Friedman test that revealed a significant difference ($\chi^2(3)$= 21.078, p<0.001, N=24). A post-hoc test using Wilcoxon Signed-rank with Bonferroni-Holm correction showed significant differences between *arrows* and *halos* (W=22.00, Z=3.299, p<0.001, r=0.673), *wedges* and *halos* (W=25.00, Z=2.689, p=0.007, r=0.549), and *halos* and *compass* (W=19.50, Z=−3.115, p=0.002, r=0.636). We can conclude that *arrows*, *wedges*, and *compass* are rated significantly better than *halos*.

User Views

To obtain user feedback, we collected statements from study participants during each trial and obtained at least one statement per out-of-view visualization technique. Subsequent qualitative analysis was conducted using inductive categorization [May14]. In this way, six (main) categories were formed from the statements (with an agreement of Krippendorff $_{cu}\alpha$=0.813): Visibility ($_{cu}\alpha$=0.853), Task Support ($_{cu}\alpha$=1.0), Attention Guiding ($_{cu}\alpha$=0.946), Familiarity ($_{cu}\alpha$=1.0), Comprehensibility ($_{cu}\alpha$=0.986), and Distraction ($_{cu}\alpha$=0.92). Key motives and recurring statements were extracted. The category development was performed by one of the authors and one person outside the research team. The two researchers went through the comments and coded them individually. Disagreements were resolved through discussion.

The participants perceived **arrows** as easy to understand. For *arrows*, no participant stated that the visualization technique needed getting used to (comprehensibility: takes time getting used to) (n=6). Fourteen participants stated that the visualization technique is easy to understand (comprehensibility: easy to understand) (n=23). In addition, the concept of an arrow seemed familiar, so that six statements fell into the category „familiarity: known concept“ (n=16). Participants also did not find the four *arrows* disturbing in the FOV, so that only two statements could be assigned to the category „distraction: disturbing in the FOV“ (n=16). The support of the tasks by the visualization technique was seen as helpful by eleven participants (task support: helpful) (n=29). Within the attention guiding category, five participants indicated that the visualization technique's way guiding is good (attention guiding: good way guiding) (n=8) and two that attention is guided when it becomes critical (attention guiding: catches attention if critical) (n=9). In summary, the visualization technique was well understood through the familiar concept of an arrow and was suitable to guide attention and thus support critical tasks.

Wedges, along with *arrows*, were seen as helpful in task support. Thus, 10 participants indicated that the visualization technique was helpful (task support: helpful) (n=29). Also, regarding attention guiding, two participants indicated that the visualization technique helped with way guiding (attention guiding: good way guiding) (n=8). Most notably, when the task became critical, for this visualization technique, with four statements, most participants indicated that attention was well guided (attention guiding: catches attention if critical) (n=9). However, eight participants also felt that the visualization concept was not that easy to understand (comprehensibility: visualization concept is not easy to understand/confuse) (n=12). Only one participant mentioned that *wedges* disturb in the FOV (distraction: disturbing in the FOV) (n=16). Three participants mentioned that the visualization technique does not disturb in the FOV (distraction: no distraction). In summary, the visualization technique is suitable to help users perform tasks in our scenario due to the low distraction in the FOV and especially the attention guiding in critical situations.

Halos were described as easy to understand by only two participants (comprehensibility: easy to understand) (n=29). However, only one participant found the visualization technique difficult to get used to (comprehensibility: takes time getting used to) (n=6). Furthermore, in the visibility category, four participants commented that the tasks were covered too much by the size of the single cues and were thus hardly visible (visibility: can hardly see tasks) (n=4). In addition, the visualization technique was perceived by 13 participants as disturbing in the FOV (distraction: disturbing in the FOV) (n=16). Within the attention guiding category, only one participant stated that the way guiding is good (attention guiding: good way guiding) (n=8) and one that attention is guided when it becomes critical (attention guiding: catches attention if critical) (n=9). In summary, the visualization technique was less helpful in guiding attention and thus supporting critical tasks due to the space of the FOV (size).

Compass was used as an interesting alternative to the usual out-of-view visualization techniques. Five participants found *compass* easy to understand (comprehensibility: easy to understand) (n=29), but four participants also found *compass* difficult to get used to (comprehensibility: takes time getting used to) (n=6). Five participants stated that they did not understand the numbers (here: degrees). For example, one participant said: „Huh? What does that mean with the numbers? Nobody gets that.“ In addition to comprehensibility, only one participant mentioned that the technique helped with task performance (task support: helpful) (n=29). It is particularly interesting that nine participants stated that attention guiding was bad (attention guiding: bad in catching attention) (n=9), which is probably related to the fixed position in the FOV. In fact, here, eight participants indicated that it only fixes one area in the FOV (distraction: occupies only fixed visual area) (n=8). However, as soon as the task became critical, two participants perceived that attention was drawn (attention guiding: catches attention if critical) (n=9). Overall, the concept of the technique was not that unfamiliar. For example, five participants stated that they were familiar with *compass* from video games (familiarity: known concept) (n=16). In summary, the visualization technique might be better suited to indicate location in a different setup, as the FOV is not greatly obscured by the fixed position. If the tasks were more widely spaced across rooms, task support might have been rated higher here.

Sentiment Analysis

We used the deductive approach and evaluated the statements of the participants (positive, neutral, negative) with an agreement of Krippendorff ${}_{cu}\alpha$=0.808. The statements about *arrows* were most often determined positive. The ratings from highest to lowest are: *arrows* (23 positive, 2 neutral, 3 negative), *wedges* (15 positive, 3 neutral, 7 negative), *compass* (13 positive, 3 neutral, 10, negative), and *halos* (9 positive, 4 neutral, 14 negative).

6.2.7 Discussion

In the following, we discuss our results as well as the methodological and technical implications of our user study.

Objective Measures

Objective measures of total duration and error rate showed no significant differences between *arrows*, *wedges*, *halos*, and *compass*. Therefore, we cannot confirm our hypothesis H_1 for the total duration, although *wedges*, *halos*, and *compass* communicate the direction to the out-of-view location directly. Previous approaches [Grü+17c; Grü+18a] focused on rapid localization of objects outside the FOV for position/direction estimation. In their results [Grü+17c], *halos* and *wedges* performed better than *arrows* in terms of direction error. In our work, we extended the visualization techniques with time-critical information by utilizing different colors. We hypothesize that the additional information made the visualization techniques more complex and thereby reduced the differences between the techniques observed in previous studies. Moreover, in our experiment, users had to perform more steps than simply localizing the objects. Therefore, in future studies, it may be beneficial to assess time for different steps individually, potentially eliciting differences between techniques for certain types of tasks.

Usability

The usability is best rated for *arrows*, followed by *wedges*, *compass*, and *halos*. We found significant differences between *arrows* and *halos* and between *arrows* and *compass*, which is reflected in the user views (see Section 6.2.6). Thus, we can confirm our hypothesis H_2 for the SUS, as *arrows* lead to a better usability.

Task Load

The task load scores showed us that *arrows* led to the lowest load, followed by *wedges*, *halos*, and *compass*. *Arrows* and *wedges* were also preferred by the participants (see Section 6.2.6). Thus, task load could indicate that both comprehension difficulties with *compass* and interference in the FOV with *halos* led to higher task load. An analysis of the individual scales revealed significant differences for the scales effort and frustration. *Arrows* and *wedges* resulted in significantly less effort compared to *halos*. Participants were also less frustrated with *arrows* compared to *wedges*, *compass*, and *halos*. Furthermore, *wedges* led to less frustration compared to *halos*. Therefore, we cannot confirm our hypothesis H_3 for task load, although the fixed position at the top of the screen leads to less visual clutter.

Individual Likert Item

The individual Likert item showed that *compass*, *arrows*, and *wedges* supported the participants to guide their attention. We found a significantly better rating for *compass*, *arrows*, and *wedges* compared to *halos*. Participants expressed that *halos* in the FOV were disturbing (see Section 6.2.6). We think that this is a possible reason for the rating. Therefore, we cannot confirm our hypothesis H_4, since *halos* were not evaluated better than *compass*, although they are contextual cues pointing in the direction of the relevant out-of-view location.

User Views

Users perceived *arrows* as easy to understand. The familiar concept of an arrow contributed to their being well accepted and successful in directing attention [Yab20; IMC07]. *Wedges* were perceived as helpful in providing task support and directing attention in critical situations. Although some users found the visualization concept of *wedges* not easy to understand, they were not perceived as interfering in the FOV. *Compass* was considered less effective for attention guidance because it occupied a fixed visual area. *Compass* could prove potentially more suitable for indicating a location in a different environment (tasks distributed across rooms), as the fixed position had less impact in the FOV. *Halos*, in contrast, were perceived as less helpful in guiding attention because they interfered too much in the FOV.

Selection of Techniques

To further investigate a concrete use case, we chose *arrows* and *wedges* based on users' positive ratings and opinions. Both were perceived as helpful in providing task support and directing attention in critical situations, which underscored their suitability for supporting critical tasks. *Arrows* were perceived as easy to understand, familiar, and not distracting in the FOV. They proved to be effective tools for targeting attention to specific areas.

Limitations

During the study, we observed that the hand tracking of the HoloLens 2 was affected by thick clothing such as sweater sleeves. Therefore, a few participants had to roll up their sleeves. In addition, the HoloLens 2's FOV is still limited, which initially confused some participants. Even though the technology has progressed, the problem of the limited FOV with optical see-through AR remains a challenge. Another limitation was the limited battery life. To address this issue, a backpack with a power bank was worn to charge the HoloLens 2 during the study.

6.2.8 Conclusion

In this study, we evaluated four different time-extended visualization techniques – *arrows*, *wedges*, *halos*, and *compass* – to determine their effectiveness in supporting users performing distributed time-critical tasks using AR. Our results provide valuable insights into the user preferences, usability, and task load associated with each technique. *Arrows* emerged as the preferred technique, praised for its ease of understanding, familiarity, and effectiveness in directing attention without distraction. *Wedges* were also well received, providing strong support for task completion and good attentional focus, although some users found them more difficult to understand initially. *Compass* received mixed feedback due to its fixed position in the FOV, which limited its effectiveness in directing attention. *Halos* were the least popular, as they were perceived as intrusive and distracting, making task performance more difficult. Objective measures such as total task time and error rate showed no significant differences between the techniques, suggesting that the additional temporal information balanced performance. However, task load ratings indicated that *arrows* and *wedges* resulted in less effort and frustration than *halos* and *compass*. Overall, *arrows* and *wedges* proved to be the most effective visualization techniques for time-critical out-of-view tasks in AR providing a good balance between usability, task support, and user preference. These results have implications for designing more intuitive and effective AR interfaces that improve user performance in distributed, time-critical tasks. Future research should investigate these techniques in more complex, real-world scenarios to further validate their effectiveness. Therefore, we are investigating *arrows* and *wedges* further in a specific use case based on the positive user reviews and opinions (see Section 6.3).

6.3 Guidance Techniques in a Contextual Use Case

In this section, we have selected the two most promising time-extended out-of-view visualization techniques – *arrows* and *wedges* – from the first study (see Section 6.2) and applied them to our contextual use case to verify whether our techniques add value.

The goal of this study is to investigate whether or not the selected time-extended out-of-view visualization techniques help users in a specific application. We focus on how well the combination of spatial and temporal information from the two selected out-of-view visualization techniques works for users in a specific use case. In order to gain insights depending on a specific use case, we put more emphasis on reviewing the visualization techniques during the processing of a bonding process. Therefore, we extended our application-based bonding process in AR from Chapter 5 and integrated the three manifestations of time by requiring the user to perform the bonding in different steps (see Figure 6.2).

6.3.1 Study Design

To review our previously selected visualization techniques, we performed a comparative within-subjects user study in head-mounted AR. We used the independent variable *technique* with three levels (*arrows* vs. *wedges* vs. *baseline*). We included a baseline condition without the extended out-of-view techniques to investigate the effect of the techniques. We used quantitative methods to evaluate users' performances, using duration in time-critical steps, timer deviation, parts distance (spacer and joining parts), System Usability Scale (SUS) [Bro96], and task load with the NASA Raw TLX (Raw TLX) [Har06] as dependent variables.

For this study, we asked: **(RQ) To what extent does an out-of-view visualization technique in a concrete time-critical use case with spatially distributed tasks affect participants' performance in terms of step duration, timer deviation, waiting time, and workload in time-critical task steps?**

H_1 We expect that out-of-view visualization techniques will improve the temporal understanding of the steps with manifestations of time criticality of the spatially distributed tasks compared to *baseline* because the temporal status of the distributed tasks is directly evident from the size and color of the individual cues.

H_2 We expect that *arrows* will be preferred by the user over *wedges* due to familiarity, as no additional time is required for understanding.

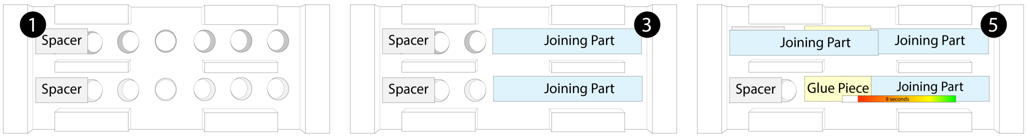
H_3 We expect that out-of-view visualization techniques will lead to different user behavior compared to *baseline*, as they are constantly displayed as proxies in the periphery, drawing attention to themselves.

6.3.2 Procedure

The experiment took place in a manufacturing laboratory (see Figure 6.6). In the beginning, we obtained informed consent from each participant. Participants were then briefly informed about the procedure and asked to put on a headset. Then, the main part of the study started, with each condition tested in a separate block. The order of the blocks was counterbalanced using a complete counterbalanced design. Within each block, participants could first try out the technique and get familiar with the workspace and task. Each condition consisted of three spatially distributed tasks with five steps each. After a condition was completed, we asked for subjective ratings regarding SUS [Bro96] and Raw TLX [Har06]. At the end of the last block, we asked participants to fill out a short questionnaire regarding demographics, eyesight, experience with AR, and their favorite condition. Each participant took about 50 minutes on average to complete the experiment. In the following, we will explain the spatially distributed tasks and the different manifestations of time from Section 4.1.1 in more detail.

6.3.3 Tasks

We designed three spatially distributed tasks, each with five steps (see Figure 6.6). The five steps were derived from the requirements for bonding processes defined by DIN 2304-1 [DIN20]. Of these, three steps integrate the three different types of temporal information: timer, countdown, and window (see Figure 4.1). In addition, we integrated two steps necessary to prepare a bonding task. While these tasks did not contain time-critical steps, they were crucial for the investigated assembly process. Each task had a dialog attached that would inform participants of its goal. We asked participants to complete all tasks as quickly as possible. In the following, we will explain the individual steps of a task and the different manifestations of time criticality in more detail.



(a) Distractor step. (b) Distractor step. (c) Time-critical step.

Figure 6.5: Top view of the gluing device with two derived distractor steps and one time-critical step: a) spacers placed on the left side of the device in the first step (1), b) joining parts placed on the right side of the gluing device in the third step (3), and c) gluing parts placed on the joining part in the fifth step (see bottom of image) and then glued to the counterpart (see top of image) (own illustration).

Step 1 (uncritical)

In the first step, two spacers have to be positioned in the gluing device[5] (see Figure 6.5a). As in Chapter 5, these keep the joining parts (metal plates) at a certain distance from each other (see Figure 6.5c).

Step 2 (timer)

Four joining parts must be flashed off. Reminder from Section 5.2: the flash-off time is the amount of time that must elapse when using cleaners, activators, or primers to allow the solvent to completely evaporate before the adhesive can be applied (see Section 2.1). In the second step, therefore, the joining parts must be placed in predetermined positions. As soon as a part is placed on the position, the corresponding time period (timer) for this part starts and the out-of-view cue turns gray. A joining part must flash off for at least 60 seconds (waiting time). After flashing off, the cue became blue again (state ready, not critical).

Step 3 (uncritical)

In the third step (comparable to the first step), two joining parts must be placed in the gluing device (see Figure 6.5b). As in Section 5.3, this is in preparation

[5] All positions are displayed using AR through contour-based highlighting and coloring.

for the subsequent gluing process, as a counterpart will be glued to these parts in the fifth step (see Figure 6.5c), so that the pot life (workability time or usage time of an adhesive) is kept as short as possible [Ras12; Hab03].

Step 4 (window)

Two glue pieces have to be placed at the displayed position and react chemically. In a bonding process, so-called mixing times of component adhesives must be observed so that the two components react chemically. In addition, however, the so-called pot life must not be exceeded since compliance with this time determines the quality of the bond [6]. To simulate this time window, the component adhesives (represented by glue pieces) had to react chemically for at least 20 seconds, but only for a maximum of 45 seconds (not to exceed the pot life). The out-of-view cue became red and larger once the window tick arrow reached the lower bound of 20 seconds (critical). It was necessary to react within 25 seconds from this point on. After reaching the upper bound of 45 seconds, it turned blue again because the time had already been exceeded and the fictitious pot life had expired.

Step 5 (countdown)

In the fifth step, the low pot life of the adhesive is simulated with a countdown. The adhesive must always be used at a certain time (cf. Section 5.2). A total of two joining parts must be glued[7] and placed in the correct position in the (gluing) device. After a glue piece was placed on the previously prepared joining parts, a countdown for each counterpart (non-glued joining part) started (see bottom of Figure 6.5c). The counterpart part must be placed on the (glued) part in the correct position before the countdown expires (see top of Figure 6.5c). The gluing positions are displayed on the previously positioned joining parts (third step). As soon as the counterpart is placed in this position, the countdown is stopped.

6.3.4 Apparatus

The experiment took place in a manufacturing laboratory (see Figure 6.6). We turned on the lights to have good tracking conditions for the AR headset (Microsoft HoloLens 2). We implemented the different visualization techniques in Unity3D[8], a 3D game development engine. For *arrows* and *wedges*, we reused the techniques from the previous study. For the initial localization of the different spatially distributed tasks, we used marker detection based on Vuforia[9].

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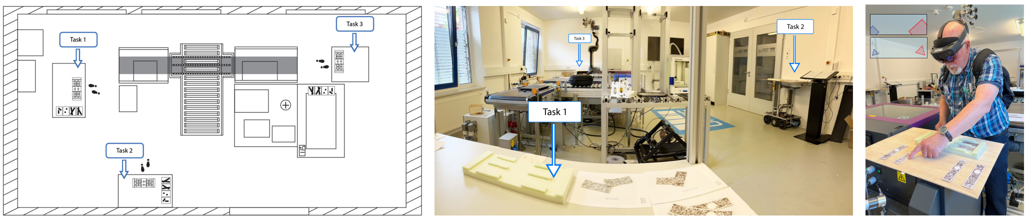
[6] `https://www.innotech-rot.de/media/private/downloads/versuche-zur-topfzeit-fraunhofer-ifam_275TMV.pdf`, last retrieved August 10, 2023
[7] For safety reasons, the part of the actual gluing is only fictitious.
[8] Unity3D (v.2020.3.36f1), `https://unity.com`, last retrieved July 16, 2023
[9] Vuforia (v.9.3.3), `https://developer.vuforia.com`, last retrieved July 16, 2023



(a) Sketch of apparatus. (b) Photograph of apparatus. (c) User.

Figure 6.6: Apparatus of experiment in the manufacturing lab: a) a sketch of the industrial manufacturing lab, b) a picture taken of the apparatus, and c) a close-up view of a study participant, where the AR display shows the visualization techniques depending on the condition and the instructions of the corresponding task (own illustration).

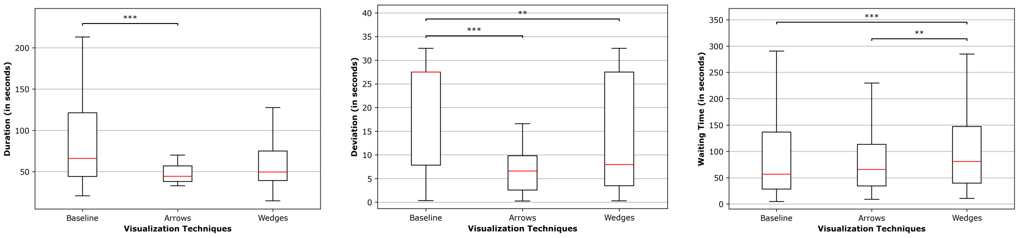
6.3.5 Participants

We recruited a total of 18 volunteer participants (11 male, 7 female, 0 diverse), aged between 21 and 65 years (M=32.89, SD=13.45) through public and online advertisements. Participants received no compensation for their time, which was communicated in the advertisement. One of the participants suffered from color vision impairments[10], 9 had normal vision, and 9 had corrected-to-normal vision. We asked the participants to rate their experience with AR, their experience with work instructions (e.g., manuals), and their experience with time-critical processes (e.g., cooking) on a 5-point Likert scale (1=no experience, 5=very high experience). The participants indicated that they had little to high experience with AR (Md=2.00, IQR=2.00), medium to high experience with work instructions (Md=3.00, IQR=1.75), and high to very high experience with time-critical processes (Md=4.00, IQR=1.75). Participants were informed that they could end the experiment at any time without any negative consequences. Clearance for this research was obtained by our institute's study board review.

6.3.6 Results

In the following, we present the quantitative and qualitative findings of our experiment.

[10] The participant with color vision impairment suffered from a tritanomaly, but was able to recognize the color blue in a turquoise hue. Since we made changes in shape and size in addition to colors (see Section 4.2.2), the participant did not report any problems with solving or recognizing criticality. The participant was therefore included in the evaluation.



(a) Step duration. (b) Deviation ideal time. (c) Elapsed waiting time.

Figure 6.7: The different time-relative quantitative measures taken in every condition. Statistically significant differences between groups are indicated by brackets and stars ($0 < *** \leq 0.001 < ** \leq 0.01 < * \leq 0.05$) (own illustration).

Step Duration

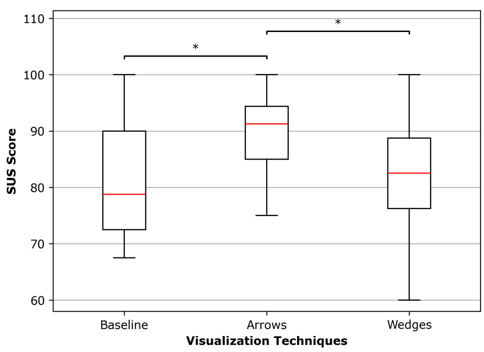
We consider the duration of the steps (window: step 4, countdown: step 5) within the spatially distributed tasks. In bonding, these steps must be completed without interruptions if possible, since only short processing times of the adhesive are available [Ras12; Hab03]. The median duration for the fourth, time-critical step (window) in seconds are (in ascending order): *arrows* (Md=44.39, IQR=18.73), *wedges* (Md=49.60, IQR=35.93), and *baseline* (Md=66.09, IQR=77.01). The median duration for the fifth, time-critical step (countdown) in seconds in ascending order are: *baseline* (Md=16.64, IQR=14.28), *arrows* (Md=17.11, IQR=11.17), and *wedges* (Md=17.92, IQR=13.19). A Shapiro-Wilk-Test showed that our data is not normally distributed (p<0.001); therefore, we ran a Friedman test that revealed significant differences for the techniques in the fourth step ($\chi^2(2)$=8.926, p=0.012, N=18). A post-hoc test for the fourth step (window) using Wilcoxon Signed-rank with Holm-Bonferroni correction showed significant differences between *baseline* and *arrows* (W=317, Z=3.659, r=0.498, p<0.001). The duration for each condition is compared in Figure 6.7a. Here, we can conclude *arrows* < *baseline* for the median step duration.

Deviation from Ideal Time

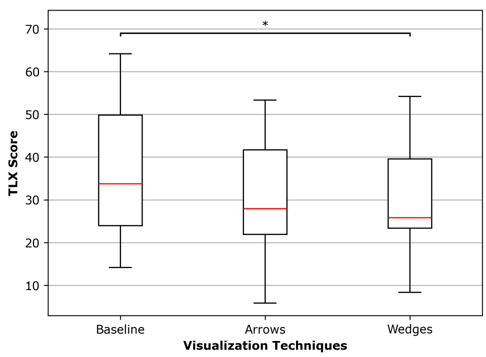
We consider the deviation from the ideal time in the fourth step (window: step 4). In a (time) window, the ideal time describes the exact time center. In bonding, the smallest possible deviation from the ideal time leads to a better bond [Hab03]. The median deviation in seconds are (in ascending order): *arrows* (Md=6.56, IQR=7.25), *wedges* (Md=7.94, IQR=24.02), and *baseline* (Md=27.50, IQR=19.69). The deviation for each condition is compared in Figure 6.7b. A Shapiro-Wilk-Test showed that our data is not normally distributed ($p < 0.001$); therefore, we ran a Friedman test that revealed significant differences for the visualization techniques ($\chi^2(2)$=15.592, p<0.001, N=18). A post-hoc test using Wilcoxon Signed-rank with Holm-Bonferroni correction showed significant differences between *baseline* and *arrows* (W=211, Z=4.572, r=0.622, p<0.001) and between *baseline* and *wedges* (W=428, Z=2.704, r=0.368, p=0.007). Here, we can conclude *arrows*, *wedges* < *baseline* for the median deviation from ideal time.

Elapsed Waiting Time after Flash Off

We consider the waiting times after flash off. The median waiting times in seconds are (in descending order): *baseline* (Md=56.67, IQR=108.33), *arrows* (Md=65.89, IQR=78.91), and *wedges* (Md=80.85, IQR=107.58). The waiting time for each condition is compared in Figure 6.7c. A Shapiro-Wilk-Test showed that our data is not normally distributed (p<0.001); therefore, we ran a Friedman test that revealed significant differences for the visualization techniques ($\chi^2(2)$=14.181, p<0.001, N=12). A post-hoc test using Wilcoxon Signed-rank with Holm-Bonferroni correction showed significant differences between *baseline* and *wedges* (W=3477, Z=−3.475, r=0.290, p<0.001) and between *arrows* and *wedges* (W=3606, Z=−3.218, r=0.268, p=0.002). For the elapsed waiting time, we can conclude that *baseline*, *arrows* < *wedges*.



(a) Usability score.



(b) TLX score.

Figure 6.8: Quantitative findings from questionnaires: a) median usability score (SUS) and b) median TLX score (Raw TLX). Statistically significant differences between groups are indicated by brackets and stars ($0 < {*}{*}{*} \leq 0.001 < {*}{*} \leq 0.01 < {*} \leq 0.05$) (own illustration).

System Usablity Scale

The median usability scores are (in descending order): *arrows* (Md=86.18, IQR= 11.25), *baseline* (Md=79.87, IQR=17.5), and *wedges* (Md=79.47, IQR=12.5). The scores for each visualization technique are compared in Figure 6.8a. Since these are ordinal data, we directly used a Friedman test that revealed significant differences for the visualization techniques ($\chi^2(2)$=7.065, p=0.029, N=18). A post-hoc test using Wilcoxon Signed-rank with Bonferroni-Holm correction showed significant differences between *baseline* and *arrows* (W=21, Z=−1.952, r=0.460, p=0.050), and between *arrows* and *wedges* (W=22, Z=2.139, r=0.504, p=0.032). For the usability score, we can conclude *arrows* > *baseline*, *wedges*.

Task Load

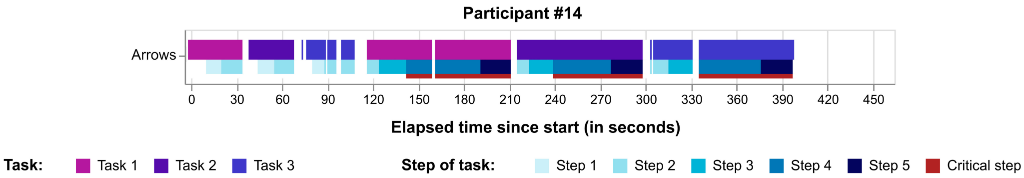
The resulting median (interquartile range) scores from lowest to highest task load are: *wedges* (Md=25.83, IQR=16.25), *arrows* (Md=27.92, IQR=19.79), and *baseline* (Md=33.75, IQR=25.83). The scores for each visualization technique are compared in Figure 6.8b. A Friedman test showed a significant difference between the conditions ($\chi^2(2)$=6.677, p=0.035, N=18). A post-hoc test using Wilcoxon Signed-rank with Bonferroni-Holm correction showed a significant difference between *baseline* and *wedges* (W=28, Z=2.043, r=0.482, p=0.041). For the task load, we can conclude *wedges* < *baseline*.

Individual Rating

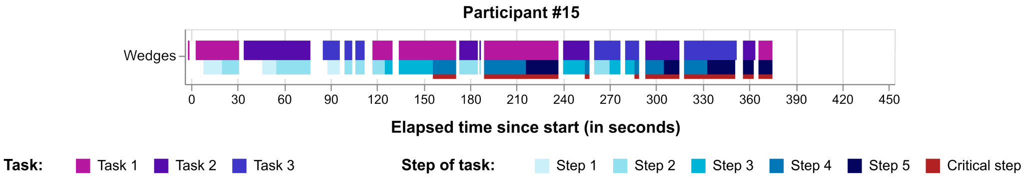
We asked participants to answer two questions about which visualization technique they felt most comfortable and uncomfortable with. The participants felt most comfortable with *arrows* (10), followed by *wedges* (6) and *baseline* (2). The participants felt most uncomfortable with *baseline* (10), followed by *wedges* (6) and *arrows* (2).

Identified Behavior Patterns

We looked at participant behavior during the study. Therefore, we recorded all positions of the tasks (including position and rotation) and of the participants during each study run. The distance between the tasks was about three to six meters (see Figure 6.6). To determine movement and behavior, we looked at a 1-meter radius around the task locations to see when a participant was there. Additionally, we were able to determine which step was being processed for each task. We visualized all behavior patterns and clustered them using an online whiteboard tool. Overall, we were able to identify three categorizing questions: 1) Did participants switch tasks? 2) Did participants return to the task more than once? 3) Did participants switch during time-critical phases of the task? Participants who switched tasks (52) and returned to each task only once (18) did not switch in time-critical steps (17) and worked through the tasks in a mostly structured manner (15) (see Figure 6.9a). This means that the participants proceeded chronologically according to a pattern (e.g., 1-2-3-1-2-3). As soon as participants returned to a task more than once (34), they very often switched in time-critical steps (33) and no longer processed the tasks in such a structured way (24) (see Figure 6.9b). For the behavioral data, we can conclude that the more frequently participants returned to a task, the more chaotic the processing became. Furthermore, the behavioral patterns were less dependent on the technique.



(a) Task was performed in a structured manner: each task was returned to only once and no time-critical switching was performed.



(b) Task was performed in an unstructured manner: each task was returned to more than once and switching was performed in time-critical steps.

Figure 6.9: Extracted behavioral patterns as representative examples from different trials in different conditions (own illustration).

6.3.7 Discussion

In the following, we discuss our results as well as the methodological and technical implications of our user study.

Understanding Time

Often, a short setting time (time to cure) is desired for reasons of production speed, so only a short pot life, i.e., a short processing time of the adhesive, is available [Ras12; Hab03]. For this reason, it is important to be as fast as possible, especially in time-critical steps, in order to not exceed the processing time. We found that the out-of-view visualization techniques could help to minimize the task time in critical steps. In this context, the duration of the fourth time-critical step (window) duration was highest for the *baseline* condition and decreased with each of the other two conditions (*arrows* and *wedges*). We found that the participants often left the task to continue another task after the window started. The out-of-view visualization technique then indicated when they had to return and the window reached the defined time period. In the fifth step (countdown), we found no significant differences in step duration. In this step, the countdown began immediately, so participants did not change tasks as often in this step. Similar to the duration of the fourth time-critical step, the out-of-view visualization techniques played an important role in the deviation from the ideal time. After positioning the glue pieces, the window was started, and participants could continue with another step in another task. When participants needed to return was mediated by the out-of-view visualization (except when the participant remained directly on task). Transferred to a concrete use case, the smallest possible deviation from the ideal time can lead to better bonding. The pot life must not be exceeded, since outdated specimens show a strongly reduced tensile shear strength by fracture pattern determination [Hab03; Hab12]. Thus, after only ten minutes in a concrete use case, the adhesive fraction can be over 90 percent[11]. Based on the data of the duration of time-critical steps, we can partially confirm our hypothesis H_1, as shown by our comparison of step duration between *baseline* and *arrows* in the fourth, time-critical step (window), but not between *baseline* and *wedges*. However, the deviation from the ideal time differed significantly between *baseline* and *arrows* and between *baseline* and *wedges*, confirming our hypothesis H_1. Another interesting observation is the elapsed waiting time after flash off. We assume that the color of the cues – here blue as non-critical after flash off – made it clear that the current step is just not critical. In the *baseline* condition, participants received no indication at all and only saw that the timer (percent display) was complete. We therefore assume that the waiting time after flash off is significantly lower without a visualization technique, since the participants simply did not know whether they now had to act quickly as soon as the joining parts had been flashed off. Transferred to a concrete use case, the visualization techniques help to save unnecessary walking and to switch to a workstation only when it is necessary in terms of time. With the increasing complexity of manual assembly tasks and the associated increase in cognitive demands, the physical demands can at least be minimized by reducing walking distances [Blä+21].

Subjective Measures

The usability, the task load, and the individual rating show us that time-extended out-of-view visualization techniques are preferred or lead to low task load compared to *baseline*. The usability score showed a significant difference between *arrows* and *wedges* and a significant difference between *arrows* and *baseline*. As in the first study, we can show that the familiar concept of an arrow contributed to their being well accepted. The task load score showed a significant difference between *baseline* and *wedges*, which shows that visual cues help to reduce the load. We can partially confirm our hypothesis H_2 as the usability and individual rating show that participants felt most comfortable with *arrows* and rated usability the highest, respectively. In this context, we can confirm that *arrows* are preferred but do not lead to lower task load.

[11] `https://www.innotech-rot.de/media/private/downloads/versuche-zur-topfzeit-fraunhofer-ifam_275TMV.pdf`, last retrieved August 12, 2023

User Behavior

During our behavior analysis, we found that the different patterns are mainly resulting from participants' habits and less from the individual conditions. In other words, participants showed very similar behavior across conditions. Accordingly, the out-of-view visualization techniques had no effect on the participants' behavior patterns, only their timings, and the participants reverted to their habitual behavior patterns regardless of the condition. This is probably related to the fact that people perceive their own habits and patterns of action as goal-oriented [Nea+12] and tend to repeat the same behaviors in recurring contexts [WR16]. Because the task did not change in a trial, participants presumably did not change their strategy to work through the task at the workstations despite the different conditions. According to Wood and Rünger [WR16], certain habits form when people pursue goals by repeating the same responses in a given context. The more frequently participants returned to a task, the more likely they were to switch within a time-critical step as well, which in turn led to a more chaotic execution of the task. This is likely due to the increasing complexity that resulted from time criticality. When participants „jumped“ between tasks in this context, it probably led to cognitive overload (although it may not have been perceived that way by the participants) [BTC17; Ill+21; Pas99]. Based on our observations, we cannot confirm our hypothesis H_3 that the out-of-view visualization techniques lead to different user behavior compared to *baseline*. We can glean another interesting observation from the elapsed waiting time after flash off. We assume that the color of the cues – here blue as non-critical after flash off – made it clear that the current step is just not critical. In the *baseline* condition, participants received no indication at all and only saw that the timer (percent display) was complete. We therefore assume that the waiting time after flash off is significantly lower without a visualization technique, since the participants simply did not know whether they now had to act quickly as soon as the joining parts had been flashed off. Therefore, the participants may have felt a higher level of urgency because they could not fully monitor the tasks without a visualization technique. Transferred to a concrete use case, the visualization techniques help to save unnecessary walking and to switch to a workstation only when it is necessary in terms of time. With the increasing complexity of manual assembly tasks and the associated increase in cognitive demands, the physical demands can at least be minimized by reducing walking distances [Blä+21].

Scalability

In a real use case, the number of proxies for out-of-view visualization techniques would have to be limited by cognitive perception capabilities. For example, it does not make sense to display several hundred tasks at the edge of the user's FOV. Many researchers describe that parallel execution of tasks due to a cognitive processing bottleneck leads to performance losses in the form of increased response latencies or error rates [Kah73; Pas94; JSK04; PKB09]. Even if parallel cognitive processing of multiple task components is possible despite processing bottlenecks [FP15], e.g., through capacity sharing [TJ03; LH08; Wic02] or crosstalk [Hom98; Mil05], studies have shown that it is necessary to limit the number of tasks [Ill+21]. For example, it is necessary to adjust the information density, as this determines the degree of understanding of the task to be processed [Kei+13; Jul+00; RHO15; RP17]. Therefore, we suggest that performance is likely to decrease with more tasks and that the spatial distribution only works up to a certain number of locations. Future studies should therefore investigate the number of tasks and the level of complexity of the individual steps at which performance begins to decline. The general scalability does not depend on visualization techniques outside the FOV, but on the underlying prioritization and scheduling algorithms responsible for selecting the tasks to be processed next and thus displayed.

Limitations

We faced some technical limitations with the Microsoft HoloLens 2 regarding marker tracking and limited FOV. For the marker tracking, we ensured that the room was well lit and the markers had a good size, while we could not do anything about the limited FOV. This means that the potential of human vision cannot be optimally used to naturally enrich visual perception through AR. However, by using the Microsoft HoloLens 2 with its limited FOV, we were able to measure the performance of what is currently possible for optical see-through head-mounted displays.

6.3.8 Conclusion

In this study, we evaluated the effectiveness of two time-extended out-of-view visualization techniques, *arrows* and *wedges*, in improving user performance during time-critical and spatially distributed tasks in an AR environment. Through a comparative within-subjects user study, we investigated how these visualization techniques work in a specific application context.

Our results indicate that the out-of-view visualization techniques significantly improved users' temporal understanding and performance during time-critical steps. Our visualization techniques showed a reduction in step duration and deviation from ideal time compared to the *baseline* condition. In addition, both visualization techniques resulted in reduced waiting times after flash-off periods, suggesting that users were better able to judge when to proceed with their tasks, thereby minimizing unnecessary delays and optimizing task efficiency. Subjective measures further supported the quantitative findings, with participants rating *arrows* higher in terms of usability and comfort. While the visualization techniques improved timing and usability metrics, they did not significantly alter participants' behavioral patterns. This suggests that while users benefited from the enhanced visual information, they still relied on their habitual task strategies. This finding highlights the importance of designing AR systems that complement natural user behavior rather than attempting to change it.

Our study also revealed the potential for scalability challenges with out-of-view visualization techniques. While effective for a limited number of tasks, an excessive number of visual cues could overwhelm users and reduce overall performance. Therefore, future research should focus on optimizing the number of tasks displayed and developing prioritization algorithms to effectively manage complex task environments. In conclusion, this study demonstrates that time-extended out-of-view visualization techniques, particularly *arrows*, can significantly improve user performance on time-critical and spatially distributed tasks in AR environments. These findings provide valuable insights for designing AR applications that improve efficiency and reduce cognitive load, contributing to more effective and user-friendly AR systems.

6.4 Summary

Workflows in various domains require careful coordination of sequential and concurrent tasks. However, the time-critical nature of these tasks can lead to increased cognitive load and potential errors, especially when tasks are spatially distributed (see Chapter 2 and Section 3.3.1). Our goal is to provide users with better temporal and spatial orientation in such workflows. Therefore, we propose the integration of AR to assist users in performing parallel time-critical tasks across different locations. In this chapter, we have shown that out-of-view visualization techniques in AR can be enriched with temporal information by encoding the current time information of the task in addition to the out-of-view position. We extended existing out-of-view visualization techniques with temporal information. We demonstrated and evaluated four visualization techniques (namely *arrows*, *wedges*, *halos*, and *compass*) extracted from previous work in a first comparative user study to obtain a selection of the best perceived time-extended out-of-view visualization technique for time-critical and spatially distributed tasks. We then continued with the best performing techniques (*arrows* and *wedges*) in a second user study, where we investigated a specific use case and compared the techniques to a baseline without spatial assistance. Thus, we provide insights into the performance of selected visualization techniques in an application-specific use case and show that step duration, as well as deviation from ideal time in a time-critical work step, can be reduced by encoding time. Especially in such time-critical steps, the addition of out-of-view visualization techniques is another support option to reduce errors and the associated stress. Moreover, we explored the behavioral data of the participants by recording their movement and time at different workstations. We were able to show that the more frequently participants returned to a process, the more likely they were to switch within a time-critical step. However, this often led to a more unstructured execution of different tasks in different locations. The more often participants returned to a task (i.e., the more they tried to work on it in parallel), the more chaotic the processing became. When tasks were switched within a time-critical step, complexity also increased due to the time pressure created. This finding is consistent with the results of our study on the number of possible parallel visualizations (see Section 5.3) – the more tasks were processed in parallel, the more time-critical it became (see Section 5.3.4) and the higher the perceived workload (see Section 5.3.6). Again, we can fall back on the explanation of our perceptual abilities (see Section 3.1.3.2). For example, spatial aspects may influence our perception of time. It is possible that participants changed within a time-critical step because a greater spatial distance (spatially distributed tasks) is mentally associated with a greater temporal distance [CHS53] (see Figure 3.9). For example, participants did not always perceive a task change as critical despite a running timer, even though the change subsequently led to a critical temporal state. However, we also assume that with increasing experience, the behavior adapts to the work situation, so that both multiple tasks can be handled (see Section 3.1.2), and critical states are better recognized, thus reducing possible spatial effects of time perception. Our findings imply that encoding time criticality and location of tasks in AR can improve users' performance. Our results can be applied to various application domains where time-critical and parallel tasks are performed that are spatially distributed and can help in the design and development of assistance systems to improve the temporal understanding of tasks.

Based on the results presented in this chapter, we have extended our demonstrator presented in Section 5.4 to include additional support for the spatial distribution of time-critical and parallel tasks. In contrast to the previous demonstrator from Section 5.4, this extended demonstrator was implemented exclusively on head-mounted devices, since the process states of the spatially distributed tasks are always visible on the display and the hands can be kept free (e.g., no tablet needs to be carried). The demonstrator visualizes both the dynamically displayed AR information at the respective assembly task (in-view) and additional cues at the edge of the display that provide temporal and spatial information about the spatially distributed tasks (out-of-view). Depending on the user's preference, the user can switch between the visualization techniques *arrows* and *wedges* using a hand menu. With this demonstrator, we can show how additional AR cues can provide information for temporal and spatial coordination to improve spatial orientation.

Figure 6.10: Extended demonstrator for head-mounted devices based on the results of the two presented studies. The demonstrator guides the user through the spatially distributed assembly process in a manufacturing lab using AR (own illustration).

7 Design of Task Overviews

Our context analysis has shown that manual labor is still an important part of industrial production. However, compared to autonomous systems, human workers cannot operate 24/7, requiring shift changes or other take-over scenarios. In this context, ensuring smooth takeovers is critical to maintaining production continuity and avoiding temporary process interruptions. The ability to adapt quickly is particularly important in situations where tasks need to be taken over.

These take-over processes are particularly critical when, as in our case, the tasks are very complex and must be completed within a specified time frame and across multiple locations (see Chapter 2, Chapter 5 and Chapter 6). Many studies suggest that knowledge transfer between shift changes needs to be improved, as inadequate information leads to incomplete understanding and, therefore, the change often fails[BV15; BS11]. In addition, many occupational accidents are also due to incomplete and poor handovers [Vis+20]. For example, poor communication during shift handover was identified as one of the causes of the Piper Alpha disaster [Bra18; WL12], in which an oil rig in the North Sea caught fire and cost lives. Therefore, an overview of all the information required during takeover is crucial to improve knowledge transfer to avoid communication errors and ensure safety and efficiency during shift changes.

Our previous studies have highlighted the potential of Augmented Reality (AR) to support and increase the efficiency of production processes (see Chapter 5), particularly through the use of head-mounted displays (HMDs) that allow users to use their hands freely and move around unhindered when performing spatially distributed tasks (see Chapter 6). While the benefits of AR for assembly tasks have been explored (see Section 5.1), there has been little research on take-over situations and quick overview of such tasks.

Therefore, in this chapter, we investigate how AR can support the user in keeping track of tasks while reducing the load induced by the scenario, and refer here to our third research question:

„RQ3: How can time-critical, parallel, and spatially distributed tasks be overviewed?“

To answer this research question, we investigate the impact of different levels of spatial registration on the efficiency and effectiveness of overview techniques in AR for manufacturing takeovers. In this context, we first analyze related work to provide an overview of previous overview techniques. For example, many papers propose conventional abstract [SB03; ELM94; Cha03] or detailed AR [ZN22; VAS20; Vea+12] visualization techniques to present overviews. While abstract visual techniques reduce the complexity of a process [SB03] by highlighting tasks and performance indicators, contextual AR overviews include relevant contextual information such as information about the environment [ZN22]. So far, overview techniques in AR have mainly been implemented for navigation [TKK08; ZN22] and orientation aids [Car+20; NS21].

Our goal is to reduce cognitive load and minimize potential errors. Therefore, we contribute three extended overview visualization techniques in AR that are capable of showing both spatial and temporal information to users with different levels of spatial registration. In the following user study, we investigate our proposed techniques in terms of their performance and the required level of spatial registration.

Parts of the work presented in this chapter were accepted as a full paper at the SUI conference in 2024 [IGH24].

7.1 Opportunities to Support Take-Over Situations

In the following, we discuss related work on take-over situations in different domains to extract possible design and state hints for our overviews for the takeover of tasks. In addition, we consider previous approaches to possible overview techniques for deriving designs and transferring them to AR.

7.1.1 Visual Take-Over Techniques

Many take-over techniques in scenarios such as collaboration with robots [Grü+20; SMK19; Suz+22] or automated vehicles [Col+21; FSB22; PPR22] have been investigated in previous work. We can distinguish between object handovers and task takeovers. Object handovers are important for intuitive human-robot interaction (HRI) because physical coordination problems often arise. Collaborative robots need to adapt to the handover speed, similar to human partners [HCM15; Koe+14]. Clear communication of the intended handover is useful [MZW24; Suz+22]. Adding visual contextual information improves the human response to the robot's intention [Grü+20]. Many studies use AR to communicate this intention [Cha+18; Wal+18; Ros+19; Grü+20; Suz+22].

Although our focus is on assisting humans to take over tasks rather than handing over tasks, the work on motion intention and object handover provides us with initial design cues; for example, adding visual contextual information such as color communication of danger zones to communicate the robot's intention may improve human response [Grü+20; SMK19]. In this context, many studies use AR to communicate the robot's intention [Cha+18; Wal+18; Ros+19; Grü+20; Suz+22]. When designing the communication of take-over requests (TORs) in automated vehicles, a quick overview [Col+21; SSWR22; Whi+19; PPR22] is particularly necessary, as the driver is usually asked to take over in critical situations.

The focus of our third research question is to provide a visual overview of tasks to improve information transfer. However, since the user knows that he/she has to take over the tasks now, we do not need to use attention-directing techniques such as auditory [CLT23; BE19; Yan+23] or vibrotactile cues [Bor+17] for warning. In the context of visual techniques, Brandenburg and Chuang [BC19] argue that drivers react faster and more accurately when viewing a skeuomorphic visualization compared to an abstract visualization. In addition, colors were used to represent different levels of urgency [Jou+23; Whi+19]. To improve information transfer in TORs, AR showed potential to assist the driver in monitoring [FSB22; LMR19], e.g., by providing driving information at the desired location in the primary field of view (FOV) [FSB22] or by leading to higher lateral performance and reduced workload as well as subjectively better results [LMR19].

7.1.2 Visual Overview Techniques

Many overview visualization techniques have been tested in previous work. According to Cockburn, Karlson, and Bederson [CKB09], we distinguish between abstract+contextual techniques (e.g., [Fu+15; ELM94; Cha03]) and AR techniques overview+detail (e.g., [Sch+11; BEN19; ZN22]) and focus+detail (e.g., [Seg+15; VAS20; TKK08]).

Abstract+Contextual Overview Techniques

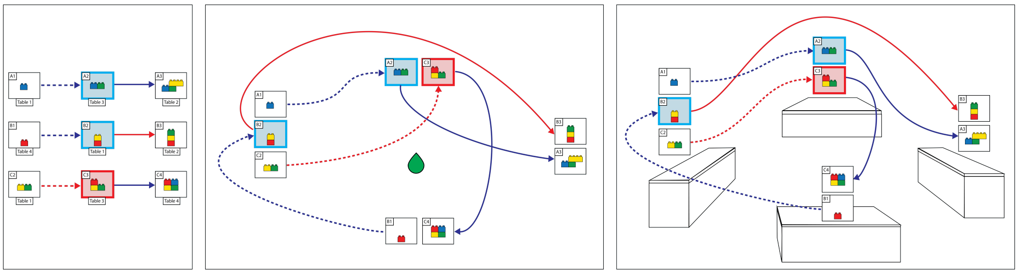
These overview techniques simplify the complexity of industrial processes by highlighting core processes and performance indicators. They present data based on the context or task at hand. This makes important information about the process easily accessible, enables quick adjustments in case of changes, and supports efficient work [SB03]. In a specific case of furniture assembly, Fu et al. [Fu+15] demonstrate how complexity can be broken down into manageable units by applying path graphs to abstract furniture structures. Yu, Al-Hussein, and Nasseri [YAHN07] explore the comparison between process flow diagrams and activity diagrams in the production of building services components and find that process flow diagrams, coupled with simulation models, provide an effective planning method for process optimization. Process maps [SB03; Ant+21; ELM94], which work with flowchart symbols [Cha03], illustrate all tasks, activities, and information associated with a process. They facilitate the understanding of complex systems and promote the adaptation of improvement efforts to the local context [Ant+21]. Other views such as concept maps [NC06] are used to organize and represent knowledge to model essential material, resource, and information flows in production and to illustrate an understanding of production processes [Hab07]. In addition, relational models [MTM91] (e.g., ER models) can be used to illustrate relationships between tasks. These models are often integrated with other representations, such as process maps [SB03].

Detail AR Overview Techniques

Overview+detail techniques use a spatial separation between focused and contextual views [CKB09]. One example is maps that display environmental information in such a way that it can be understood in relation to each other and in a larger context. In this context, numerous mapping techniques have already been investigated in AR [Sch+11]. For example, Shaikh et al. [Sha+19] present a collaborative analysis tool for AR visualization of map-based data. Here, the user views a conventional map with a mobile AR device and the spatial AR information is overlaid. Other works use so-called minimaps (small, simplified maps, usually displayed in the corner of a screen or user interface) to provide an overview of out-of-view objects [BEN19] or to aid navigation [ZN22; NS21]. For example, to better visualize points of interest (POIs), Carmo et al. [Car+20] combined an AR view with the display of the POI location in different views such as frame, minimap, and radar, with the AR view with the minimap being preferred. In addition to displaying two- or three-dimensional maps in AR, other works position three-dimensional information within the real environment and use the 3D registered information to provide an overview. Unlike overview+detail techniques, these focus+detail techniques minimize the seam between views by displaying the focus in context while keeping the context of surrounding areas visible but less prominent. For example, Verma, Agrawal, and Sarasvathi [VAS20] and Tonnis, Klein, and Klinker [TKK08] project information into space to aid navigation. Verma, Agrawal, and Sarasvathi [VAS20] show that AR provides a better experience than traditional 2D maps or paper maps. To improve location understanding for outdoor AR applications, Veas et al. [Vea+12] investigated multi-view AR and variable perspective views. Their results confirm the validity of the approach and the applicability of the methods to many application domains. Another interesting work is provided by Segovia et al. [Seg+15], who used AR as an information visualization tool in the manufacturing industry. The results showed that the use of AR enabled easier interaction and reduced the time needed to access information.

7.2 Conceptual Design of Overview Techniques

In this section, we look at the design considerations necessary to create effective task overviews using AR. Our goal is to improve communication and reduce cognitive load when taking over tasks in complex production environments. First, we will present our overviews with different levels of spatial registration. We will then show the types of information we have encoded.



(a) Baseline. (b) Map view. (c) Location-bound view.

Figure 7.1: Three different AR overview techniques with different levels of spatial registration: a) diagram as baseline without registration, b) map with weak registration, and c) location-bound with strong registration, showing time, status, and location information in three segments of time. We investigate the following segments of time: previous, current, and future step of a task. The line structure indicates the segment of time. The dashed line comes from the previous step, the solid line points to the future step. The different colors indicate the current state of a step: red for a critical state and blue for a non-critical state [IGH24].

7.2.1 Selection of Overview Techniques

We designed our overviews along a spectrum of spatial registration – from none (diagram view as *baseline*) to weak (*map view*) to strong (*location-bound view*).

By varying the spatial registration of our views from none to strong, we can answer which technique is appropriate. If a simple diagram without spatial registration proves effective, a simple heads-up display (HUD) might suffice. This would have the advantage of being comfortable to wear for long periods of time, and it would better protect privacy because, unlike AR, it does not require a camera. In contrast, a *location-bound view* would require AR.

The following overviews are derived from insights gained in related work on visual overview techniques and their application in different contexts (see Section 7.1).

Baseline (Diagram View)

Our *baseline* uses a process diagram overview [SB03; ELM94; Cha03]. Process diagrams are widely recognized for their ability to simplify and clarify the complexity of industrial processes by visually representing key processes and performance indicators (see Section 7.1.2). Such diagrams improve access to critical information and facilitate quick adjustments in response to changes, thereby supporting efficient workflow management [SB03; Ant+21]. Users interact with an abstract representation of task structure through process diagrams that highlight the sequence and dependencies of tasks within the manufacturing process. This overview does not contain any spatial registration apart from the textual information of the respective location (see Figure 7.1a) and thus offers an abstract, superordinate view without a direct spatial context.

Map View

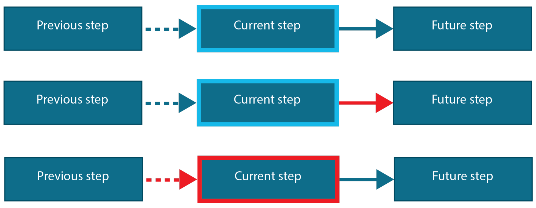
The map-based overview is based on overview+detail AR techniques [ZN22; VAS20]. This approach leverages the strengths of AR maps, which have been shown to aid spatial understanding and task localization within an environment [Sch+11; Sha+19]. The *map view* provides users with a contextual understanding of the workplace, illustrating how different tasks are spatially distributed and how they relate to each other within the physical layout of the manufacturing site. This overview contains weak spatial registration because it maps tasks onto a spatial representation of the environment, bridging the gap between no and strong spatially registered views. However, cognitive mapping is still required to relate one's own person in space in relation to the locations of the tasks.

Location-Bound View

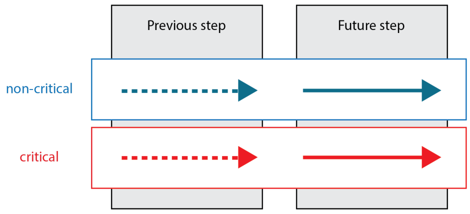
The *location-bound view*, which uses AR to display task information directly at workstations, builds on previous studies that have demonstrated the benefits of embedding AR visualizations in the user's primary FOV to improve task performance and reduce cognitive load [FSB22]. This overview takes advantage of AR's potential to anchor task-specific information directly in its relevant physical context [Vea+12; Seg+15; VAS20]. The *location-bound view* aims to provide a seamless integration of digital and physical work environments, which can enhance the immediacy and relevance of information delivery. This overview involves strong spatial registration, providing a context-specific overlay of information directly in the physical workspace.

7.2.2 Task Information

To make our overviews, which are variable in spatial registration, as practical as possible, we used our time segments of tasks, which we defined based on Section 4.1.3 (see Figure 7.2). This allowed us to determine the extent to which we could consider future and past steps in a process. We were also able to ensure that the overviews were not graphically overloaded, thus ensuring scalability in real application environments. Based on the results of the second research question, we know that in order to support spatially distributed tasks, we need both time information and location information of tasks (see Chapter 6). Furthermore, based on our context analysis in Chapter 2, we found that users need to know what to do next, so we also need to encode status information in the task overviews. In the following, we therefore present the required information (namely (a) location information, (b) status information, and (c) temporal information) that we have encoded in the task overviews.



(a) Temporal states of steps.



(b) Structure and color of lines.

Figure 7.2: We consider (a) three different temporal states of steps in the assembly task overview based on Section 4.1.3: 1) previous step, 2) current step, and 3) future step. The current steps are highlighted. The color of the highlighting indicates whether the step is critical (red) or non-critical (light blue). The line structure (b) encodes whether the arrow points to the current or future step. The color encodes whether a step is/will be critical (red) or non-critical (blue) [IGH24].

Location Information

Location information is crucial for the person taking over a task to know where to continue. This includes the exact location within the workspace where the next steps should be performed. We have coded the location information in the different overviews as follows: In the *baseline* (see Figure 7.1a), under each step of a task, the corresponding workstation where it should be executed is indicated. This ensures that users can easily identify their starting point. In the *map view*, tasks are grouped by workstation, and a green drop indicates the user's current location and orientation in the room (see Figure 7.1b). This helps users orient themselves spatially and navigate to the correct location. In the *location-bound view*, task steps are displayed directly at the respective workstations, and the user sees these steps at the locations where actions need to be taken (see Figure 7.1c). This view integrates task information with the physical environment, reducing the need for mental mapping. Location information is crucial because it allows the person taking over to immediately understand where the previous work was left off and where to continue. Therefore, this design decision is consistent with findings from previous studies that highlight the importance of spatial context (e.g., [Bra18; VAS20]).

Status Information

Status information answers the question of what a user needs to do next. In order for users to effectively take over tasks, it is crucial that they are immediately aware of the current task status. Therefore, in our overviews, the current task is highlighted with a different color (light blue or red) and a bold outline (see Figure 7.2a). This approach is supported by the expert interviews conducted during our context analysis, which emphasized the importance of clear task delineation to avoid confusion and ensure smooth workflow transitions (see Section 2.3). For example, in the context of automated vehicles, visual cues were found to significantly improve situational awareness and response times (e.g., [Col+21; BC19]). Incorporating status information into AR overviews can significantly improve user comprehension and efficiency [SB03; BC19]. It ensures that users are always aware of the progress and any critical issues that need to be addressed.

Temporal Information

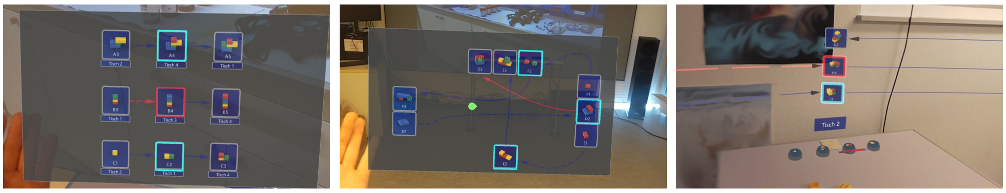
Temporal information is crucial for indicating which tasks are critical. To convey urgency, our overviews use color coding; arrows and highlights turn red instead of blue to indicate critical tasks (see Figure 7.2b). This method is supported by research showing that color differences can effectively communicate levels of urgency and improve user response times (e.g., [Jou+23; Whi+19]). In addition, our context analysis revealed that timely task completion, especially in processes involving adhesives, is necessary to maintain production flow (see Chapter 2). For example, if a part was bonded in the previous step, the new user knows that the next step must be performed quickly to avoid problems with the adhesive setting [BV15; BS11].

7.3 Comparing Different Overview Techniques

In this section, we compare three overview visualization techniques with different levels of spatial registration in AR presented in the previous section (see Section 7.2). This allows us to investigate how different degrees of spatial context affect the effectiveness of task management and user performance in industrial settings. This gradation from none to strong registration is crucial for interpreting the results of our study, as it allows us to discern the influence of spatial registration on task efficiency and user experience.

Our goal is to provide people with a quick overview to improve information acquisition when they take over tasks to enable better temporal and spatial orientation of tasks and to reduce cognitive load and minimize potential errors. Therefore, we implemented an AR assembly process, shown in the overviews in three segments of time (see Section 4.1.3), to gain insight into user performance and the required level of spatial registration.

[1] Participants in the study experienced significantly improved visual quality that could not be adequately captured in the recordings, which appeared reduced in saturation and color dynamics due to technical limitations of the HoloLens 2.



(a) Baseline. (b) Map view. (c) Location-bound view.

Figure 7.3: Three different conditions[1] with different levels of spatial registration: a) diagram as baseline without registration, b) map view with weak registration, and c) location-bound view with strong registration. Since the steps of the tasks in the location-bound view are linked to individual workstations (locations), only a portion of the view from a workstation is shown here [IGH24].

7.3.1 Study Design

To investigate our previously designed overview techniques, we conducted a comparative within-subjects user study in AR using a head-worn device. We had the independent variable overview technique with three levels of spatial registration (*baseline* vs. *map view* vs. *location-bound view*) (see Figure 7.3). We included a baseline condition with a traditional process diagram view [SB03; Ant+21; ELM94] without spatial registration to investigate the effect of the overview techniques. We used quantitative methods to evaluate users' performances, using orientation time, duration, critical solving time, progress deviation, System Usability Scale (SUS) [Bro96], and task load with the Raw TLX [Har06] as dependent variables.

For this study, we asked: **(RQ) How important is the spatial registration of takeover in time-critical spatially distributed assembly with AR?**

H_1 We expect that *map view* and *location-bound view* will improve the location understanding of the steps of the spatially distributed tasks compared to *baseline*, because the user's location is directly evident from the overviews.

H_2 We expect that *map view* and *location-bound view* will improve the temporal understanding of the steps of the spatially distributed tasks compared to *baseline*, as the user can better plan the temporal state of the distributed steps by knowing the exact location.

H_3 We expect that the *location-bound view* will reduce the user's orientation time compared to *map view* and *baseline*, because the respective workstations directly display the steps of the tasks in the room, making it easier to see which steps need to be completed.

H_4 We expect that the *map view* will be preferred by the user over the *location-bound view* due to familiarity, as no additional time is required for understanding.

7.3.2 Procedure

In the beginning, we obtained informed consent from each participant. Participants were then briefly informed about the procedure and asked to put on a headset. Then, each condition was tested in a block. The order of the blocks and tasks was counterbalanced using a complete counterbalanced design. Within each block, participants could try out the overview technique and get familiar with the workspace and task. Each condition consisted of three spatially distributed tasks with five steps each. After a condition was completed, we asked for subjective ratings regarding SUS [Bro96] and Raw TLX [Har06]. At the end of the last block, we asked participants to fill out a short questionnaire regarding demographics, eyesight, experience with AR, and their favorite condition. Each participant took about 40 minutes on average to complete the experiment.

7.3.3 Tasks

The study contained three spatially distributed tasks around the user. For all tasks, participants had to perform five steps[2] to complete a brick figure. Three steps (previous step, current step, and future step) per task were displayed in the overviews (see Section 4.1.3). A current step was completed by pressing a button at the correct workstation. The buttons were identified by an image of the corresponding brick figure. For each task, we designed four non-critical steps and one time-critical step to integrate time criticality as a time window. This allowed us to increase the complexity of the tasks and see how well critical steps were detected in the overviews (c.f. Section 7.2.2). After completing a step whose successor was marked as critical by a solid red line, the line was dashed and the time for the current step began running five seconds after the completion of the previous step. This allowed participants to walk to the time-critical step within the 5 seconds in order to complete it as quickly as possible. Participants then had a total of 30 seconds to successfully complete the step. We asked participants to work on the three tasks as evenly as possible so that they would all be completed at the same time. A task could only be changed after the current step had been completed. The brick figure always had to be placed at this workstation, which meant that it was always at the previous step of the corresponding current step. The participants were only allowed to hold one brick figure at a time. The goal was to walk back and forth between the stations as little as possible.

7.3.4 Apparatus

The experiment took place in a laboratory (see Figure 7.4). We turned on the lights to have good tracking conditions for the AR headset (Microsoft HoloLens

[2] The first step was always the previous step, which did not require any active building, but showed users where the pre-built brick figures were located (see Section 4.1.3).

2). We implemented the different visualization techniques in Unity3D[3], a 3D game development engine. For the initial localization of the different spatially distributed tasks, we used marker detection based on Vuforia[4].

Figure 7.4: Apparatus of the experiment in the laboratory with the location-bound view and a total of four distributed tables as workstations. One of the workstations is located below the figure (not shown) [IGH24].

7.3.5 Participants

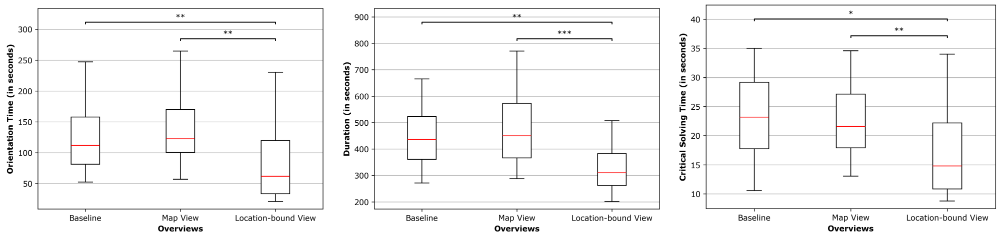
We recruited a total of 24 volunteer participants (14 male, 10 female, 0 diverse), aged between 22 and 66 years (M=34.29, SD=11.83) through public and online advertisements. Participants received no compensation for their time, which was communicated in the advertisement. One of the participants suffered from color vision impairments[5], 11 had normal vision, and 13 had corrected-to-normal vision. We asked the participants to rate their experience with AR, their experience with maps (e.g., navigation systems), and their experience with time-critical processes (e.g., cooking) on a 5-point Likert scale (1=no experience, 5=very high experience). Participants reported low to high experience with AR (Md=2.50, IQR=2.25), medium to high experience with maps (Md=3.00, IQR=1.00), and

[3] Unity3D (v.2022.3.11f1), `https://unity.com`, last retrieved April 8, 2024

[4] Vuforia (v.10.19.3), `https://developer.vuforia.com`, last retrieved April 8, 2024

[5] The participant with color vision impairment suffered from a tritanomaly, but was able to recognize the color blue in a turquoise hue. Since we made changes in the line structures to indicate time segments (see Section 4.1.3), the participant did not report any problems with solving or recognizing temporal states and criticality. The participant was therefore included in the evaluation.

that they had high to very high experience with time-critical processes (Md=4.00, IQR=1.00). Participants were informed that they could end the experiment at any time without any negative consequences. Clearance for this research was obtained by our institute's study board review.



(a) Orientation time. (b) Total duration. (c) Critical solving time.

Figure 7.5: The different time-relative quantitative measures taken in every condition. Statistically significant differences between groups are indicated by brackets and stars ($0 < *** \leq 0.001 < ** \leq 0.01 < * \leq 0.05$) (based on [IGH24]).

7.3.6 Results

In the following, we present the quantitative and qualitative findings of our experiment.

Orientation Time

We consider the orientation time of our three tasks per condition. The time indicates how long it took participants to start working on the tasks after starting the condition, and is an important indicator of how quickly participants can adapt to the new condition. The median duration in seconds for the orientation time in ascending order are: *location-bound view* (Md=61.79, IQR=86.19), *baseline* (Md=111.63, IQR=76.41), and *map view* (Md=122.75, IQR=69.94). The times for each overview are compared in Figure 7.5a. A Shapiro-Wilk-Test showed that our data is not normally distributed ($p<0.001$); therefore, we ran a Friedman test that revealed significant differences for the overviews ($\chi^2(2)=9.083$, $p=0.011$, $N=24$). A post-hoc test using Wilcoxon Signed-rank with Bonferroni-Holm correction showed a significant difference between *baseline* and *location-bound view* ($W=54.0$, $Z=2.743$, $r=0.560$, $p=0.005$) and between *map view* and *location-bound view* ($W=56.0$, $Z=2.686$, $r=0.548$, $p=0.006$). For the orientation time, we can conclude *location-bound view* < *baseline* and *location-bound view* < *map view.*

Total Duration

We consider the total duration of our four tasks per condition. The median duration in seconds for the total task duration in ascending order are: *location-bound* *view* (Md=310.38, IQR=120.25), *baseline* (Md=436.24, IQR=162.57), and *map view* (Md=450.15, IQR=206.41). The durations for each overview are compared in Figure 7.5b. A Shapiro-Wilk-Test showed that our data is not normally distributed ($p<0.001$); therefore, we ran a Friedman test that revealed significant differences for the overviews ($\chi^2(2)=14.083$, $p<0.001$, N=24). A post-hoc test using Wilcoxon Signed-rank with Bonferroni-Holm correction showed a significant difference between *baseline* and *location-bound view* (W=41.0, Z=3.114, r=0.636, p=0.002) and between *map view* and *location-bound view* (W=30.0, Z=3.429, r=0.699, $p<0.001$). For the duration, we can conclude *location-bound view* < *baseline* and *location-bound view* < *map view*.

Critical Solving Times

To see how well critical steps were detected in the overviews, we consider the critical solving time of our three tasks per condition (see Figure 7.5c). The time indicates how long it took to complete the critical task after the timer started. The median duration in seconds for the critical solving time in ascending order are: *location-bound view* (Md=14.79, IQR=11.36), *map view* (Md=21.59, IQR=9.24), and *baseline* (Md=23.19, IQR=11.42). A Shapiro-Wilk-Test showed that our data is not normally distributed ($p<0.01$); therefore, we ran a Friedman test that revealed significant differences for the overviews ($\chi^2(2)=6.333$, p=0.042, N=24). A post-hoc test using Wilcoxon Signed-rank with Bonferroni-Holm correction showed a significant difference between *baseline* and *location-bound view* (W=66.0, Z=2.40, r=0.489, p=0.015) and between *map view* and *location-bound view* (W=52.0, Z=2.80, r=0.572, p=0.004). For the critical solving time, we can conclude *location-bound view* < *baseline* and *location-bound view* < *map view*.

Task Progress Deviation

To see how well the overviews supported consistent task completion, we compare the deviation of task progress across steps per condition (see Figure 7.6). The median deviation in ascending order are: *map view* (Md=0.47, IQR=0.47), *location-bound view* (Md=0.82, IQR=0.47), and *baseline* (Md=0.82, IQR=0.47). A Shapiro-Wilk-Test showed that our data is not normally distributed ($p<0.001$); therefore, we ran a Friedman test that revealed significant differences for the overviews ($\chi^2(2)=8.004$, p=0.018, N=24). A post-hoc test using Wilcoxon Signed-rank with Bonferroni-Holm correction showed a significant difference between *baseline* and *map view* (W=2221.0, Z=2.489, r=0.147, p=0.013) and between *map view* and *location-bound view* (W=2045.5, Z=2.885, r=0.170, p=0.004). For the deviation, we can conclude *map view* < *baseline* and *map view* < *location-bound view*.

Task Load

The resulting median (interquartile range) scores from lowest to highest task load are: *location-bound view* (Md=28.75, IQR=13.13), *baseline* (Md=40.42,

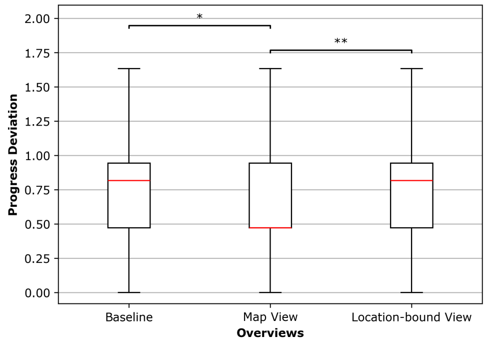


Figure 7.6: Median progress deviation per condition. Statistically significant differences between groups are indicated by brackets and stars ($0 < {*}{*}{*} \leq 0.001 < {*}{*} \leq 0.01 < {*} \leq 0.05$) (based on [IGH24]).

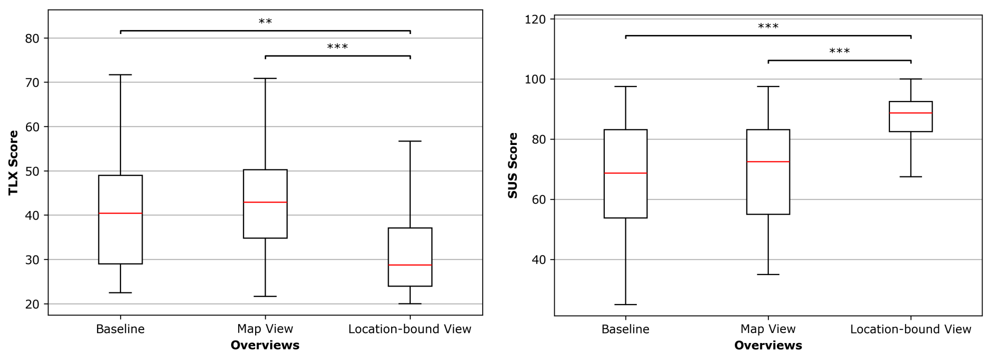
IQR=20.00), and *map view* (Md=42.92, IQR=15.42). The scores for each overview are compared in Figure 7.7a. A Friedman test showed a significant difference between the conditions ($\chi^2(2)=11.247$, p=0.004, N=24). A post-hoc test using Wilcoxon Signed-rank with Bonferroni-Holm correction showed a significant difference between *baseline* and *location-bound view* (W=43.0, Z=3.058, r=0.624, p<0.002) and between *map view* and *location-bound view* (W=37.0, Z=3.229, r=0.659, p<0.001). For the task load, we can conclude *location-bound view* < *baseline* and *location-bound view* < *map view*.

System Usablity Scale

The median usability scores are (in descending order): *location-bound view* (Md= 88.75, IQR=10.00), *map view* (Md=72.50, IQR=28.13), and *baseline* (Md=68.75, IQR=29.38). The scores for each overview are compared in Figure 7.7b. Since these are ordinal data, we directly used a Friedman test that revealed significant differences for the visualization techniques ($\chi^2(2)=21.913$, p<0.001, N=24). A post-hoc test using Wilcoxon Signed-rank with Bonferroni-Holm correction showed significant differences between *baseline* and *location-bound view* (W=24.0, Z=−3.603, r=0.736, p<0.001) and between *map view* and *location-bound view* (W=34.0, Z=−3.318, r=0.677, p<0.001). For the usability score, we can conclude *location-bound view* > *map view* and *location-bound view* > *baseline*.

Individual Rating

After each condition, we asked participants to rate the statement „the shown overview helped me a lot“ with a 5-point Likert item (1=strongly disagree, 5=strongly agree). The results are shown in Figure 7.8. Participants stated that *baseline* (Md=4.00, IQR=1.50), *map view* (Md=4.00, IQR=2.00), and *location-bound view* (Md=5.00, IQR=1.00) did support them. We performed a Fried-



(a) TLX score. (b) Usability score.

Figure 7.7: Quantitative findings from questionnaires: a) median TLX score (Raw TLX) and b) median usability score (SUS). Statistically significant differences between groups are indicated by brackets and stars ($0 < *** \leq 0.001 < ** \leq 0.01 < * \leq 0.05$) (based on [IGH24]).

man test that revealed a significant difference ($\chi^2(2)$=11.681, p<0.003, N=24). A post-hoc test using Wilcoxon Signed-rank with Bonferroni-Holm correction showed significant differences between *baseline* and *location-bound view* (W=17.5, Z=−2.799, r=0.571, p=0.005) and between *map view* and *location-bound view* (W=19.5, Z=−2.962, r=0.605, p=0.003). For the rating, we can conclude *location-bound view* > *map view* and *location-bound view* > *baseline*. Furthermore, at the end of the experiment, the participants were asked to vote for the overview that let them feel the safest and unsafest. Seventeen participants stated that they felt the safest with *location-bound view*, while four voted for *map view* and three voted for *baseline*. On the contrary, 14 participants stated that they perceived *baseline* as the unsafest overview, while nine voted for *map view* and one voted for *location-bound view*.

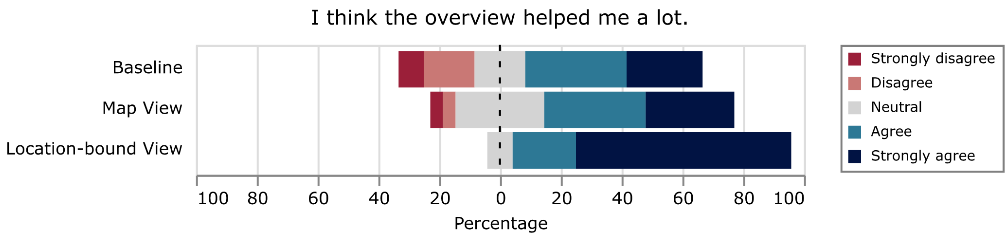


Figure 7.8: Results from Likert item questionnaire (based on [IGH24]).

7.3.7 Discussion

In the following, we discuss our results as well as the methodological and technical implications of our user study.

Time Efficiency during Task Execution

For production speed, a quick orientation is often desirable to maintain process continuity [Ill+21]. For this reason, it is important to have a quick overview of all necessary information during a takeover to avoid incomplete understanding[BV15; BS11]. In this context, we found that especially the *location-bound view* can help to minimize the orientation time, which confirms our hypothesis H_3. The orientation time is important, which indicates how much time is needed to start working on the tasks after the takeover. The duration of orientation time was highest in the *map view* condition, followed by the *baseline* condition. We hypothesize that the higher orientation times of the *map view* and *baseline* conditions are due to cognitive mapping. In the *location-bound view*, the tasks were already displayed in the room and planning could begin immediately. Thus, participants did not have to first understand and combine the locations in the room, which partially supports our hypothesis H_1. In addition, there is only a short processing time for critical steps. For example, when parts need to be glued during manufacturing, the processing time for gluing is very short [Ras12; Hab03]. Therefore, it is important to be as fast as possible, especially in critical steps, so that the processing time is not exceeded. To see how well critical steps were identified in the overviews, we looked at critical solving time to see how long it took to complete a critical task (see Section 7.3.6). After completing a step whose successor was marked as critical by a solid red line, the line was dashed and the time for the current step started running five seconds after the previous step was completed. Again, we found that the *location-bound view* in particular, followed by the *map view* and the *baseline*, can help minimize the solving time, confirming our hypothesis H_2. Therefore, we can assume that critical steps were „found" faster due to the *location-bound view* and due to the reduced cognitive mapping required, thus improving communication [Vis+20]. In addition to the orientation time and the critical solving time, the total duration of the tasks also provides an indication of the level of understanding. In this context, the total duration was comparable to the orientation time, which partially confirms our hypothesis H_1.

Consistency in Task Completion

When completing the tasks, we asked participants to complete all three tasks as evenly as possible. This allowed us to see how well the overviews supported consistent task completion. It is interesting to note that the participants completed the tasks significantly more consistently with the *map view* compared to the *location-bound view* and the *baseline*. Although the *map view* appears to be worse in terms of understanding the location compared to the *location-bound view* and the *baseline* as more understanding is required for cognitive mapping, the ability to plan the tasks was significantly better and participants were better able to anticipate and link future tasks, which allowed for consistent processing. As a cartographic representation, the *map view* is likely to provide a better overview of the geographical context of the tasks [Sch+11]. This can lead to improved planning because participants can see how different tasks are geographically related, which allows them to plan more efficiently and decide the best order in which to complete tasks, for example, to avoid unnecessary walking or duplication of effort. In contrast, the *location-bound view*, which provides a narrower or less comprehensive view due to the limited FOV, could make this type of strategic planning more difficult. This view might focus attention more on the immediate environment or specific tasks, without a clear connection to other tasks or their locations.

Subjective Measures

The usability, the task load, and the individual rating show us that *location-bound view* was preferred compared to *baseline* and *map view*. The usability score showed a significant difference between *baseline* and *location-bound view* and a significant difference between *map view* and *location-bound view*. As mentioned in our hypothesis H_4, we cannot show that the familiar concept of a map contributed to their being well accepted. The task load score showed the same significant differences as the usability score, which shows that the understanding of the location and thus the task load can be improved by the location-bound presentation of tasks. We cannot confirm our hypothesis H_4 as the usability and individual rating show that participants felt most comfortable with *location-bound view* and rated usability the highest, respectively. In this context, we can confirm that *location-bound view* is preferred and lead to lower task load.

Scalability

In a real use case, the number of tasks would have to be limited by cognitive perception capabilities, similar to our temporal states of steps. For example, it does not make sense to display several hundred tasks in the overviews, because the information density determines the degree of understanding of the tasks to be processed [Kei+13; Jul+00; RHO15; RP17]. Therefore, we suggest that performance is likely to decrease with more tasks and that the spatial understanding only works up to a certain number of tasks. Future studies should therefore investigate the number of tasks and the level of complexity of the individual steps at which performance begins to decline. The overall scalability does not depend on the overviews, but on the underlying prioritization and scheduling algorithms that are responsible for selecting the tasks to be processed next and thus displayed.

Limitations

We faced some technical limitations with the Microsoft HoloLens 2 regarding marker tracking and limited FOV. For the marker tracking, we ensured that the room was well lit and the markers had a good size, while we could not do anything about the limited FOV. This means that the potential of human vision cannot be optimally used to naturally enrich visual perception through AR. However, by using the Microsoft HoloLens 2 with its limited FOV, we were able to measure the performance of what is currently possible for optical see-through HMDs. Furthermore, the simplified tasks used in our study were intended to represent a variety of industrial scenarios, but may be limited in their generalizability as they do not reflect the full complexity of these tasks. While our overview techniques were based on previous visualization techniques, they were specifically adjusted to support take-over tasks in industrial environments. As a consequence, it is difficult to compare these techniques to other approaches that were not adjusted to the use case. Future studies could extend the comparison to other AR techniques. Despite our heterogeneous group of participants, feedback from industry experts would have been valuable to assess the practicality of the techniques. Future studies should include experts to increase relevance for specific industry scenarios.

7.3.8 Conclusion

In a real work environment, time-critical, parallel, and spatially distributed tasks often need to be taken over by other people in the middle of the process. In such cases, the current status of the tasks and possible relationships are often unclear to the taker.

We investigated the influence of different degrees of spatial registration on the efficiency and effectiveness of overview techniques in AR for manufacturing takeovers and developed three overview techniques: a diagram view without registration (*baseline*), a *map view* with weak registration, and a *location-bound view* with strong registration. The overview techniques encode different types of information: location information, which indicates the exact location of the tasks, status information, which indicates the current status of the task, and temporal information, which indicates the temporal urgency of the tasks. In a comparative user study, the three overview techniques were evaluated in terms of their performance and the level of spatial registration required. The study showed that the *location-bound view* significantly reduced orientation and task processing time by integrating task-relevant information directly into the user's physical environment. This simplified cognitive mapping and led to more efficient task processing and higher user satisfaction. Although the *map view* provided a better geographic contextual overview and facilitated planning and consistent processing, the direct and intuitive display of task-relevant information in the *location-bound view* led to better performance.

Future work should focus on further developing AR overviews to cover a wider range of industrial tasks and investigating their scalability and adaptability in different manufacturing environments. In this way, AR could be established as an adjunct tool to improve communication in industrial process take-over scenarios and ensure that the transition between the different stages of the process is as seamless and error-free as possible.

7.4 Summary

In many manufacturing environments, the frequency of task takeovers, such as shift changes and temporary employee absences, creates a significant risk of errors and inefficiencies. These takeovers are critical but vulnerable points in the production process where the potential for information loss and miscommunication is high, leading to costly errors and safety risks. As a result, there is a need to improve the takeover of complex manual tasks in industrial environments where accuracy and speed are critical to maintaining operational continuity (see Chapter 2).

In this chapter, therefore, we investigated the final research question of how AR can support the overview of time-critical, parallel, and spatially distributed tasks.

We show that overviews can be designed with AR by first extracting necessary task information such as (a) temporal information, (b) status information, and (c) location information (see Chapter 6), and then applying the different time segments of tasks such as previous step, current step, and future step for scalability and clarity (see Chapter 4). We demonstrated and evaluated three overviews with increasing levels of spatial registration (namely *baseline* without registration, *map view* with weak registration, and *location-bound view* with strong registration) in a comparative user study to gain insights into their performance and effectiveness in facilitating task acceptance and the required level of spatial registration. In particular, the *location-bound view* significantly reduced orientation and task completion times by integrating task-relevant information directly into the user's immediate physical environment, thereby simplifying the cognitive mapping process. These results highlight the potential of AR to reduce cognitive load, minimize errors, and improve efficiency in completing complex tasks. Furthermore, we show that while the *map view* provided better geographic context, which facilitated planning and consistent processing, the direct and intuitive display of task-related information in the *location-bound view* led to more efficient task performance and higher user satisfaction. These results suggest that integrating AR into task takeover not only reduces the risk of error during critical task transitions, but also significantly improves operational efficiency.

To conclude this chapter, we would like to briefly present our demonstrator, which shows the developed overviews based on our final study (see Figure 7.9). A hand menu allows the user to switch between the overview techniques, depending on the user's preference for spatial registration. The demonstrator shows the potential of AR systems to support planning, orientation, and task completion of complex (in our case time-critical, parallel, and spatially distributed) tasks during takeovers.

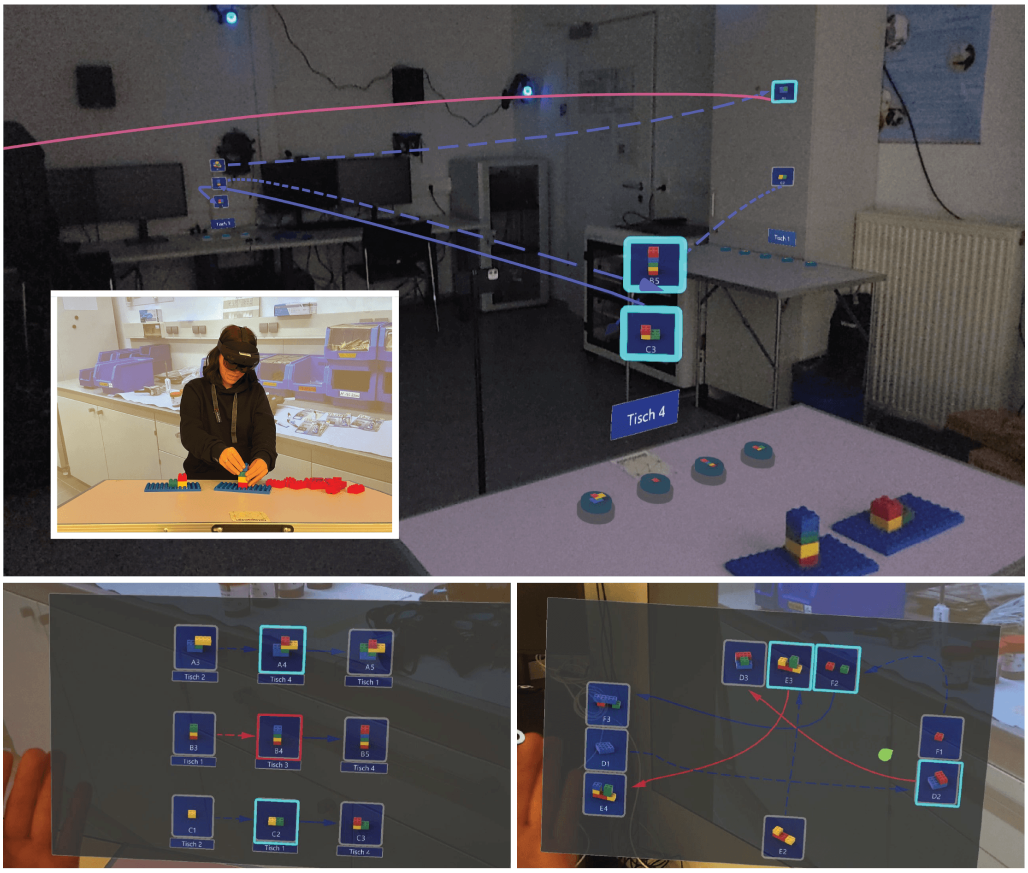


Figure 7.9: Developed demonstrator for head-mounted devices based on the final study. The demonstrator displays overviews in AR. The overviews include the previous, current, and future step of a task, as well as additional time, status, and location information (own illustration).

8 Conclusion

In this chapter, we conclude the work described in all the previous chapters. We begin with a brief summary of the work done in this thesis. We then highlight the contributions of this work to the research questions described in Section 2.5. Here, we summarize our contributions and then provide detailed answers to the research questions. Finally, we provide an outlook for future work, highlighting important limitations and predicting when and in what application area we expect the technology to be used.

8.1 Recapitulation

This thesis investigated how Augmented Reality (AR) can be used to reduce the complexity of time-critical, parallel, and spatially distributed tasks.

To identify the specific challenges of this thesis, we first presented the results of an industrial use case observation as part of the context analysis of the Human-Centered Design (HCD) process. We then conducted interviews with experts and explained the resulting requirements for supporting time-critical, parallel, and spatially distributed tasks. Based on this, we defined the research questions, described the contributions to overcoming the identified challenges, and selected the context of production and assembly as a representative use case because these areas often involve time-critical, parallel, and spatially distributed tasks.

This was followed by a detailed overview of the necessary background information. The focus is on human perceptual capabilities, including visual perception, multitasking capabilities, and time perception. We explained the basics of AR technology, how it works, and how it differs from other technologies. In addition, work environments were described, looking at the characteristics, execution, and challenges of tasks in the context of cognitive psychological principles of human perception.

The next step was to develop the conceptual design decisions derived from the context analysis and previous work. We developed and discussed concepts for the representation of time and defined which time segments are necessary for autonomous task planning. The practical relevance of providing people with a comprehensive overview of their tasks was emphasized. Furthermore, the conceptual choices for visual AR support were described, including the chosen AR form factors and visualization techniques identified in collaboration with focus groups.

Possible solutions for visual AR support at individual workstations to support the execution of time-critical and parallel tasks within the field of view (FOV) were investigated. We identified relevant literature and found ways to enable hands-free working with AR devices. In a user study, we compared AR instructions on tablets and head-mounted displays (HMDs) with traditional paper instructions and egg timers, highlighting the individual benefits of each technology. The best technical solutions were improved based on the results of the first study. In a second study, we investigated how many parallel visualizations are useful in terms of execution time and error rate, and found a trade-off between execution time and error rate depending on the degree of visualization parallelism.

We also investigated how to improve the execution of time-critical and parallel tasks when they are also spatially distributed and therefore out of view. The results of the focus groups, which developed an information design to support such tasks, were implemented. Four techniques for out-of-view visualization in AR were identified and extended by our design. In a user study we compared all techniques and showed their individual advantages. In a second study, we selected the best techniques and applied them to our specific use case to verify whether the selected techniques improve user performance under realistic conditions. Our results show that existing out-of-view visualization techniques can be encoded with temporal information and improve user performance when performing time-critical, parallel, and spatially distributed tasks.

Finally, we investigated how an overview of processes involving time-critical, parallel, and distributed tasks can be designed to provide users with all the necessary information quickly. We derived information from context analysis, previous work, and the results of the research questions to design potential overview techniques. Three overview techniques with different degrees of spatial registration and defined time segments for the tasks were developed and compared in a user study. The results show that overview techniques with high spatial registration significantly reduce cognitive load and improve task performance by integrating contextual information directly into the user's FOV.

8.2 Contributions to the Research Questions

In the following, we will highlight our contributions to the research questions addressed in this thesis. We will summarize the contributions to each research question and provide detailed responses to the research questions.

RQ1: How can time-critical and parallel tasks be visualized within the field of view?

Our context analysis and background information on the work environment have shown that many tasks are performed at individual workstations and are therefore predominantly in the user's FOV. To bridge waiting times and increase productivity, these tasks can be performed in parallel. Despite existing research on AR instructions, important factors such as hands-free operation, time criticality, and parallel execution have been neglected, making it difficult to transfer this research to contextual applications. Therefore, we investigated how AR can support hands-free execution of time-critical and parallel tasks in the user's FOV and, based on the results of our focus groups, superimposed the necessary contextual information on the tasks to enable visual AR instructions at individual workstations. In an initial study, we compared AR instructions on tablets and HMDs with traditional paper instructions and egg timers. Our results showed that both AR methods had advantages, including faster familiarization and shorter completion times. The tablet instructions were subjectively rated the best by the participants. Based on these results, we selected the tablet instructions for location-based tasks and improved the AR instructions. In a second study, we investigated the effects of different degrees of visualization parallelism. We found that limiting the number of tasks displayed simultaneously improved performance and reduced error rates, especially for inexperienced users. The study also showed that increasing the number of simultaneously visualized tasks reduced processing time but also increased the error rate, suggesting a cognitive processing bottleneck. Overall, our results show that AR instructions can help improve performance and understanding of temporal and spatial factors in the execution of time-critical and parallel tasks. We were able to show that the use of AR reduces training time and increases processing efficiency.

Summarized. When visualizing time-critical and parallel tasks in the FOV, our research shows that AR instructions increase safety and efficiency, especially for inexperienced workers. Overall, AR was found to improve performance and understanding of temporal and spatial factors in several application domains. When presenting parallel tasks, performance was improved and error rates were reduced when the number of simultaneously displayed tasks was limited. Furthermore, based on the results, we developed concepts for the visualization of instructions to support time-critical workflows in both location-based and distributed work environments.

RQ2: How can time-critical, parallel, and spatially distributed tasks be guided outside the field of view?

In addition to the challenge of performing time-critical and parallel tasks at individual workstations, our context analysis and background information on the work environments showed that tasks may also be performed across multiple distributed workstations, so some tasks may be out of view. Despite existing research on supporting out-of-view tasks with AR, complexity factors such as inherent time criticality have not been addressed, making transferability to contextual use cases difficult. Therefore, we investigated how AR can be used for time-critical, parallel, and spatially distributed tasks outside the user's FOV and, based on the results of our focus groups, considered out-of-view visualization techniques in addition to the in-view visualization techniques from the first research question to account for the spatial distribution of these tasks. In a first study, we used a qualitative focus to compare four out-of-view visualization techniques (*arrows*, *wedges*, *halos*, and *compass*) enriched with additional temporal information. Our goal was to identify the techniques that most effectively allow users to perceive spatial and temporal information while performing tasks. Our results showed that the two visualization techniques, *arrows* and *wedges*, subjectively performed the best. Based on these results, we selected two visualization techniques, *arrows* and *wedges*, and conducted a second study with a quantitative focus. Here, we focused on the application of the two techniques in our specific use case in a more realistic environment. We evaluated the performance of these techniques against a baseline without spatial support. Our results showed that existing out-of-view visualization techniques can be improved by encoding temporal information, thus increasing user performance when performing time-critical, parallel, and spatially distributed tasks. This included a reduction in step time and deviation from ideal time in time-critical tasks, as well as a reduction in errors and task load. In addition, behavioral data from participants showed that frequent switching between tasks within a time-critical step led to unstructured execution, which increased complexity due to the resulting time pressure. Overall, our results suggest that encoding time criticality and task location in AR can improve user performance, which is applicable in various application domains where time-critical and parallel tasks are spatially distributed.

Summarized. To guide time-critical, parallel, and spatially distributed tasks outside the FOV, we have extended and evaluated various out-of-view visualization techniques. In two user studies, we enhanced the techniques by incorporating timing information, which significantly improved user performance on spatially distributed tasks. Among the most effective techniques adapted specifically for head-mounted optical see-through AR displays are visual cues such as *arrows* and *wedges* that indicate both the direction and timing of tasks. These methods help users complete tasks more efficiently by providing both spatial and temporal orientation. This approach demonstrates the potential of AR to improve the execution of complex, distributed workflows.

RQ3: How can time-critical, parallel, and spatially distributed tasks be overviewed?

In addition to the process-inherent challenges and the focus on the execution location of the first two research questions, our observations in the context analysis showed that a smooth takeover is critical to ensure production continuity and avoid temporary process interruptions. From this, we deduced that a comprehensive overview of all information needed during the takeover is essential to improve knowledge transfer, avoid communication errors, and ensure safety and efficiency during the takeover. To address this challenge, we have developed AR overview techniques with different degrees of spatial registration that convey both temporal and spatial information of the tasks. Our study included three techniques: a diagram view with no registration (*baseline*), a *map view* with weak registration, and a *location-bound view* with strong registration. The results showed that the *location-bound view* significantly reduced cognitive load and improved task performance by integrating task information into the user's physical environment.

Although the *map view* provided a better overview of the geographic context, the intuitive and direct display of task information in the *location-bound view* led to more efficient task processing and higher user satisfaction. These results highlight the potential of AR to minimize errors and increase efficiency.

Summarized. To provide an overview of time-critical, parallel, and spatially distributed tasks, we have developed three AR overview techniques with varying degrees of spatial registration. Our techniques incorporate different levels of spatial registration to map tasks in the user's FOV and integrate contextual information that reduces cognitive load and improves task performance. A comparative study showed that strong spatial registration, which integrates task information directly into the user's physical environment, significantly reduces cognitive load and improves task performance. Our results highlight the potential of AR to minimize errors and increase efficiency in industrial processes.

8.3 Future Work

The research presented in this dissertation has demonstrated the potential of AR to support time-critical, parallel, and spatially distributed tasks. Although the results already provide insight into our current capabilities, we would like to highlight directions that should be further explored in future studies to fully exploit the capabilities of AR and overcome current limitations.

Therefore, it is important to overcome the current technological limitations. This includes image recognition on complex object surfaces, such as reflective, glossy, or mirrored surfaces, as well as recognition of objects on low-contrast backgrounds, especially in the case of color similarity or different lighting conditions. However, modern vision systems supported by machine learning and specialized hardware are making increasing progress in this area of research. In addition, current optical see-through head-mounted AR devices have some limitations that need to be overcome before widespread use is possible. These include limited FOV, limited battery life, and potential comfort issues with prolonged use. Future work should focus on technological advances to create AR devices that are practical and comfortable for long-term use in real-world environments.

Another important point is to validate the effectiveness of AR in practice and to conduct the studies with real users in real environments. While we have gained valuable insights through controlled experiments, the next step is to deploy the studies in real-world work environments and gather feedback from end users. This real-world validation will help identify unforeseen challenges and opportunities.

In addition, future research must continue to focus on improving the working conditions of people performing time-critical, parallel, and spatially distributed tasks, as they are often exposed to high cognitive load. This includes, for example, the further development of improved AR interfaces and interaction techniques, such as the design of intuitive visualizations, the optimization of the amount and type of information displayed, and the development of adaptive systems that adjust support based on the user's current cognitive state or experience. A somewhat provocative, but in our view important, observation also involves a general rethinking. Working under such conditions would have to be fundamentally changed in the future, which could be achieved, for example, by redesigning or restructuring tasks. For example, tasks could be optimized by using AR to automate certain cognitive processes, such as recording or logging environmental data, error detection, or diagnosis. At this point, however, it is important to note that humans should not be degraded to the status of „slaves“ to a system. In order to allay the fears of the reader, we would like to take a brief look at another key aspect that we should consider in future work. This is the integration of appreciation [AF05; Fag18] and participatory user involvement in the development of AR systems. The HCD process used in this dissertation already emphasizes the importance of user involvement. In the future, however, more attention should be paid to involving users not only in the design process, but also in further development and design after the system has been introduced. The first steps in this direction are already being taken through the establishment of meaningful work [Col+22; Sai22; LUH20] or the consideration of User Experience (UX). The goal is not only to focus on the functional aspects of AR systems, but also to consider the broader impact on users' well-being and job satisfaction. By following the principles of appreciative technology design, the experiences and needs of users can be taken into account, allowing us to foster an appreciative culture.

8.4 Concluding Remarks

This dissertation has laid the foundation for understanding how AR can support complex work tasks. The results highlight the potential of AR to reduce task complexity and cognitive load. In the future, the integration of appreciation, user participation, and real-world validation will be critical to realizing the full potential of AR technologies. By addressing current limitations and continuing to innovate, we can look forward to a future where AR is an integral part of the workplace, increasing both productivity and user satisfaction.

Figures

Tables

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