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Masterarbeit

Increasing trust in human-robot interaction through data visualization in augmented reality

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Abstract

"Can we trust a robot?", is a question that becomes more and more relevant as new robots and interaction technologies are being developed all the time. Already for a simple autonomous system, such as weather forecast for aviation control, it is imperative to investigate the trust in the system. Otherwise an ignored warning might lead to disastrous consequences, such as a plane crash. Trust is also prevalent in human-robot interaction and a major topic in current research. We want to contribute to this field of research by investigating whether visualizations for augmented reality can improve trust in human-robot interaction with industrial robot arms. Recent publications and their findings for human-robot interaction and augmented reality for human-robot interaction will be discussed, as well as, trust in human-robot interaction, and data visualization in augmented reality. With the help of an expert focus group novel visualizations were developed and be discussed. From the expert feedback we extracted some recommendations for the development of visualizations for large industrial robot arms. The suggestions for visualizations from the focus group were developed, implemented and then tested in a user study with a large industrial robot arm. While the results of the study showed no significant effect on any measured variable, the additional feedback given by the participants showed their great interest in the developed visualizations. The study shows that there is some potential for visualizations to improve the interaction with the robot.

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1 Introduction

Can we still trust machines? This is a question repeatedly asked when a new groundbreaking project in computer science reaches the public. Publications like Chat-GPT[1], a large-language model-based artificial intelligence (AI) that can generate human-like text and code, or the Boston Dynamic Robots[2], such as the human-like Atlas robot that walks on two legs and can clear some parkour obstacles, rekindle the discussion on trust in machines, for example, there is a huge concern that AI chatbots cannot be trusted[5]. Those are just two examples from a multi-faceted problem, which is still in need of a multitude of research. Therefore, it is not easy to tell if we can still trust machines, because the question is too vague for a simple answer. What do we mean by trust in this case and what exactly are machines? Do we talk about AI, cars, smartphones, or human-like robots? In this thesis, we look at a specific sub-sample of trust in a specific sub-sample of machines. We investigate trust in industrial robotic arms for timber fabrication and implement a visualization-based approach to increase it during human-robot interaction (HRI).

Robots come in various shapes and sizes, from small room cleaning robots to building-sized construction robots. They are machines that can move autonomously and complete tasks on their own. The development of new and more capable robots leads to the situation, that people need to interact with robots in their daily lives, either at work or at home. How people can see what the robot does, give the robot instructions, or extract information from the robot data are some examples of this interaction with various types of robots and it is a large topic in current research, which can be seen by multiple meta-survey publications [3, 12, 22, 28]. In the development of new processes for timber fabrication, for example, there is a growing interest in humans working beside industrial robotic arms. The fabrication process has two specific requirements, which increase the necessity of human-robot collaboration. First, some materials are too difficult to handle so the big industrial robots would break them, or the tasks are too fine-grained for the robots to handle and are easily performed by a human, for example screwing. Second, the pieces build in timber fabrication are often single pieces, produced for a specific purpose. Therefore, it would be inefficient to program all tasks for the robot, especially complex tasks, as it is time-consuming and inefficient to automate a process that would only be done once.

How to improve such human-robot interaction is an important research field. There are a lot of approaches using augmented reality (AR), from giving the robot voices [13] to augmenting the robot [15] or its surroundings [26]. AR is a description of all systems that augment physical objects or surroundings environments in the real world, regardless of the technology used [28]. Many current interactions still rely on tablets or displays, but there is a trend to use AR, through head-mounted displays such as the Microsoft Hololens 2[3]. These allow the user to use both hands for a task,

[1] https://openai.com/blog/chatgpt

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

[3] https://www.microsoft.com/de-de/hololens/hardware

while still being able to see projected information about the robot. For example, Rosen et al. [26] projected the intended path of a robot arm in the surrounding space, so that the human user can avoid a collision by moving out of the way.

To enhance the human-robot interaction it is important, that the user can trust the machine because trust is a crucial part of a successful human interaction [7]. A result of a previous workshop is that one of the main concerns is the trust in the robot while engaging with a big industrial robot arm, because the users did not know what exactly the robot was going to do or how it would proceed, they did not feel safe. We want to reduce this distrust by using data visualization. This means using the robot's internal data and building visualizations so that the users around such a robot feel safer. Because testing such visualization on-site can have problems such as the risk of injury and material cost, it could be beneficial to test new interaction techniques in virtual reality. This leads to our main research question:

- Can visualizations increase the trust a human user has in an industrial robot arm while conducting a collaborative task?

In this thesis, we want to design visualizations for the interaction with industrial robot arms, which help the user to trust the robot and therefore increase the user experience. For this, the thesis will start with a brief literature review, in which we will look at the current state of the art in AR visualizations and trust building with robots. We will discuss the focus group and how we designed and developed visualizations based on the result of the focus group. Afterward, we explain the use case in which the visualizations are deployed and tested. Next, we describe the study that was conducted and discuss the results. In the end, we give a summary of this work and discuss its limitations and propose research questions, which would be interesting to investigate. [4]

[4] I want to thank my supervisors Aimée Sousa Calepso and Xiliu Yang for the great support i received. Furthermore, I want to thank Christian Krauter, Claus Vogelsang, Wolfgang Vogelsang and Heike Zinsmeister for proofreading my thesis, and also all the participants that took part in the focus group or the user study.

2 Related Work

In this chapter, we summarize the already existing work and set our goals into context with them. The relevant publications were found by using online search engines, namely Google Scholar and Connected Papers, and using keywords, such as *Augmented Reality*, *Human-Robot Interaction*, *Data Visualization*, *Trust*, and combinations of these. Furthermore, the references and citations of the relevant publications, found in the online search, were used to find additional publications. First, we look at the state of the art in human-robot interaction (HRI)2.1, especially regarding industrial robotic arms. Second, we discuss the use of augmented realityA (AR) for HRI2.2. Afterwards, we dive into trust in HRI, and how to evaluate it. In the end, the current state of the art in data visualization with a focus on robotics and AR is discussed.

2.1 Human-Robot Interaction

From social robots posing as bartenders [14], and cleaning robots for our homes[1] to industrial robotic arms[2], the differences in form, scale, and interaction modality are manifold. How people interact or collaborate with such robots is the research field called human-robot interaction (HRI) [8]. It ”focuses on developing robots that can interact with people in various everyday environments” and tries to elevate robots from being just tools to collaborators, companions, guides, tutors, and all kinds of social interaction partners [3]. HRI is a field of study where different areas of expertise are needed. An engineer is needed to develop the robot motions and interfaces for the interaction, whereas it is wise to include an expert in social science for the human part of the interaction. The variety of this topic can be seen in the number of different literature reviews and books published in the last few years [3, 12, 22, 28].

In their book, Bartneck et al. [3] focus on HRI for everyday life, especially on social robots. They also define nine different applications for robots, one being collaborative robots. In addition, they address multiple problems that can hinder the success of robots in our everyday life. One is the user expectation through media and fiction, the expectation of what robots can actually do might be higher, than what they actually can do. Also, people could get to attached to robots, especially social robots, and be over-dependent on them. Furthermore, robots in public spaces are prone to be abused by people passing by, for example, they are pushed over.

All robots that work in close proximity to humans or are intended to physically interact with humans are called so cobots [2]. Hentout et al. [12] collected publications to give a comprehensive picture of the state-of-the-art HRI with industrial cobots from 2008 and 2017. Cobots are often deployed to assist or replace humans in tasks that are repetitive or dangerous. The problem of HRI in industrial

[1] https://www.irobot.de/de_DE/roomba.html

[2] https://www.kuka.com/de-de/produkte-leistungen/robotersysteme/industrieroboter

collaborative applications was split into multiple categories and further sub-categories. Interesting for this work are the categories of *safety in industrial cobotics* and *virtual & augmented reality*. There is no straightforward way to design safe cobotic systems because there is no safety standard yet and it is hard to asses these systems before commissioning them. The authors found that there are multiple ways to create a safe environment for industrial cobots. From *pre-collision approaches*, where robot sensors are used so that the robot can avoid the human in its workspace, to *risk analysis approaches* in which the situation is analyzed for possible risks and safety issues before deploying. Most of those techniques focus on the robot, and how the robot can avoid unwanted collisions with the human.

For example, Vogel et al. [30] build a tactile floor, which can recognize where people are standing, to regulate the robot's speed. They split the area around the robot in three different safety zones. The floor changes the speed of the robot if it detects a human standing in one of the danger zones. Additionally, the zones were visualized for the humans on the floor using projectors. Close to the robot is the red-critical area, surrounded by a yellow-warn area, followed by a green-free area. If a human is detected in the red-critical area the robot stops, if the human is inside the yellow-warn area the robot slows down, and if there are no humans detected or only in the green-free area nothing happens. Vogel et al. [30] call the tactile floor hard-safety and the projection soft-safety.

Hentout et al. [12] do not differentiate between hard- and soft-safety, but the *virtual and augmented reality-based approaches* are only used to give the human user information and not to interfere with the robot itself. Using AR to display either a safe space, where the robot will not reach, or the working zone of the robot, like Vogel et al. [30]. Such zones enable the human user to avoid a collision with the robot. Furthermore, the authors suggest the use of AR-HMD to meet industrial standards, whereas virtual reality (VR) can be used for immersive simulations and as a real-time 3D interface to the robot. In their category *virtual & augmented reality*, they look beyond their approaches for safety. The authors found, that AR can be used to enhance the interaction with the robot, by making additional information available. For example, giving instructions and displaying production status updates. VR is instead used for virtual training or testing. In the end, they conclude, that there is a lot of traction in the research with cobots, but missing applications in real industrial environments. Furthermore, they see a movement to standardize the development with cobots and a focus on safety and security.

In the field of timber fabrication, the use of industrial robots for the manufacturing process has been stale, if compared to other industries, for example, the automotive industry. This is due to the fact that the timber fabrications are often single pieces and it would be too expensive and time-consuming to program and build machines to build them automatically. Therefore, a more interactive approach is needed, such as interactive programming using AR. In recent years the industry is looking for more sustainable ways of building and here timber structures provide a low-emission solution, compared to other materials therefore the demand for new fabrication methods is rising. Kunic et al. [19] developed a workflow for the automation from design to a layered robotic assembly of reversible timber structures, aided by human-robot collaboration. They developed a construction kit consisting of thirteen discreet elements. The human collaboration in this case is used as a fail-safe if the automatic process encounters a problem, such as a misaligned piece or a problem while screwing. Then the human will guide the robot to the right position and from there the robot will continue working on its own again.

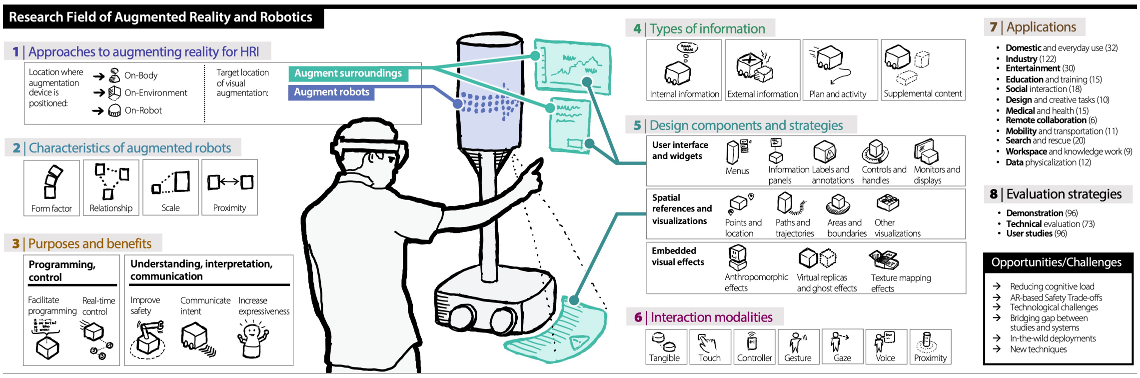

Figure 2.1: The eight dimensions and their categories from Suzuki et al. [28]

As demonstrated, in the field of HRI focused on industrial robots there is a wide variety of topics. This work focuses specifically on the interaction with big industrial robot arms used in timber fabrication. Here, collaboration is necessary, because timber can be a difficult-to-handle resource, where big industrial robots have problems not to break it. The human in the process has to help with executing such a task to create an undamaged end product. To enable a seamless collaboration humans and robots must exchange information in some way. Using Augmented Reality is one possibility to achieve this, and will be discussed in the next section.

2.2 Augmented Reality for Human-Robot Interaction

In recent years Augmented Reality (AR) has been used more and more to enhance HRI. AR is a description of all systems that augment physical objects or surrounding environments in the real world, regardless of the technology used [28]. Commonly you have audio guides in museums, displaying navigation on the front windows of cars, or head-mounted displays (HMDs) for tasks such as displaying cable management in buildings. In HRI the use of AR technologies ranges from displaying emotions as cartoon faces on a robot through a handheld device [33], to displaying live data from the robot through HMDs [26]. Suzuki et al. [28] are not only looking at different robots for HRI but give an extensive overview of the use of AR for HRI. As a result of their work, they present a taxonomy of AR and robotics with eight design space dimensions, see Figure 2.1.

The first dimension is *approaches to augmented reality*, where they discuss the different hardware types and where the hardware is placed, and the target location of the visual augmentation. For the placement of the visualization, they further differentiate between augmenting the robot or the surroundings. Next, they discuss the *characteristics of augmented robots*, where they differentiate the four categories, form, relationship, scale, and proximity. As the third dimension, they look at the *purposes and benefits of visual augmentation*. On a high level, they categorize the dimension as *programming and control*, and *understanding, interpretation, and communications*. The next dimension is the *classification of presented information*, with four categories *internal information*, *external information*, *plan and activity*, and *supplemental content*. The previous dimensions discuss what to show in AR, while the remaining four focus on a different topic each: *Design components and strategies for visual augmentation* focus on how the AR content is presented. Here three categories were found, *UIs and widgets*, *spatial references and visualizations*, and *embedded visual* *effects*. Next, they split up the interaction into two dimensions the *level of interactivity* and the *interaction modalities and techniques*. *Application Domains* is the next dimension where they found several categories, for example, *industry* or *data physicalization*. Last but not least are the *evaluation strategies*, where they differentiate in *evaluation through demonstration*, *technical evaluation*, and *user evaluation*.

Peng et al. [23] investigated the use of a robotic arm for an interactive fabrication system their Robotic Modeling Assistant (RoMA), where a human designer works together with their RoMA. Because the designer should have hands-on modeling experience, they decided to use a robotic arm for printing. The human and robot are opposite of a rotating disc on top of which the model will be built. On the human's side the designing of the piece happens and on the RoMA's side the printing happens. This allows open-space 3D printing which allows the human and machine in close proximity. However, the robot arm and human are only working on the piece separately for safety reasons, either the human is creating new designs or the robot is printing. Even though the switch between those two stages is fast and easy, it is no simultaneous work. For the input, they used an AR-HMD with a controller. They recommend using a human-friendly robot, to relax the safety measures they had to take and allow simultaneous work. In the design space dimensions of Suzuki et al. [28], this approach has the following properties. It is an on-body approach to augment the surroundings. The characteristics of the augmented robots are a robotic arm as a form factor, a 1:1 relationship between human and robot, being body-scale, and being co-located with distance. The purpose and benefit of the visual augmentation is to facilitate programming, and the classifications of the presented information are external information, as well as, plan and activity. As design components, they use labels and annotations, points and locations, and virtual replicas. The interaction is indirect and with a controller. This approach falls into the *Design and creative Tasks* application domain and used a demonstration as an evaluation strategy.

Another example that has a robotic arm as the form factor is the publication from Gruenefeld et al. [9]. They investigate AR visualization for robot motion intent in combination with industrial cobots. Due to safety sensor technology industrial robots shut down when a collision is detected which results in a downtime where the robot needs to be restarted. To minimize this downtime, they developed three visualizations to help the human users to understand the robot's motion intent. *Path* shows the path the robot will take in the next five seconds, *Preview* shows robot meshes at interpolated waypoints, and *Volume* shows a cylinder cut in slices. All visualizations are colored from red (close) to blue (far away) according to the distance from the human user to the actual robot. Grünefeld et al. conducted a user study to evaluate the different visualizations. The study revealed that the participants found the *path* and *preview* visualization to be more exhausting and thus like the *volume* visualization most. The authors contribute this to the small field of view of the Microsoft Hololens, which is the HMD they used in the study, and the amount of head movement required to see the whole visualization. This head movement took the attention away from the task which annoyed the participants of the study. The authors conclude, that visualizations through head-mounted AR devices can help to improve the mediation of intents between robots and humans, so humans can avoid collisions.

Pascher et al. [22] conducted a review of publications on how to communicate such robot motion intent. They found that in addition to different kinds of robots, there are different types of intent and multiple roles for the human. This makes designing a visualization to convey a robot's motion intent to a complex problem because each of these different settings needs different kinds of visualizations and observations. In order to make the AR adaptable to different settings, they developed a model for

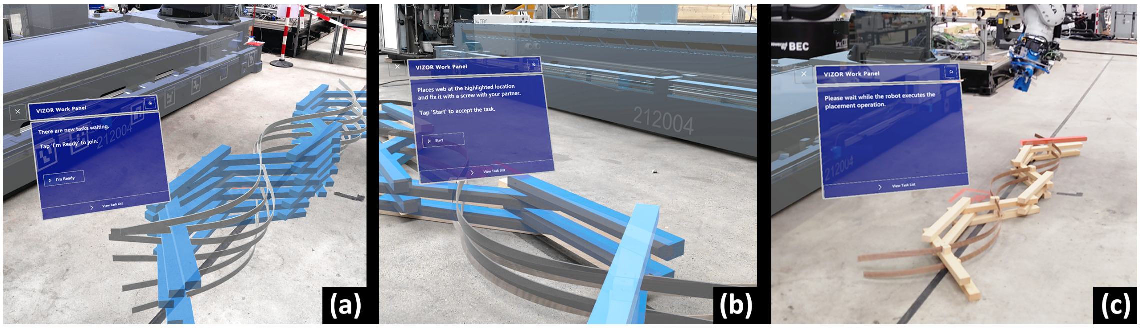

Figure 2.2: Screenshots of the VIZOR interface developed by Yang et al. [32]

intent communication from robot to human. An additional contribution from Pascher et al. [22] is, that they discuss problems and future research possibilities for the communication of robot motion intent. Most of the research focuses on single problems and on only 1:1 relationships between humans and robots. According to Pascher et al. [22], this lays the foundation for the development of more complex settings such as multi-user scenarios. In addition, they propose to combine different types of intent to improve the user experience, which needs to be tested through research. They also suggest challenging their model to improve the design space.

Yang et al. [32] developed a software framework to facilitate human-robot collaboration in fabrication using AR. It consists of a Grasshopper[3] plugin and an integrated Hololens application. Those two parts are connected with each other and the robot via a ROS[4] server. ROS is the Robot Operating System, which is a set of software libraries and tools that facilitate the task of building robot applications. In this case, it is used as a server to communicate tasks and their progression to all parts of the system. Grasshopper is used to enable rapid prototyping of mixed reality workflows. The AR application is used as an interface for human users, who can see their current task, a digital twin of the real robot and they can control important system elements through a user interface (see Figure 2.2). The authors tested their framework with a case study. This framework is the foundation for the AR application used in this thesis.

Besides their extensive overview of current work, Suzuki et al. [28] also formulate open research questions, challenges, and opportunities for AR and robotics research. Two of the challenges they propose are tackled in the work of this thesis *Making AR-HRI Practical and Ubiquitous*, as well as, *Designing and Exploring New AR-HRI*. We test AR visualizations in a real production environment by conducting a user study in a fabrication hall for timber fabrication. In doing so, we evaluate whether AR-HRI can be practical and if such visualizations can increase trust in an HRI system. Furthermore, we explore novel visualizations for industrial robot arms, and contribute suggestions for new methods for AR-HRI with the help of an expert focus group.

[3] https://www.grasshopper3d.com/

[4] https://www.ros.org/

2.3 Trust in Human-Robot Interaction

An important part of every interaction is the trust you have towards the agent you are interacting with. First it is necessary to define trust and then to look how it effects the interaction with robots. The Merriam-Webster Dictionary defines trust as "assured reliance on the character, ability, strength, or truth of someone or something" [21]. If one tries to measure this definition of trust, then the result will be the combination of multiple variables that are based on the experience with the trusted party. This is similar to the definition of trust as "multidimensional latent variable that mediates the relationship between events in the past and the former agent's subsequent choice of relying on the latter in an uncertain environment" by Kok and Soh [17].

Gebru et al. [7] find that trust is one of the primary characteristics of a successfully interaction. In their review on human-machine trust evaluation they look at the problem from two perspectives, human- and machine-centered. This separation of the problem is common in current research and also done in multiple other publications [16, 17]. In other words we look at the trust humans have in a machine on the one hand and how trustworthy a machine can be on the other hand. The lack of trust or a wrong level of trust in a autonomous system can lead to a disuse or misuse of the system and therefore needs to be avoided. To achieve this, the authors recommend to provide enough feedback on the cognitive state of the machine in use. Also, they discuss how to effectively evaluate machine trust. Due to the subjective nature of trust it remains difficult to provide a definitive solution for trust measurement. However, there are multiple options to measure trust in machines. Scales based on self-reported measurements are the most common solution, such as the *Human-Robot Interaction Trust Scale* (HRITS) developed by Pinto et al. [25], which will be described in detail below. However, these scales still need to be validated and tested with different scenarios and settings, according to Gebru et al. [7]. Measurement approaches using psycho-physiological sensors such as EEG, fMRI, and GSR are not relying on any subjective values. Evaluating the signals from such sensors using modern algorithms can give valuable insights on the trust of a human user while interacting with a robot. Setting up the sensors and training the algorithms need time and expertise, compared to the self-reported scales. Therefore, one needs to consider whether the additional workload is worth it to gather the objective measurements. All of the measurements need to be further validated, as they are rather new and should be tested with various use cases.

In another review Kok and Soh [17] look at the state of the art in research on trust in robots. They present approaches they found in related work that can help building trust towards a robot. The authors describe them in increasing order of complexity, but remark that this order is no indication for the relative importance of the tools. The simplest tool, in their opinion, is the design, which not only includes how a robot looks like, it also includes how a robot is presented. If the expectation towards a robot is different to its actual capabilities, then the user will develop distrust which will decrease the user experience during the interaction. In addition to the design, the robot has to gain, maintain and calibrate the users trust, to enable a successful interaction. The authors found four strategies to achieve this, namely *heuristics*, *exploiting the process*, *computational trust models* and *theory of mind approaches*. *Heuristics* are basically rule-of-thumb responses ro certain events that occur. They are used to *combat overtrust* and *repair trust*. *Exploiting the process* focuses on how the robot behaves. Simple information about the behavior of the robot improved its trustworthiness already, for example, a robot showing emotions or a robot conveying its incapabilities solely via informative arm movements. A more dynamic approach is using *computational trust models*, which directly models the human's trust in the robot, and is then used to control the robot's actions. The last proposed tool is *endowing robots with a theory of mind*. Kok and Soh [17] argue, that trust is just one aspect of the human user's mental state and therefore, if a robot has the ability to reason and respond to the demands and expectation of a human partner, it can increase the trust the user has. In addition to the mentioned tools to generate trust the authors introduced three challenges for the trust research in HRI. The first challenge they present is the *measurement of trust "in the wild"*. As the name suggest, the research needs to be taken from the lab to real scenarios and from using disruptive measurement techniques towards techniques that do not take the user out of the flow of the task. Next, they suggest to *bridge trustworthy robots and human trust*. While the relation from the human perspective has been researched profoundly, the robot-centered perspective has been picked up only recently. Combining both perspectives has been explored to some extend, but here many open questions remain. The third and last challenge the authors defined, is the building of *rich trust models for real-world scenarios*. Such models are necessary, because in a real-world setting, a multitude of elements come together to affect the human user's trust in the robot, which means that trust needs to be modeled as a rich multidimensional construct. While existing models have yielded impressive results with technologies such as the Online Probabilistic Trust Inference Model for Asymmetric Human-Robot Collaborations (OPTIMo) [31].

Pinto et al. [25] validate the scale they developed to measure trust in HRI by means of the above mentioned HRITS. The HRITS is based on the *Human-Computer Interaction Trust Scale* from Gulati et al. [10] (HCTS) to evaluate the trust in a system that includes human and robotic actors. As the HCTS was developed to be used for as many use cases in the field of human-computer interaction as possible, the customization was to fill in the placeholders in the survey with appropriate words describing the use case for which the scale would be used. Pinto et al. [25] had the questionnaire translated to Portuguese, because they are from Brazil and needed a translated version to conducted a large study to validate their HRITS. Similar to validation of the HCTS by Gulati et al. [10], the authors used first and second order confirmatory analysis to validate their questionnaire. Their results were satisfactory in terms of convergent reliability and internal constancy. For future research Pinto et al. [25] promote to include more items such as moral aspects or emotional trust. Further, cultural and gender effects on trust in technology should be investigated. A modified version of the HCTS, similar to the HIRTS, but in English is used in this work as a measurement for trust.

2.4 Data Visualization using Augmented Reality

Enhancing HRI with AR can be done in many different ways, as described in the section before. The basic function of AR in HRI is that it provides an additional interface for the interaction of humans with robots. If one wants to use AR for more than a new user interface, it becomes imperative to include some kind of data. To achieve this Szafir and Szafir [29] propose to connect HRI with data visualization. They reviewed publications from the most prominent conference on the two research topics and found only a small number of papers that are overlapping these two topics. Even then it is mostly a short reference and not an actual fusion of research methods. However, they argue that researchers of either topic can greatly benefit from each other. Robot interface design often needs to provide the user with information about multiple sensors, such as cameras. Some research looked at how such data could be visualized and how important information could be highlighted. How such data can be visualized to help the user analyze it has been neglected mostly and the authors think that this is where the HRI community can learn a lot from the visualization (VIS) community. They found many robotic interfaces use suboptimal designs in the HRI community, which could be

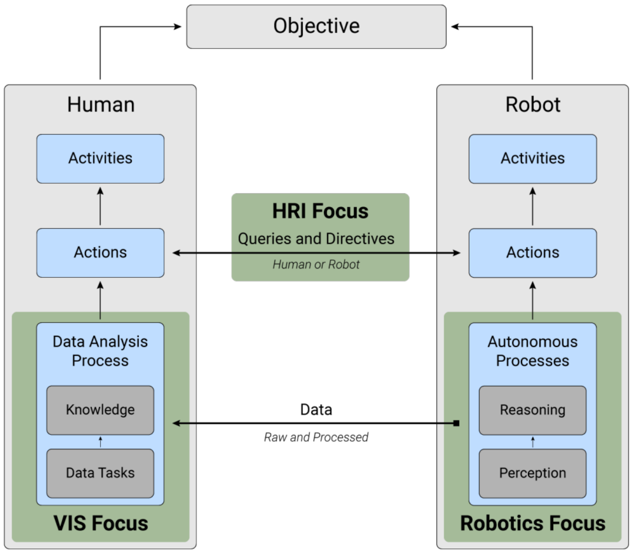

Figure 2.3: Framework form Szafir and Szafir [29], that highlights Data Analysis Processes as a critical consideration for robot interface design

avoided if they had some kind of design guidelines. For that, they designed a framework to give an overview of where and how data visualization can be connected with HRI (see Figure 2.3). Szafir and Szafir [29] propose a data flow in two steps, first sending queries and directives from the human user to the robot, and second sending raw or processed data from the robot to the data analysis process of the human user. HRI traditionally focuses on sending queries and directives, as the human and robot actively interact with each other at this level. The second direction, data streaming is mostly used for robot autonomy, rather than to improve the interaction between humans and robots. Incorporating such data into the human data analysis process could help to achieve the goal of the team in a better and faster way. Szafir and Szafir [29] also describe seven common data tasks employed in HRI and give examples of how they could benefit from VIS standards. In summary, they characterize four major HRI applications using the described framework and data tasks.

Data visualization is mostly seen as the visualization of big data or continuous data for the purpose of visual data analysis. Langner et al. [20] designed a conceptual framework (MARVIS) for visual data analysis by combining mobile devices and AR-HMDs. They achieved this by extending the two-dimensional screen of a tablet with three-dimensional visualizations using the HMD. The authors invited experts for the development of this framework and interviewed them on specific ideas regarding the use of mobile devices and AR-HMDs. As a result, the authors defined the characteristics of MARVIS: It should be usable while being mobile, so no stationary displays were used. However, they focused on seated usage because that is the most comfortable position for complex data analysis. According to the authors, the center of the interaction should be the mobile device because they are widely used and the interaction comes more naturally than the 3D gestures of the HMDs. Therefore, they also suggest using the mobile device as an interface, by either using the touchscreen or the device movement. Langner et al. [20] assume the spatial awareness of the devices and suggest that AR is used to support and provide context for the mobile device instead of substituting it. For example, the authors implemented multiple use cases, such as scatterplot matrix (SPLOM) navigation. SPLOMs are a widely used multi-dimensional visualization technique, where a multidimensional scatterplot is split up into all possible mappings of data dimensions to x-y axes. In MARVIS, the currently observed scatterplot is visible on the mobile device, while the rest of the plots are placed around the device and can be seen through the HMD. As another example, the extension of map visualizations was implemented. Here the map visualization that is visible on the mobile device is extended as a simpler map with less detail beyond the screen through the HMD. Langner et al. [20] conclude with the definition of multiple research problems that need to be addressed in future work. Such as an integration of the interaction using the AR-HMD and the specific content and location of the AR visualizations.

Ens et al. [6] deigned 17 key challenges in immersive analytics. Over several years of workshops, seminars, and conferences a group of 24 international experts came together to define these challenges. Immersive Analytics is defined by them as ”*the science of analytical reasoning facilitated by immersive human-computer interfaces*“ with the goal to ”explore the applicability and development of emerging user-interface technologies for creating more engaging and immersive experiences and seamless workflows for data analysis applications“. They present state-of-the-art immersive analytics from empirical studies to commercial products and platforms. Several recent immersive analytic systems try to use either AR or virtual reality (VR) to achieve a better analysis [6, 27]. The challenges, like designing guidelines for spatially situated visualizations, indicate that there is much more potential for the use of AR for immersive analytics.

2.5 Conclusion

We want to investigate whether visualizations in AR can have an effect on trust in HRI with industrial robot arms. There are many publications regarding visualizations for AR, as can be seen in the survey by Suzuki et al. [28]. The surveys by Gebru et al. [7] and Kok and Soh [17] show that trust in HRI is an active research topic as well. As Szafir and Szafir [29] declare data visualization has yet to become combined with HRI, but there are points to connect the two topics. We use the existing visualizations as a baseline for a focus group to develop novel visualizations for industrial robot arms. The contribution we want to make is two-fold. We want to see if there is a connection between visualizations and trust, which has not been a focus of many publications. Furthermore, we want to investigate big industrial-grade robot arms, which are much less investigated then the smaller cobots. In the next section the specific use case that we designed for the study will be demonstrated.

3 Use Case

In this chapter we describe the use case that is the foundation of this work. First we present the scenario, this includes the industrial setting for which the HRI is intended, as well as, the research setting in which the actual study takes place. Second, we define the task that has to be achieved by human robot interaction and explain in detail the individual steps and at which points where the human needs to interact with the robot to achieve the goal of the task.

3.1 Scenario

The investigated scenario is a timber fabrication workplace with a Kuka KR420 R3330[1], this can be seen in Figures 5.1 and 5.2. This industrial robot arm has a maximum payload of 512 kg and a reach of 3.3 m reachable through six rotatable joints and in our scenario, it has one additional degree of freedom because it is mounted on a linear treadmill. The robot is located in the Large-Scale Construction Robotics Laboratory (LCRL)[2] of the Cluster of Excellence "Integrative Computational Design and Construction for Architecture" (IntCDC)[3] in Waiblingen near Stuttgart. This workplace is used for projects that include gluing, nailing, and milling timber. In order to reduce the need for preparation and material waste for this study no actual timber assembly is done, but rather the robot

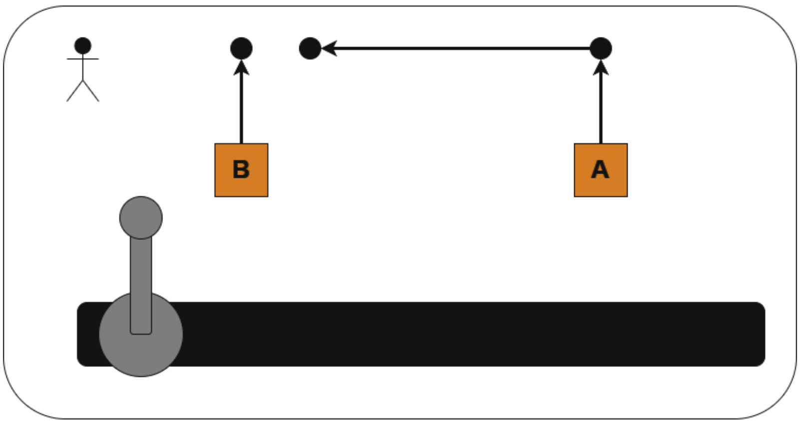

Figure 3.1: Top-down sketch of the environment with the human user and the Kuka KR420 on a linear rail. The boxes are also visible, as well as, the directions in which they are pushed by the robot.

[1]https://my.kuka.com/s/product/detail/01t58000002hnjHAAQ?language=en_US

[2]https://www.f01.uni-stuttgart.de/fakultaet/aktuelles/news/Forschungsneubau-LCRL-Large-Scale-Construction-Robotics-Laboratory/

[3]https://www.intcdc.uni-stuttgart.de/

Human Task	Robot Task
Pick up (Box A)	-
Move (Box B)	Move (Box A)
Copy (Box B)	Push (Box A)
Move (Box A)	Move (Box B)
Tape (Box A)	Push (Box B)
Move (Box B)	Move (Box A)
Fold (Box B)	Push (Box A)

Table 3.1: This table shows the order of the tasks the human and the robot have to finish. Tasks in the same row are happening simultaneously. The interesting tasks are those where the human and the robot have to move at the same time because they have to cross the same space (rows 2,4, and 6).

moves around boxes, which are common moving boxes with measurements of 61x30x32cm, and standing on one of the almost quadratic faces. The setup can be seen in Figure 3.1, the boxes are placed in front of the linear rail at either end. On top of these boxes we placed different objects the user has to interact with. For the interaction beyond the visualization, the VIZOR project by Yang et al. [32] is used. This is an AR tool to help the user interact with the Robot Operating System (ROS) based backend, to receive and confirm tasks.

3.2 Tasks

In our scenario, normally the goal would be to assemble an object which requires different individual pieces and a sequence of different operations by the human and the robot. We look at the operation of moving an object from one place to another for different assembly steps and different locations. The goal of our process is to create a copy of a drawing (see Figure 3.2). To achieve this goal, the human user and the robot need to complete different tasks surrounding the boxes (see Table 3.1). For each task the human has to start and complete through the VIZOR interface, the robot will only start with the next task if the human user has finished the corresponding task. To start the process the human enters the work area (see Figure 3.1) and picks up a piece of paper on Box B. Then the user should move to Box A, to then copy the drawing lying there, while the robot moves to Box B and in the next step pushes the Box B away from itself. Now, the actors need to switch places and go to the box where the other actor was until now and will cross paths in the process. In the last step, the human user needs to fold the paper at Box A, while the robot pushes Box B in the direction of Box A where the human user is currently standing.

These tasks were created as a simulation of a fabrication task that involves manual work, where the user needs to focus on tasks while the robot is moving. This results in a repeated attention shift for the human between the task and the robot. It simulates real-world applications that require the full attention of the human such as the task of driving screws into wood during a fabrication process. The picture drawing task is safe, as no wood or screws were involved. In addition, as already mentioned above, the study created minimal material waste, as the only waste are some paper notes.

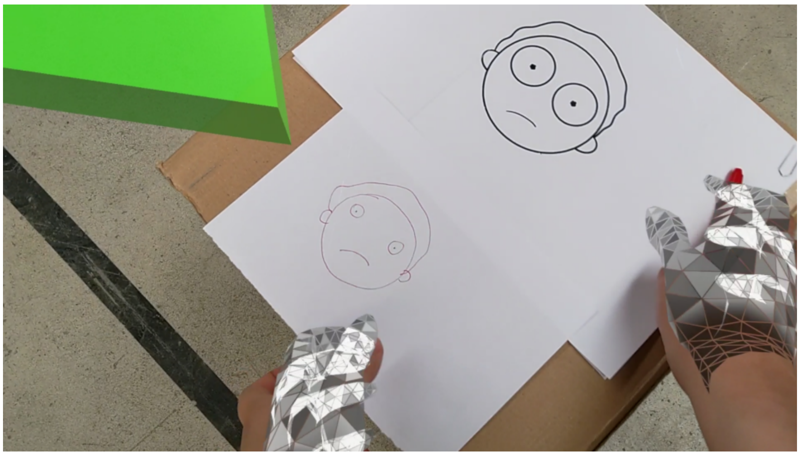

Figure 3.2: This is a picture taken with the Hololens during the interaction and shows the drawing to be copied and the copy created by the human user.

The described scenario is used as the baseline for the expert group described in Chapter 4 and in this scenario the user study takes place (see Chapter 6). The participants of the user study need to complete all of the tasks described in this chapter three times for each condition of the study.

4 Focus Group

In this chapter we describe the focus group we conducted to develop novel visualizations to increase trust in HRI with industrial robots. First, we explain what the motivation behind the focus group was and why it was chosen instead of other methods, such as individual interviews. In the next section we describe the procedure of the focus group and who participated. Afterwards, we present the results of the focus group that consist mostly of the result of a brainstorming session in subgroups. In the end, we defined design recommendations for the development of visualizations for industrial robot arms.

4.1 Motivation

The related work (see also section Section 2.2) includes multiple publications in which visualizations for HRI are presented [28]. Some, in particular for cobots and industrial robots [12]. The goal of this thesis is to implement some of those visualization and/or come up with new ones that improve trust in industrial robot arms. To decide on specific visualizations and to gather different perspectives on the topic a focus group was conducted. The input of experts from different fields of study could give us important insights into the problem. The method of the focus group was chosen [1] because it gives the possibility to discuss with experts, with the chance to probe into different questions, if further explanation is wanted. Compared to interviews with one expert at a time, a focus group needs less time and may lead to new perspectives when the experts discuss as a group. Interviews might lead to more detailed explanations, as the interviewee can probe into singular topics if it seems that there is more to be said. In addition, interviews are simpler to conduct, due to a guideline of questions the interviewee can use to go through the interview. Compared to that, a focus group needs more moderation and the conductor has to see, that everybody has enough time to talk and present their viewpoint. Questionnaires, on the other hand, give the option of fast feedback from a large number of people. A drawback of questionnaires is that it might be difficult to present the problem so that the people understand the questions properly, and there is no chance to ask further questions about a specific topic. Considering all the pros and cons, we chose to conduct a focus group because it gives the most detailed feedback in a short period of time.

4.2 Procedure

Multiple people with scientific backgrounds in human-computer interaction, visualization, and robotics were invited to participate in the study via mail. The participants were selected for their knowledge of different topics related to the research question at hand. In the end, four persons came together online using Webex Meetings[1]. There was no compensation for the participation in the focus group. The whole meeting lasted 90 mins and was recorded for further analysis and lasted about. Beforehand, they filled out a short questionnaire with demographic data and short questions on their expertise in AR and robotics, as well as, a consent form and agreed to the DSGVO (see Appendix B). Their average age was 27.5. All of them were University members and one participant considered themselves as expert in AR and another classified themselves as expert in robotics. The other two participants had knowledge in both topics. During the Webex meeting, they were first introduced to the topic with a short video from a previous workshop that used the same robotic platform as this work (see Chapter 3). “What kind of visualization can help improve the trust in this situation?”, was the task they were given. After answering all questions the participants had about the use case and scenario, they were split up into two subgroups of two people each to discuss the task and develop visualizations. To gather their thoughts a MIRO[2] board was used as a virtual whiteboard. In the case that they got stuck and needed ideas, we prepared visualizations and ideas from related work to hand out for inspiration. In the end, this backup material was not needed, both subgroups had more ideas to discuss than the time given and needed no additional input. The whole group came together again and the subgroups presented their results and the whole group debated over the results.

4.3 Results

The focus group resulted in two Miro documents (see Appendix B) and the recordings of the meeting. All participants were intrigued by the discussion format, as most of them participated in a focus group for the first time. First, both groups discussed the notion of trust. Both of the groups came to the conclusion, that safety is one of the main aspects of trust while working with such a big industrial robot like the Kuka KR420 R3330. A recurring point was that it is a big difference if the human knows they are not in danger, or if they have to be careful that they could be hurt. Currently, user studies with industrial robot arms are under strict safety regulations so no human can get hurt in the process, for example, there is a speed limit on the robot movement which is far from its maximum speed. This would have a big impact on the behavior of possible human users of the system and their trust in the system. Further, it was discussed why the user should trust the visualizations of the robot if they are already distrusting the robot itself. During their brainstorming, the two subgroups had different approaches to finding answers for the question at hand which will be detailed in the following subsections.

4.3.1 Group A

Group A started by discussing what the visualization would be actually showing and what would be necessary for such visualizations. From there, they developed different ideas, that could improve the safety of the user and, therefore, the trust in the system (see sketches in Figure 4.1). Then they developed multiple simple prototypes of visualizations. They proposed the use of notifications to warn the user of the moving robot. A warning system like this would reduce the chance of the

[1] https://www.webex.com/de/index.html
[2] https://miro.com/de/

human user being scared by sudden sounds or movements. Further, they imagined a trajectory for the robot movements, that shows the path the robot will take. They suggested combining multiple visualizations to enhance the safety of the user. In addition, they brought up the question of whether to separate the trajectory visualization from the actual robot to avoid users ignoring the actual robot. Another visualization they discussed, was the concept of safety zones as either marking the space the robot can reach and therefore is dangerous or by marking a safe space in which the human user would be safe from any collision with the robot. As a further point, they proposed color coding the visualizations to add another level of information for the human user. They suggested similar to Krauter et al. [18], to use different colors to signal different levels of danger. Furthermore, they pointed out, that it takes time to build trust and that the visualizations can act as a catalyst which reduces the time it takes for that.

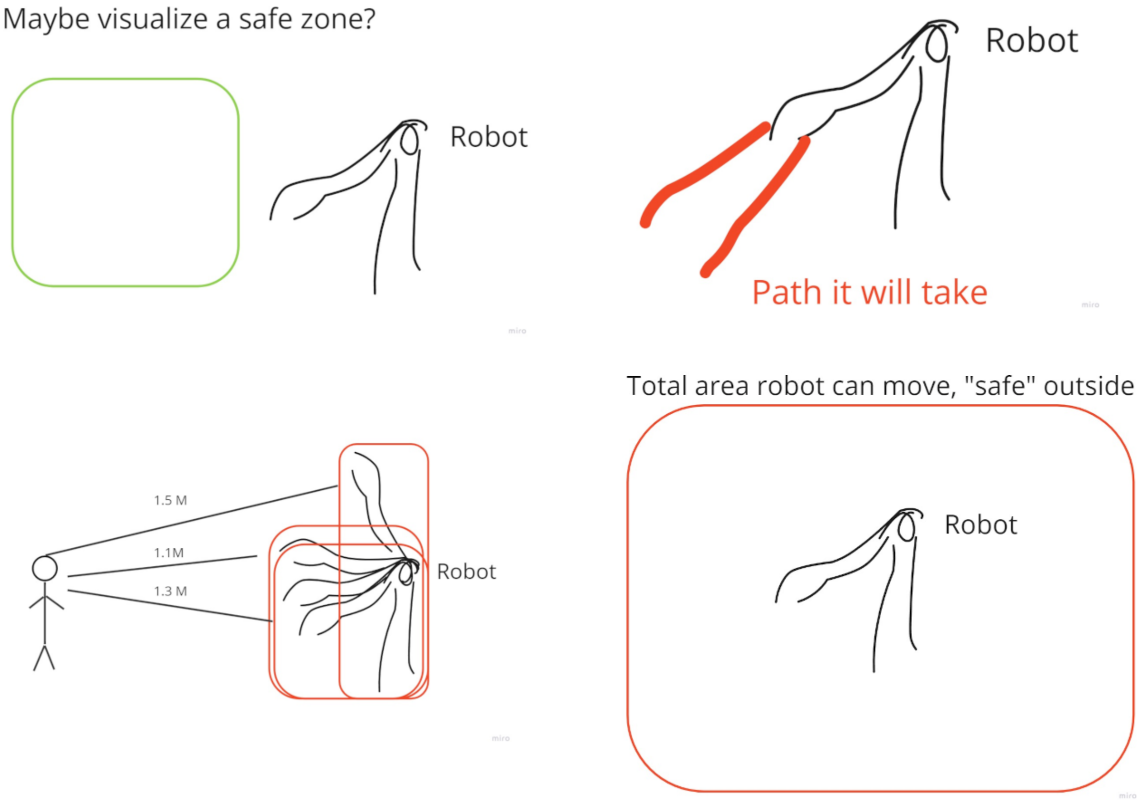

Figure 4.1: Sketches of visualizations form group A of the focus group. From top left to bottom right: A safe zone for the human, trajectory visualization, color coding for different distances, and a zone that marks the area where the robot can move.

4.3.2 Group B

Group B had a different approach than the group A. First, they defined trust as a combination of safety concerns, performance, and collaboration. Safety concerns include regulatory processes as well as the subjective feeling of safety. Performance is the evaluation of how well the robot is doing its tasks. The collaboration aspect should take into account the potential of other humans in the environment and whether they are safe and doing their tasks correctly. Starting from this definition, group B immediately had multiple visualizations in mind. In the time given, they discussed two ideas for a visualization and elaborated further on these ideas. Their first idea was to display the trajectory of the robot joints and the second one was to have a visualized safety bubble around the user that changes colors when the user is in a dangerous position (see Figure 4.2). For the trajectory, they proposed to implement a color coding for either the speed of the robot or the time it takes until the robot reaches a given part of the trajectory. Another proposal was to show the whole trajectory and light up the parts that will be dangerous for the user in a given time frame. Related to this they also remarked, that it might be confusing and the vision too cluttered if the whole trajectory is shown at once. Either transparency or only showing discrete steps could help to avoid this. This could be implemented by introducing a user interface where the user can set their preferred settings for the trajectory visualization. At the end of their discussion group B also remarked that robot arm movement is not a singular path, but multiple joints moving at the same time. This should be kept in mind while designing visualizations for such a task. Their second idea was the safety bubble, which is a sphere around the user that highlights when the user moves too close to dangerous areas. They proposed different color codes depending on the imminence of the danger. A problem of the safety bubble they discussed was that the danger could be behind the user and, therefore, not visible to them. To solve this problem one could either highlight the edges along the field of view or show a path to safety with arrows in the user's view.

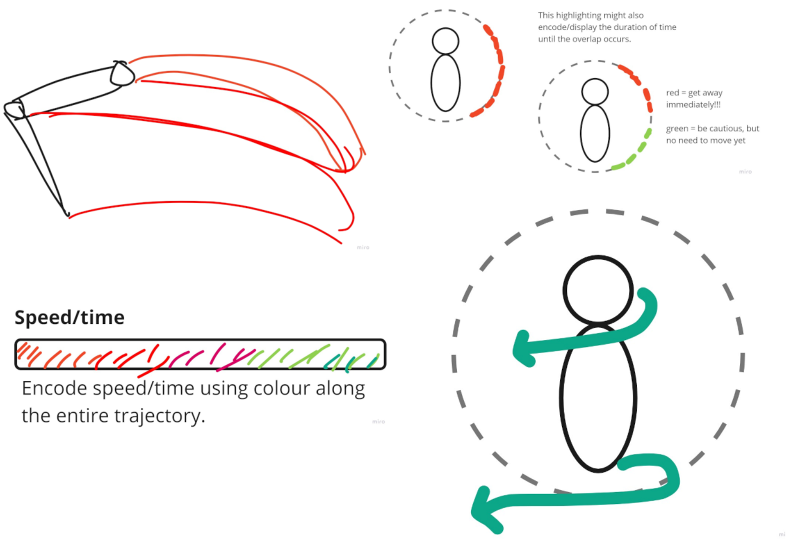

Figure 4.2: Sketches of visualizations form group B of the focus group. From top left to bottom right: multiple trajectories for each robot joint, a color coded-safety bubble, color coding for trajectory visualizations, and adding arrows to the safety bubble

4.4 Design Recommendations

From the collected expert input, we derive four design recommendations for visualizations used in AR for HRI using big industrial robot arms:

1. **Determine the point of reference:** Be clear whether the visualization's point of reference is the user's position, or whether the visualization is independent of it. For example, the *safety bubble* indicates the path to safety with an arrow and a colored sphere, which are both relative to the user's position. An other example is information that is only passingly given such as the proposed trajectory, which is at its core independent of the user's position These two aspects can also be mixed to enhance the user experience, for example, the trajectory could only be visible in an area around the user if there is the chance of a collision in the near future.
2. **Avoid visual clutter:** Especially with the trajectory of the robot's movement or even a complete holographic twin of the robot it is important to think about visual clutter. A human has only a limited attention span and if the field of view of the user is filled with trajectories it will be difficult to see and react to the actual robot. The same holds for a holographic robot twin, where the movement of the twin could distract from the actual danger of the real robot. The visualization should not cover potential dangerous objects or movements, for example the arrow from the safety bubble should not occlude a cable on the ground.
3. **Use time sensitive visualization:** It makes no sense to visualize the entire movement of a robot to the human user before starting production. One the hand it is nearly impossible to remember the whole movement of the robot, and on the other hand some movements might not be relevant for the user at that time. There is also a danger if you only display the movement for the next task: The user might seem themselves in a safe place, but is already at risk in the next robotic task. Depending on robot speed and the range of the robot movements choose well the duration for a dynamically changing visualization.
4. **Get their attention:** The human user might be focusing on a task of their own and have no mind to check the visualizations around them. Even in the extreme case when the user faces another direction, the visualization should still work. It should have a way to grab the user's attention.

In this chapter we explained why and how we conducted the focus group. Then we presented the results of the brainstorming sessions and discussions, which lead to development of the two visualizations presented in the next Chapter 5. Furthermore, we defined some design recommendations for the development of AR visualizations for industrial robot arms.

5 Visualizations

In this section, the visualizations that were designed during the focus group and then chosen to be implemented are presented and categorized using the taxonomy from Suzuki et al. [28]. Two of these visualizations were further developed to be tested in a user study: *Trajectory* and *Safety Bubble*. Based on the results of the focus group, these two visualizations were chosen because they address the challenges of AR in HRI from different perspectives. The VIZOR project from Yang et al. [32] is a software framework to facilitate human-robot collaboration using AR. For this work, the framework was extended to support the use of visualizations like the *Trajectory* and the *Safety Bubble*. The AR application was developed for the Microsoft Hololens 2 using the Unity game engine[1] and the visualizations were implemented with Unity as well[2]. The robot motions were recorded beforehand and then hardcoded into the project. Both visualizations need those motions to function and it makes the study we conducted (see Chapter 6) more comparable because all participants saw the same robot movement.

5.1 Trajectory

Both groups of the focus group (see Section 4.3) had the idea for some kind of trajectory visualization, therefore this was the first choice to be implemented (see Figure 5.1). This is also a visualization that is present in other publications [9], to show robot motion intent and thus increase the trust of the human user towards the robot. The *trajectory* implemented shows the movement of each robot joint with a red line going from each start position to the corresponding end position. The robot positions used to create the *Trajectory* are extracted from the prerecorded motions. In addition to these lines, the robot's position is visible at certain steps along the *Trajectory*. The joints are shown as white spheres, connected with gray lines to show the position of the robot. This abstract representation of the robot was chosen for two reasons. On the one hand, the lines obstruct the view much less than for example holographic copies of the robot. On the other hand, the computational power of the Hololens is quite limited and, therefore, it is advised to minimize the polygons in the scene, and simple lines do not need much of computational power compared to other visualizations. One particular result of the focus group was to use a time frame to show a certain part of the future. This was implemented by showing the trajectories for multiple tasks of the robot. The current task is displayed as opaque and the next two tasks are shown with increasing transparency. Every time the robot finishes one task the visualization will be updated and the next task will become opaque and the subsequent ones become more visible.

[1] https://unity.com/de

[2] https://github.tik.uni-stuttgart.de/JonasVogelsang/MasterThesis

Figure 5.1: Picture taken with the Hololens while running the study software. The *trajectory* visualization is visible and in front is the VIZOR interface by Yang et al. [32] the human user has to interact with. The white spheres represent the joints of the robot and are connected through the gray lines to represent the robot's position at a given time step. The red lines show the movement of a single joint.

In the design space dimensions of Suzuki et al. [28], this visualization has the following properties. It is an on-body approach to augment the surroundings. The characteristics of the augmented robots are a robotic arm as a form factor, a 1:1 relationship between human and robot, being large for the scale of the robot, and being in near proximity to each other. The purposes and benefits of the visual augmentation are to improve safety, as well as, communicate intent and the classification of the presented information is plan and activity. As design components, they use points and locations, paths and trajectories, and virtual replicas. The level of interactivity is low because it is only output.

5.2 Safety Bubble

This visualization was proposed by group B in the focus group (see Section 4.3.2) and well received in the plenary discussion. Further, this visualization is fundamentally different from the *Trajectory* visualization, because the *Safety Bubble* is user-centered, compared to the robot-centered *trajectory*. The *Safety Bubble* was implemented by planting a sphere around the user and coloring the vertices red, which would be in a dangerous zone. This should lead to a slowly filling out of the bubble while moving closer to the dangerous area. In addition to this sphere, an arrow was placed at the point where the user would enter the dangerous area. This area was created by putting a bounding box

Figure 5.2: Picture taken with the Hololens while running the study software. The *Safety Bubble* visualization is visible and in the background is the VIZOR interface by Yang et al. [32] the human user has to interact with. The red sphere surrounding the user (hardly visible) and the red arrow are projected in the middle of the picture.

around the prerecorded movements of the robot for the next three tasks. The safe area was defined as the area where the human user a has 1.5-meter distance towards the bounding box. The direction of the arrow gave an indication in which direction the human user could reach a safe area.

In the design space dimensions of Suzuki et al. [28], this visualization has the following properties. It is an on-body approach to augment the surroundings. The characteristic of the augmented robots are a robotic arm as form factor, a 1:1 relationship between human and robot, being large for the scale of the robot, and being in near proximity to each other. The purpose and benefits of visual augmentation is to improve safety and the classification of the presented information is supplemental content. As design components, the *Safety Bubble* uses areas and boundaries, and other visualizations. The level of interactivity is low because it is only output.

In this chapter, we presented two visualizations that we developed based on the results of the focus group in Chapter 4. The *Trajectory* and *Saftey Bubble* were integrated into the VIZOR project from Yang et al. [32]. This application will be used in the user study that is described in detail in the next Chapter 6.

6 Study

In this chapter we describe in detail how we conducted the in-situ study to investigate if the visualizations have an impact on the trust in the robot system. First, we report the demographics of the study participants. In the next section, we describe the procedure of the study and describe in detail the questionnaires used for the evaluation of the study. Then we present the results of the study which consists of the quantitative analysis of the the questionnaires and qualitative feedback in form of written feedback notes by the participants.

6.1 Participants

We invited participants from the different institutes involved with the projects, through university messenger groups and our circles of acquaintances. In the end twelve people took part in the study in the LCLR in Waiblingen. This small sample size is partly due to the fact that public transportation from Stuttgart to the LCLR in Waiblingen was severely limited due to construction work. Therefore, a lot of people could not manage to spend the time to participate. Furthermore, the time with the robot was limited, so that in the end there were only four days of study possible. Six of the participants identify as male and six as female. They were on average 30 years old, from a 20 year old participant to a 43 year old. All of the participants were university members, four students, seven PhD students and one postdoc. Seven of the participants had no expertise with robotics at all, while one considered themselves an expert, and the other four classified themselves as having plenty of experience with robotics. Only four people had no experience with AR before the study. Seven people had used AR before but would not call themselves experts. Only one participant considers themselves to be a expert of AR. Seven participants were German. The rest where either from Australia, Israel, Peru, USA or China.

6.2 Procedure

The participants were welcomed in the LCRL and then guided to the area were the industrial robot arm is standing. For the safety of everyone involved, the area, where the robot moved, was sealed off using barrier tape. First the participants had to read and sign the consent form and privacy information (see Appendix C). Afterwards they were introduced to the Microsoft Hololens 2 used for the study. To reduce the risk of injury, the user saw a line on the ground, which marked a safe zone, an area where the robot could not reach and thus the user could relax and wait there. If they had no previous experience or need a refreshment on the interaction techniques of the Hololens,

NoVis	Safetybubble	Trajectory
NoVis	Trajectory	Safetybubble
Trajectory	NoVis	Safetybubble
Trajectory	Safetybubble	NoVis
Safetybubble	Trajectory	NoVis
Safetybubble	NoVis	Trajectory

Table 6.1: The order of conditions created using a balanced latin square generator in order to reduce order-effects in the analysis of the study data. Each row represents the order of the conditions for one participant. After six participants the first order will be used again.

they could go through the tutorial on how to interact with this HMD from Microsoft. All following questionnaires were merged into one big questionnaire using limesurvey[1] The limesurvey server is run by the university and prevents the data to be leaked somewhere in the internet.

The participants filled out a questionnaire with demographic data and a self-generated ID, so that it will be possible to delete their data afterwards if they want without losing the anonymity of the data, which is in-line with the ethics rules of the institute. Additionally, they had to rate their expertise in robotics and in AR. In the next step, the tasks were explained to them, safety instruction were given, and the participants also received safety shoes for their protection. When the participants felt comfortable with the Hololens and the shoes, they could enter the area of the study and begin with the first condition. The independent variable of the study was the *Visualization* and had three levels. These are the two visualizations we developed in Chapter 5 (*Trajectory* and *Safety Bubble*) and as a baseline for comparison no visualization (*NoVis)* was the last level The three levels correspond to the three conditions used in the study. In each run the participants saw one of the three *Visualization* levels. The conditions were balanced using a latin square to reduce any learning effect the participants might have (see Table 6.1). For our three conditions this leads to six different condition orders. After each condition, they removed the Hololens and filled out further forms used for the evaluation of the study.

First, they had to answer two questions using a 5-point likert-scale, they were "I trusted the robot during the execution of the task" and "I felt safe during the execution of the tasks". Next, they had to fill out three questionnaires that were adopted from related work: The NASA-Tlx [11], the System-Usability Scale (SUS) [4], and the Human Computer Trust Scale (HCTS) by Gulati et al. [10]. The SUS analyzes the usability of a system as the name suggests o see usable the system was. Brooke [4] defined ten statements on different characteristics of a system and how the user felt during the use, for example, "I thought the product was easy to use". The participants had to rate on a five-point likert scale if they agree with the statement (1) or not (5). In the analysis the *SUS Score* is calculated by adding up all results from statements with a odd number and then subtracting five. The sum of the results from the statements with even numbers needs to be subtracted from 25. These two numbers, then need to be added and multiplied by 2.5, the result is the *SUS Score* and can range from 0 to 100.

[1] https://www.limesurvey.org/de

The Nasa-Tlx is used to evaluate the workload of the tasks. Hart [11] developed six questions on different aspects that affect the overall workload: mental, physical, and temporal demand, performance, effort and the frustration level. These Factors need to be rated on a 21 point scale from low to high, with the exception of the performance rating which goes from perfect to failure. In our case we inverted the performance scale in the analysis, because of the design of the questionnaire in limesurvey did not provide a additional label and we dismissed the first part of the Tlx by weighting all factors the same, which is common in its use [11]. To calculate the *Raw-Tlx Score* for analysis, all values need to be multiplied by five and then the sum needs to be divided by six, it can range from 0 to 100.

The HCTS was adjusted similar to the HRITS by Pinto et al. [25] (see Appendix C) to measure the trust in the interaction with the robot arm. This resulted in a questionnaire with eleven statements where the user has to state their agreement on a five point likert scale, from strongly agree (1) to strongly disagree (5). The statements can be split up into four components which are the main contributors to trust according to the authors: risk perception, competency, benevolence, and reciprocity. The first three items abut risk perception need to be inverted for the analysis as the statements have a negative connotation. As Pesonen [24], the results were then summed up to calculate a trust scale. After each condition and before finishing the study the participants could give additional written feedback. The whole questionnaire can be seen in the Appendix C.

6.3 Results

In this section we present the results from the questionnaires used to evaluate the user study, which are explained in detail in Section 6.2. First we analyze the quantitative data which is composed of the two questions on trust defined in Section 6.2, as well as, the three questionnaires SUS, Nasa-Tlx, and HCTS. Afterwards we present the qualitative results, namely the written feedback from the study survey and some notes taken from spoken feedback.

6.3.1 System-Usability Scale

We analyzed the *SUS Score* calculated after Brooke [4] for each Visualization. The ten questions were ranked by the participants at a five-point Likert scale, see Figure 6.1. *NoVis* has a mean of $35.83 (SD = 24.04)$, *Safety Bubble* a mean of $38.61 (SD = 21.38)$, and the *Trajectory* a mean of $38.8 (SD = 29.58)$. A one-way repeated ANOVA found no statistically significant main effect of Visualization on the SUS Score, $F(2, 16) = .1673, p > .847$. We conducted post-hoc paired-sample t-tests with Bonferroni correction applied to compare the main effect of Visualization. The pair-wise comparisons revealed no statistical significance for all comparisons *NoVis* vs. *Safety Bubble* ($p > .596$), *NoVis* vs. *Trajectory* ($p > .426$), and *Safety Bubble* vs. *Trajectory* ($p > .973$).

6.3.2 NASA-TLX

We analyzed the *Raw-Tlx Score* calculated after Hart [11] for each Visualization. The six questions were ranked by the participants at a twenty-one point scale, see Figure 6.1. *NoVis* has a mean of $9.04 (SD = 5.87)$, *Safety Bubble* a mean of $9.91 (SD = 5.89)$, and the *Trajectory* a

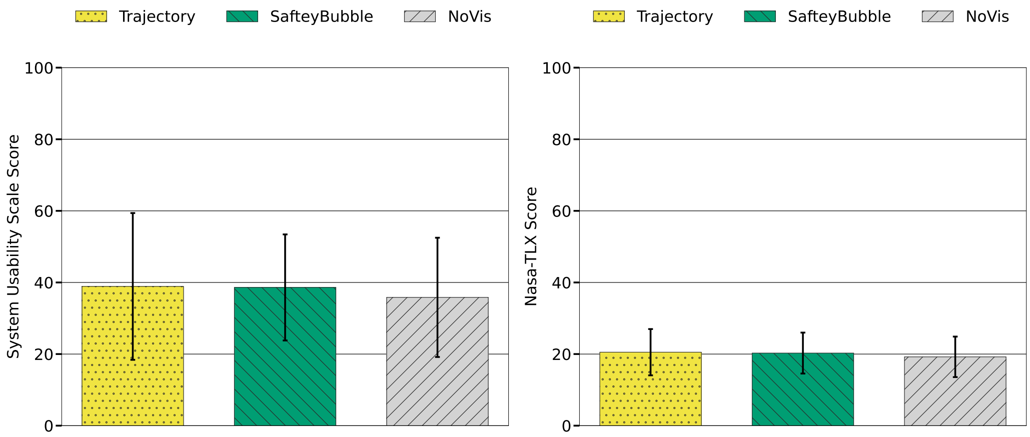

Figure 6.1: The figure shows the results of the study for the SUS and Nasa-Tlx. On the left side is the *SUS Score* for the three conditions, here *NoVis* has a mean value of $35.83(SD = 24.04)$, *Safety Bubble* a mean of $38.61(SD = 21.38)$, and the *Trajectory* a mean of $38.8(SD = 29.58)$. On the right side is the *Raw-Tlx Score* for the three conditions, here *NoVis* has a mean of $29.00(SD = 8.40)$, *Safety Bubble* a mean of $31.33(SD = 9.44)$, and the *Trajectory* a mean of $27.00(SD = 7.71)$.

mean of $10.70(SD = 7.70)$. A one-way repeated ANOVA found no statistically significant main effect of Visualization on the Raw-TLX Score, F(2, 16) = .1712, p > .844. We conducted post-hoc paired-sample t-tests with Bonferroni correction applied to compare the main effect of Visualization. The pair-wise comparisons revealed no statistical significance for all comparisons *NoVis* vs. *Safety Bubble* ($p > .623$), *NoVis* vs. *Trajectory* ($p > .670$), and *Safety Bubble* vs. *Trajectory* ($p > .904$).

6.3.3 Human Computer Trust Scale

We analyzed the *HCTS Score* similar to Pesonen [24] for each Visualization. The *HCTS-score* was calculated by summing up the answers for the for sub categories of the HCTS. *NoVis* has a mean of $29.00(SD = 8.40)$, *Safety Bubble* a mean of $31.33(SD = 9.44)$, and the *Trajectory* a mean of $27.00(SD = 7.71)$. The eleven questions were ranked by the participants at a five-point Likert scale, see Figure 6.1. A one-way repeated ANOVA found no statistically significant main effect of Visualization on the HCTS Score, F(2, 16) = 1.865, p > .186. We conducted post-hoc paired-sample t-tests with Bonferroni correction applied to compare the main effect of Visualization. The pair-wise comparisons revealed no statistical significance for all comparisons *NoVis* vs. *Safety Bubble* ($p > .158$), *NoVis* vs. *Trajectory* ($p > .594$), and *Safety Bubble* vs. *Trajectory* ($p > .180$).

6.3.4 Further Questions

We analyzed two further questions we asked, which were ranked at a five-point Likert scale by the participants for each Visualization, see Figure 6.2. For the trust in the robot during the study *NoVis* has a mean of $3.44(SD = 1.34)$, *Safety Bubble* a mean of $2.89(SD = 1.29)$, and the *Trajectory* a mean of $3.67(SD = 1.25)$. A one-way repeated ANOVA found no statistically significant main

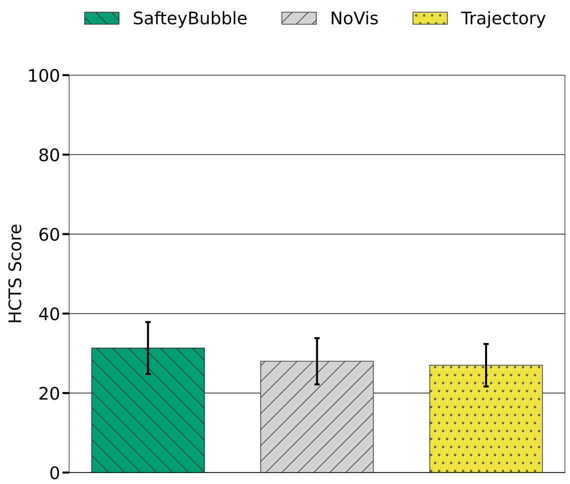

Figure 6.2: The figure shows the results of the study for the HCTS. *NoVis* has a mean of $29.00(SD = 8.40)$, *Safety Bubble* a mean of $31.33(SD = 9.44)$, and the *Trajectory* a mean of $27.00(SD = 7.71)$.

effect of VISUALIZATION ON THE TRUST IN THE ROBOT DURING THE STUDY. ("*I trusted the robot during the execution of the tasks.*"), F(2, 16) = 2.7368 , p > .095. We conducted post-hoc paired-sample t-tests with Bonferroni correction applied to compare the main effect of VISUALIZATION. The pair-wise comparisons revealed mo statistical significance for all comparisons *NoVis* vs. *Safety Bubble* ($p > .384$), *NoVis* vs. *Trajectory* ($p > .766$), and *Safety Bubble* vs. *Trajectory* ($p > .244$).

For the feeling of safety during the study *NoVis* has a mean of $3.33(SD = 1.41)$, *Safety Bubble* a mean of $2.2(SD = 1.31)$, and the *Trajectory* a mean of $3.67(SD = 1.70)$. A one-way repeated ANOVA found no statistically significant main effect of VISUALIZATION ON THEIR FEELING OF SAFTEY DURING THE STUDY. ("*I felt safe during the execution of the tasks).*"), F(2, 16) = 3.4750, p < .055. We conducted post-hoc paired-sample t-tests with Bonferroni correction applied to compare the main effect of VISUALIZATION. The pair-wise comparisons revealed no statistical significance for all comparisons *NoVis* vs. *Safety Bubble* ($p > .095$), *NoVis* vs. *Trajectory* ($p > .715$), and *Safety Bubble* vs. *Trajectory* ($p > .109$).

6.3.5 Qualitative Data

The participants could leave feedback in the form of free text fields after each condition and at the end of the study. Some participants had problems with the *Safety Bubble* and said that, the they could "*...barley see the red arrow...*" and "*...it was not in the field of vision anymore...*".

Another participant found the visualization to be "*only a slide red blur in the middle of my sight*" and another said: "*The safety bubble was basically useless* [...]" and "[...] a need to look for the warning defeats the purpose of the warning [...]". However, one participant also found "*the concept* [...]" of the safety bubble [...] "*is really promising and easy to understand* [...]" and another one wrote "[...]*both systems are a good foundation for a useful implementation*". Two people did not see the the

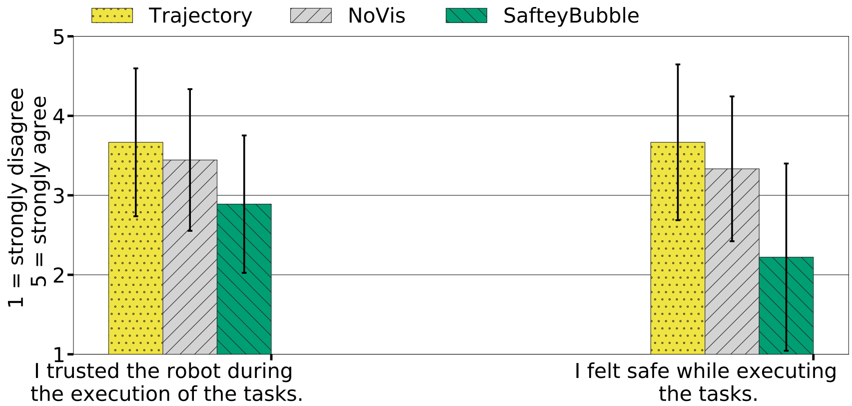

Figure 6.3: The figure shows the results of the study for the two further questions asked. On the left side is the trust in the robot during the study, for which *NoVis* has a mean of $3.44(SD = 1.34)$, *Safety Bubble* a mean of $2.89(SD = 1.29)$, and the *Trajectory* a mean of $3.67(SD = 1.25)$. On the right side is the feeling of safety during the study for which *NoVis* has a mean of $3.33(SD = 1.41)$, *Safety Bubble* a mean of $2.2(SD = 1.31)$, and the *Trajectory* a mean of $3.67(SD = 1.70)$.

difference between *NoVis* and *Safety Bubble* ("*No real difference to the visualization before*", "*Felt basically the same as the previous condition*"). Multiple people said that the "*Hololens field-of-view is way to small*" and it is "[...] *a fairly small portion of my field-of-view*".

About the *trajectory* the participants said that "*the visualization worked well* [...]" and that it "[...] *gives me more confidence in the robotic motion* [...]". One participant suggested color coding for the *trajectory* to "[...] *indicate areas which the robot arm were to start,stop, and/or change speed.*" Further, a participant mentioned that they "[...] *like the idea of having safety areas* [...]", because "*such a concept is already present* [...] *in the factory floor* [...] *it translates directly into AR*".

In this chapter we presented the results from the user study. We could not detect a significant effect of the *Visualization* on any of the investigated variables. The meaning of these results will be discussed in the Chapter 7

7 Discussion

In this chapter, we discuss the results of the study and the overall contribution of this work. First, we describe what the goal of this work was, so we can set the results of the study in the context. Then, we try to reason why the results of the study are what they are and what the takeaway message of the study is. In the end, we discuss the two *Visualizations* we developed in Chapter 5.

7.1 User Study

We conducted a user study to test if visualizations have an effect on the trust of a human user in a robotic system that uses industrial robot arms. We hoped to see a significant difference for the HCTS and the general trust in the system if either the *Safety Bubble* or the *Trajectory* visualization is used compared to the baseline *NoVis*. However, the results show no significant differences in the HCTS scores and the same goes for the Nasa-Tlx and SUS scores. That means that the visualizations have no effect on either the trust in the system, the workload of the tasks, or the usability of the system. With this, we have to answer the research question negatively and can say that our visualizations do not help a human user in HRI with industrial robot arms. While there is no positive effect of the visualizations, there is also no negative effect so they do not decrease the usability or damage the trust in the system. The reason for this could be that the visualization takes up only a small part of the whole system. Interestingly, the overall score of the system usability score is quite low, even though the study participants did not complain about any problems with the system. In retrospect, the questionnaires could be explained more clearly to the participants. However, more explanation needs to done carefully to not give the participants any leading information. The score of the NASA-Tlx indicates that the task chosen to simulate timber fabrication might have been too easy to complete. With tasks that are closer to real tasks, the workload might have shifted. The low scores of the HCTS show that there is room to improve the trust in robotic systems with large industrial robotic arms. We added the visualizations into the VIZOR application by Yang et al. [32] to integrate the visualizations in a working HRI system. However, the other functions of the system could have overshadowed the visualizations. In addition to that, both visualizations had their problems in the implementation, especially the *Safety Bubble*.

7.2 Safety Bubble

As one can see in Figures 6.1 to 6.3, there is no effect of the *Safety Bubble* visualization on the trust, workload, or system usability. For the *Safety Bubble* this can be explained by the implementation and the limitation of the Hololens. Many of the participants wrote as feedback, that they did not see the visualization. The visualization was developed to turn red if the human user is within a certain distance of the robot and its future movements. It was decided, that a realistic safety distance of at least 1.5 meters should be kept to the robot. However, in combination with including the movement of the next tasks the area which would be in “danger” was as big as the whole study area. Therefore, the human user was constantly inside the danger area and the *Safety Bubble* was constantly visible as a red sphere around the user. Further, the limited field-of-view made it impossible to actually recognize the *Safety Bubble* as a sphere. Most participants only noticed a red blur in their field of view in addition to the red arrow. The arrow indicated the shortest way towards a safe area and was received quite positively in the written feedback. However, the position of the arrow was criticized, as it was not always directly visible and therefore missed its function as a warning symbol. Nevertheless, the participants found the idea of the *Safety Bubble* intriguing. The concept of a user-centered visualization can add a level of dynamic information to HRI. The *Safety Bubble* needs to be reiterated and evaluated with different use cases to see if it could have an effect on the trust.

7.3 Trajectory

As one can see in Figures 6.1 to 6.3, there is no effect of the *Trajectory* visualization on the trust, workload, or system usability. Nevertheless, the visualization was better received than the *Safety Bubble*. The study participants liked the additional information the *Trajectory* gave them and felt more confident while using the system. However, there are ways to improve the *Trajectory*. Making it more responsive to the actual movement of the robot, for example, or mixing it up with the dynamic visualization approach of the *Safety Bubble* and only visualizing the trajectories near the user.

In this chapter, we discussed the results of the study in regard to our research question. Furthermore, we discussed the results in detail for the two visualizations we developed and argued why or why not they have worked. In the next chapter, we will describe the limitations of this thesis.

8 Limitations

In this chapter, we describe the limitations of this work. First, we talk about some general problems that occurred during the creation of this work. Next we will cover the limitations of the implementations of the visualizations. In the end, we discuss the limitations of the study including a focus group and the in-situ HRI experiment.

8.1 General Problems

The time available with the actual robot was limited due to other projects. Further, there were problems reaching the space where the robot was placed, due to construction on the public transportation system. Limited testing with the actual hardware and in the actual space reduced the number of design iterations for the visualizations, which could have improved the study results. With a general interest in virtual reality (VR) and the extended effort to build and deploy implementations to AR, the authors wanted to conduct the study in VR as well. However, the time was too short in the end and it was not possible to conduct the study in VR.

8.2 Implementation Limitations

The visualization *Safety Bubble* did not work correctly. The first problem was the definition of a safe space. It was decided, that in a real production setting it should be at 1.5 meters for the movements of the next three tasks the robot has to do. The resulting zone where the bubble would be active was basically the whole space and the visualization would be present at all times. This arrow should have been placed in the line of sight of the human user at all times and not at the point where the danger zone begins. The field of view of the Hololens is actually very small which decreases the effectiveness of different visualizations drastically. A lot of head movement is required to see the whole visualization. Through the Hololens, the *Safety Bubble* was not recognizable at all, as many participants mentioned, it only looked like a red filter overlayed on the scene, but did not provide the human user any new information. The arrow indicating where to go in case of danger was not even noticed most of the time. Lastly, the movement of the robot was preprogrammed and the visualizations fixed to the different recorded tasks which makes the adaptation to different situations quite difficult in the moment. Future systems should be more dynamic in the generation of visualizations.

8.3 Study Limitations

The number of participants in the study was small, only twelve participants took part, hence all results have to be looked at cautiously. The participants were all recruited from the university and therefore the results might be biased, and the workers that interact with the robot in the real world might have different opinions on the topic. Some participants mentioned that they did not trust the robot as much as the human behind it. The place where the study took place was really open and there was a lot of interaction between the participants and the people who conducted the study, many of the participants were familiar with them before the study and thus already had a high level of trust. It was necessary to find a balance between the number of conditions and the amount of time a participant needed to take part in the study, because of the limited time with the robots. For this reason, we could only test the two visualizations, safety space, and trajectory, separately, with a condition without any visualization as a baseline. There was no time to test combinations of the two visualization or other visualizations such as safety areas or a color-coded version of the other visualizations-

Despite the limitations we conducted a focus group, developed novel visualizations, and evaluated them in a user study. The problems we encountered will be valuable lessons for the future. In the next chapter, we will give a short overview of everything we have done in this work.

9 Conclusion

In this thesis, we give an overview of the current state of the research in HRI. With many different robot shapes, sizes, and goals there are many open research questions to be answered. One of these is the task of integrating AR into the interaction between humans and robots. We showed that there are different ways in which AR can be integrated within HRI and explained the taxonomy by Suzuki et al. [28], which can be used as a design space for new visualizations. Further, we looked at the current state-of-the-art in trust measurement for HRI. There we explain the HCTS and HRITS, the trust scales we adopted for our user study. With the gathered information we invited some experts for a focus group. In this brainstorming session, we developed novel visualization to increase trust in HRI with big industrial robot arms. Additionally, we extracted some design recommendations from the focus group that one should keep in mind while developing such visualizations. These design recommendations are to keep the *point of reference* clearly in mind, *avoid visual clutter*, *use time-sensitive visualizations*, and *get the attention* of the users. Next, we presented the two visualizations we implemented in Unity following the suggestions of the focus group, namely the *Trajectory* and the *Safety Bubble*. The *Trajectory* visualization shows where each joint will move during the next tasks and is fixed to the robot. This is only a passive visualization with no regard for the position of the user. The *Safety Bubble* is centered around the user, in the form of a transparent red sphere that turns visible when the user moves too close to the robot or its immediate future positions, complemented by an arrow that indicates the shortest way towards a safe area. We tested the two visualizations in a user study and compared them with the baseline, which was using no additional visualization. Twelve participants took part in the study and provided feedback through questionnaires. We used the raw Nasa-TLX, SUS, and a modified HCTS as questionnaires. The results showed no significant effect of the visualizations for any of the questionnaires, but in their written feedback multiple participants showed interest in the visualizations and gave tips on how to improve them. The analysis of the study is complemented by a discussion of the limitations. In the last Chapter 10 we talk about future studies and research questions that emerged from this work.

10 Future Work

As discussed in the chapters before, this work tested novel visualizations for industrial HRI using AR and investigated if they could help improve the trust towards the robot in use. While the results of the study have shown no significant effect of the visualizations on any measured variable, the participants were intrigued by the idea of the two visualizations. Considering the comments received during the focus group and the feedback received by the study participants, there are multiple topics that could be investigated in the future.

Many of the participants in the study showed an interest in the visualizations and wanted to test them if they were reiterated. The *Trajectory* has multiple open questions which could be investigated. For the study, an abstract representation of the robot has been chosen with an arbitrary color code. While there are studies for cobots that investigate the design of trajectory visualizations [9], there might be a difference while working with large industrial robotic arms. The same is true for the question of how much of the trajectory will be shown.

In this work, the movement of the robot was preprogrammed and the robot did not deviate from the given path and the visualizations did not need to adjust. If the robot would deviate from the trajectory, this could lead to distrust instead of an increase in trust.

The *Saftey Bubble* needs more design iterations to become usable. For example, one could investigate a color coding for different levels of danger similar to Krauter et al. [18]. Furthermore, it can be investigated what the actual safe distance is and how much of the robot's future movement should be considered. The placement, direction, and design of the arrow that shows the path to safety need to be validated as well. There could be more variations of the visualizations and possible combinations of them all. Further interviews with experts could give valuable insight into the design of a trust-increasing visualization. Further studies with reiterated visualizations and more participants could reveal a trend.

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All links were last followed on July 18, 2023.

A Kurzzusammenfassung

“Können wir einem Roboter vertrauen?” ist eine Frage, die durch das ständige Entwickeln neuer Roboter und Interaktionstechnologien immer relevanter wird. Es ist wichtig, dass wir in ein einfaches autonomes System vertrauen können, wie zum Beispiel in eine Wettervorhersage für die Flugkontrolle. Wenn hier eine Warnung ignoriert wird, kann das desaströse Folgen haben: in Flugzeug könnte abstürzen. Vertrauen in der Mensch-Roboter-Interaktion ist ein großes Forschungsgebiet. Wir möchten zu diesem Forschungsgebiet beitragen, indem wir untersuchen, ob wir mit Hilfe von Visualisierungen das Vertrauen in Mensch-Roboter-Interaktionen mit industriellen Roboterarmen erhöhen können. Wir besprechen aktuelle Veröffentlichungen und deren Ergebnisse für die Bereiche Mensch-Roboter-Interaktion und Visualisierungen für Augmented Reality genauso wie die Forschung in das Vertrauen in Mensch-Roboter-Interaktion und die Erforschung der Nutzung diverser Daten zur Visualisierung für Augmented Reality. Mit Hilfe einer Expertengruppe haben wir neuartige Visualisierungen entwickelt und können Designvorschläge für die Entwicklung von Visualisierungen für große industrielle Roboterarme geben. Zwei der Visualisierungen wurden implementiert und mit Hilfe einer Nutzerstudie getestet. Die Ergebnisse zeigen keinen signifikanten Effekt der Visualisierungen auf eine der beobachteten Variablen, aber das zusätzliche Feedback der Studienteilnehmer in Textform zeigt ein großes Interesse an der Weiterentwicklung der Visualisierungen. Es ist also Potential vorhanden um die Visualisierungen und damit die Interaktion und das Vertrauen, in den Roboter zu verbessern.

B Focus Group

Focus Group - Increasing trust in Human-Robot Interaction through Data Visualization in Augmented Reality

This is the form for participating in the focus group for the master thesis "Increasing trust in Human-Robot Interaction through Data Visualization in Augmented Reality" from Jonas Vogelsang.
If you have any further questions, you can ask them to: Jonas.A.S.Vogelsang@gmail.com

* Gibt eine erforderliche Frage an

1. What is your gender? *

Markieren Sie nur ein Oval.

- Male
- Female
- Prefer not to say
- Sonstiges: ____________

2. How old are you? *

____

3. What is your nationality? *

____

4. What is your profession?

____

5. How experienced are you with robotics? *

Markieren Sie nur ein Oval.

no experience
1 ◯
2 ◯
3 ◯
4 ◯
5 ◯
highly experienced

6. How experienced are you with Augmented Reality?

Markieren Sie nur ein Oval.

no experience
1 ◯
2 ◯
3 ◯
4 ◯
5 ◯
highly experienced

7. I have read and confirmed the consent form and the privacy information *

Wählen Sie alle zutreffenden Antworten aus.

- [ ] Yes
- [ ] No

Privacy Information (Article 13 DS-GVO)

Regarding the collection of data in the focus group „Increasing trust in human-robot interaction through data visualization in augmented reality " of the Visualization Research Center of the University of Stuttgart (VISUS)

Responsible body under data protection laws
University of Stuttgart
Keplerstraße 7
70174 Stuttgart
Germany
Phone: +49 711/685-0
E-Mail: poststelle@uni-stuttgart.de

Data protection officer
University of Stuttgart
Data protection officer
Breitscheidstr. 2
70174 Stuttgart
Tel: +49 711 685-83687
Fax: +49 711 685-83688
E-Mail: datenschutz@uni-stuttgart.de

Used and collected data

In the study we collect:

- The data from the respective questionnaires
- Video recording of the discussion

Besides the data explicitly asked for in the survey, there will be data collected which is needed by the web servers of the university. For further information see here.
https://www.uni-stuttgart.de/en/privacy-notice/

Usage Purpose of the Collected Data

- Conduction of the survey as part of a research project

At VISUS we are doing research regarding the development and design of visualizations, as well as Virtual and Augment Reality (VR and AR) applications. The focus group „Increasing trust in human-robot interaction through data visualization in augmented reality" wants to investigate novel visualizations in AR that can help collaborative tasks with an industrial robot arm. For the results to be evaluated, the focus group procedure has to be completed. However, **the focus group can be cancelled at any time.** In this case, the incomplete results are deleted during evaluation and not considered further.

Further usage:
Usage of the data in consecutive research projects concerned with Augmented Reality at VISUS.
Usage of the data within the respective publications of the research.

By not agreeing to the data collection there will be no consequences. However, a participation in the study is not possible.

Legal Basis

1. Conduction of the survey as part of a research project

Art. 6 Paragraph. 1 lit. e together Art. 6 Paragraph. 3 Datenschutz-Grundverordnung (DS-GVO) together with § 13 Abs.1 Landesdatenschutzgesetz Baden-Württemberg, Art. 6 Paragraph. 1 lit. c in Verbindung mit §§ 70, 75 Landeshaushaltsordnung.

2 Optional Agreement to further usage
Art. 6 Paragraph. 1 lit. a DS-GVO

Data Recipients

- Evaluated Research Data: Worldwide readers /users of scientific publications.

- Raw Data within a repository: users that have been permitted to use the data within the university and the provider of the repository within the university. For reviewing processes for scientific publications the raw data could be passed to the reviewers and the publisher.

The data above can potentially also be processed outside the EU in countries, where there are no comparable data protection laws. These can mean potential restrictions of your rights.

- For receiving your compensation in cash, you have to sign a receipt and provide your address and full name. The internal accounting of the university will process this receipt.

Based on policies the University archive must be consulted before deletion of data. The archive then decides on whether or not to keep the data.

Duration of the Storage Period

- All research data are stored till 10 years after the completion of a research project.

Potentially, the concerned data will be transferred to the respective university archive, which can store it indefinitely.

Your rights

- You have the right to receive information from the university concerning the data saved in relation to your person and/or to have incorrectly saved data corrected.
- In addition, you have the right to deletion or to have the processing restricted or to object to the processing.

For this purpose, please contact the data protection officer of the University of Stuttgart via Email.

- You have the right to complain to the supervisory authority, should you be of the opinion that the processing of the personal data relating to you breaches legal regulations.

The competent supervisory authority is the State Data Protection and Freedom of Information Officer of Baden-Württemberg - Landesbeauftragte für den Datenschutz und die Informationsfreiheit Baden-Württemberg

Focus Group Description

Description of the Focus Group “Increasing trust in human-robot interaction through data visualization in augmented reality” of the Visualization Research Center of the University of Stuttgart (VISUS)

At VISUS we are doing research regarding the development and design of visualizations, as well as Virtual and Augmented Reality (VR and AR) applications. The focus group **“Increasing trust in human-robot interaction through data visualization in augmented reality**” wants to investigate how visualizations in AR and VR can help collaborative tasks involving humans and industrial robots. **The focus group can be cancelled at any time**.

1. Procedure

- The group will be introduced to the use case and scenario.
- After answering all questions, the group will be split in subgroups.
- In the smaller groups the participants will brainstorm on the topic.
- After a given amount of time the whole group will come together and discuss the results of the brainstorming
- In total, the focus group will take up to 90 minutes.
- The participation will not be rewarded.

2. General Conditions of Participation:

- You are between 18 years and 55 years old.

3. Data Usage and Processing

- The discussion in the end will be recorded, but only be used for transcription.
- Within publications, the data will be provided in an anonymized form.

4. Further usage of the data

The data will only be used in research purposes.

Point of Contact

In case of questions please contact:

Aimee Sousa Calepso
Visualization Research Center of the University of Stuttgart (VISUS)
Allmandring 19
70569 Stuttgart
Germany

E-Mail: aimeee.sousacalepso@visus.uni-stuttgart.de
Phone.: +49 (0) 711 685-88629

Form of Consent

Please read this form carefully. In case of questions, feel free to ask the present researcher.

- I have read the survey description and agree with the concerned data usage and processing.
- The agreement and participation is entirely voluntary. Not participating does not result in any kind of disadvantage.
- **I'm free to cancel the study at any point and thereby withdraw my consent.**
- Withdrawing the consent after completing the study is not possible, as the data from one specific person cannot be identified in retrospect.
- I have read the privacy information and agree to it.
- I have received a copy of the information sheets.

Location, date . . . .

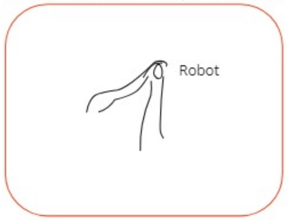
Signature volunteer . . . .

Location, date . . . .

Signature investigator . . . .

Maybe visualize a safe zone?

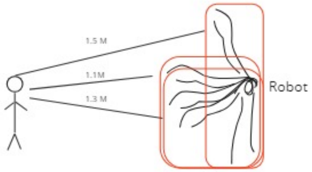
Total area robot can move, "safe" outside



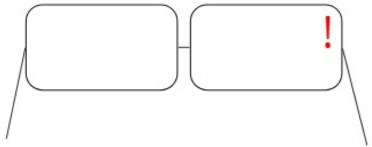
show not the path but the closest distance to the user? maybe dependant on the speed?

maybe combine area it can move in with trajectory vis to show boundaries of next movement(s)

separating visualization (trajectory) from actual movement? Bot at the same time could be dangerous



simple notification before it starts moving, maybe animated.
reduce the chance of being scared by sudden sound or movement



Maybe visualize distance with warning, encode distance or danger level with colors, see "Don't catch it ... "
green zone/ distance all good
yellow zone/ distance no great or sudden movements
red move away/ robot gets stopped?

not only for right now but for the next X movements/ x minutes ....?

Time needed to gain trust
- vis to speed up?
- onboarding?
- maybe training with Video, AR or in VR?
- AR could be best as the transition to using trajectories could carry the trust

Comments/ Discussion:
safety zones computed in advance or live?
- for next 5 minutes it is save here
- contrast to live vis
- right now there are zones for the robot to stop if a human comes close
- what needed for live and close up collaboration with the robot?

No real interaction currently, will it change or stay a workplace safety thing

computer vision to detect what the robot is holding/ working with to include in safety zone/ whatever calculation

Explain what the visualization is actually showing!

Vis only part of the atmosphere:
+ sound
+ motion speed
+ motion linear or not?

decrease speed? Communicate with the robot (to eg decrease speed)

Feedback source = Robot or not? People might only trust feedback directly from the robot or only from another source, i.e. not the robot itself.

kinematic solver black box
- xyz, rotation
- or angles

there is uncertainty

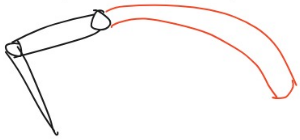
Multiple tears of visualization based on experience confidence?
zones (see left) could change even (probably not the red one)

What about actions of the robot that extend beyond its reach? like carrying a big wooden plank or shotting with a nail gun?

this shoul be included in the visualization

Trust is:
- Safety concerns: regulatory and mental/subjective
- Performance (?): is the robot doing the job correctly?
- Collaborative: are other humans in the environment being safe and doing the task correctly?

Showing the trajectory of the path the robot arm is taking

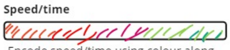


Is the alignment of the arm and trajectory accurate enough to be trustworthy? This is a mostly technological constraint at the moment. Perhaps give a buffer zone around the actual trajectory for safety.

Q: How do we encode speed/time into this trajectory? As for more complex trajectories there may be moments where the human wants/needs to be in the path of the arm for a short period of time.

A: We could use colour to encode either speed/time, or localised temporal distance between the user and the movement path

Speed/time

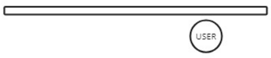


Encode speed/time using colour along the entire trajectory.

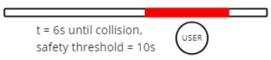
Main downside is that it might be hard to tell when exactly the robot will reach any given point of the trajectory.

Localised temporal distance

Show the entire trajectory using default encodings as a baseline.



When the user moves their body close to the trajectory, the system calculates how long it would be (e.g., in seconds) until there is a potential collision. If this distance is less than a given threshold, the section of the trajectory will light up.



t = 6s until collision,
safety threshold = 10s

Q: How much of the trajectory do we actually show? As showing all of it at once may be confusing/distracting/too cluttered.

A: Show only a portion of the trajectory, in different possible ways:

Transparency

Have the next x seconds of arm movement be opaque, the rest is transparent.

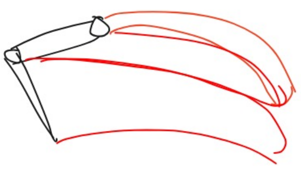
Discrete steps

Only show the next set of movements and not everything. However this is context/task dependent. Up to the designer/roboticist to determine these discrete steps.

User controllable/customisable

Maybe a user interface to control:
- How much of the trajectory to see
- When the trajectory is visible or not
- etc.

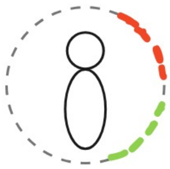
Q: The problem with trajectories is that a robot arm is not a singular path, but is the movement of the entire arm and its joints. How do we visualise that?



Showing a "safety bubble" around the user

If the safety bubble is in the way of the robot arm or any of its joints, the bubble might light up with a specific colour indicating where in the bubble they are overlapping.

This highlighting might also encode/display the duration of time until the overlap occurs.

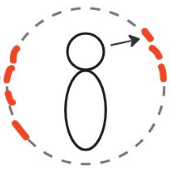


red = get away immediately!!!

green = be cautious, but no need to move yet

This idea is a more "egocentric" approach to this visual warning system, where the information is shown around the user. The other idea of the trajectories is a more "exocentric" approach where the user looks inwards into a visualisation of the arm movement.

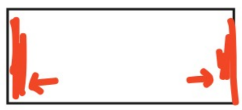
Q: What happens when the danger sign of the bubble is behind the human?



Path to safety

Maybe show a path on the floor or an arrow indicating where the human needs to walk to in order to get to safety.

Edge highlighting along field of view



Either colours or arrows maybe?

Q: What if there's multiple intrusions into the bubble?

Have failsafes when there is going to be a collision (but this is not really visualisation).

Aggregation???

C User Study

Increasing trust in Human-Robot Interaction through Data Visualization in Augmented Reality

There are 29 questions in this survey.

Demographic questions

What is your gender?

❗ Choose one of the following answers

Please choose **only one** of the following:

- ◯ Male
- ◯ Female
- ◯ Other [ ]

This is a question help text.

How old are you? *

❗ Only numbers may be entered in this field.

Please write your answer here:

[ ]

What is your nationality? *

Please write your answer here:

[ ]

What is your profession? *

Please write your answer here:

How experienced are you with robotics? *

Please choose **only one** of the following:

- ◯ 1
- ◯ 2
- ◯ 3
- ◯ 4
- ◯ 5

How experienced are you using Augmented Reality? *

Please choose **only one** of the following:

- ◯ 1
- ◯ 2
- ◯ 3
- ◯ 4
- ◯ 5

Please Enter the self generated ID: *

Please write your answer here:

Condition 0

Condition *

Only numbers may be entered in this field.

Please write your answer here:

I trusted the robot during the execution of the tasks. (From 0 = trust totally to 5 = no trust at all) *

Please choose **only one** of the following:

- 1
- 2
- 3
- 4
- 5

I felt safe while executing the tasks. (from 0 = not safe at all, to 5 = totally safe) *

Please choose **only one** of the following:

- 1
- 2
- 3
- 4
- 5

System Usability Scale
Please rate how you feel about the following statements from 0 = Strongly Agree, to 5 = Strongly Disagree *

Please choose the appropriate response for each item:

	1	2	3	4	5
I think that I would like to use this system frequently.	○	○	○	○	○
I found the system unnecessarily complex.	○	○	○	○	○
I thought the system was easy to use.	○	○	○	○	○
I think that I would need the support of a technical person to be able to use this system.	○	○	○	○	○
I found the various functions in this system were well integrated.	○	○	○	○	○
I thought there was too much inconsistency in this system.	○	○	○	○	○
I would imagine that most people would learn to use this system very quickly.	○	○	○	○	○
I found the system very cumbersome to use.	○	○	○	○	○
I felt very confident using the system.	○	○	○	○	○
I needed to learn a lot of things before I could get going with this system.	○	○	○	○	○

Human-Computer Trust Scale
Please rate how you feel about the following statements from 0 = Strongly Agree, to 5 = Strongly Disagree *

Please choose the appropriate response for each item:

	1	2	3	4	5
I believe that there could be negative consequences when using the robot system.	○	○	○	○	○
I feel I must be cautious when using the robot system.	○	○	○	○	○
It is risky to interact with the robot system	○	○	○	○	○
I believe that the robot system will act in my best interest	○	○	○	○	○
I believe that the robot system will do its best to help me if I need help	○	○	○	○	○
I believe that the robot system is interested in under- standing my needs and preferences	○	○	○	○	○
I think that robot system is competent and effective in assisting my task.	○	○	○	○	○
I think that the robot system performs its role as assistent very well	○	○	○	○	○

	1	2	3	4	5
I believe that the robot system has all the functionalities I would expect from	◯	◯	◯	◯	◯
When sharing something with the robot system I believe that I will get a response	◯	◯	◯	◯	◯
When sharing something with the robot system, I expect to get back a meaningful & knowledgeable response	◯	◯	◯	◯	◯

Nasa TLX

Please rate how you feel about the questions, from very low(0) to very high(20).

*

Please choose the appropriate response for each item:

	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Mental Demand - How mentally demanding was the task?	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○
Physical Demand - How physically demanding was the task?	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○
Temporal Demand - How hurried or rushed was the pace of the task?	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○
Performance - How successful were you in accomplishing what you were asked to do?	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○
Effort - How hard did you have to work to accomplish your level of performance?	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○
Frustration - How insecure, discouraged, irritated, stressed, and annoyed wereyou?	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○

If you have any feedback, comments or remarks, please share them here:

Please write your answer here:

Condition 1

Condition *

Only numbers may be entered in this field.

Please write your answer here:

I trusted the robot during the execution of the tasks.
(From 0 = trust totally to 5 = no trust at all) *

Please choose **only one** of the following:

- 1
- 2
- 3
- 4
- 5

I felt safe while executing the tasks. (from 0 = not safe at all, to 5 = totally safe)

*

Please choose **only one** of the following:

- ◯ 1
- ◯ 2
- ◯ 3
- ◯ 4
- ◯ 5

System Usability Scale Please rate how you feel about the following statements from 0 = Strongly Agree, to 5 = Strongly Disagree *

Please choose the appropriate response for each item:

	1	2	3	4	5
I think that I would like to use this system frequently.	○	○	○	○	○
I found the system unnecessarily complex.	○	○	○	○	○
I thought the system was easy to use.	○	○	○	○	○
I think that I would need the support of a technical person to be able to use this system.	○	○	○	○	○
I found the various functions in this system were well integrated.	○	○	○	○	○
I thought there was too much inconsistency in this system.	○	○	○	○	○
I would imagine that most people would learn to use this system very quickly.	○	○	○	○	○
I found the system very cumbersome to use.	○	○	○	○	○
I felt very confident using the system.	○	○	○	○	○
I needed to learn a lot of things before I could get going with this system.	○	○	○	○	○

Human-Computer Trust Scale Please rate how you feel about the following statements from 0 = Strongly Agree, to 5 = Strongly Disagree *

Please choose the appropriate response for each item:

	1	2	3	4	5
I believe that there could be negative consequences when using the robot system.	○	○	○	○	○
I feel I must be cautious when using the robot system.	○	○	○	○	○
It is risky to interact with the robot system	○	○	○	○	○
I believe that the robot system will act in my best interest	○	○	○	○	○
I believe that the robot system will do its best to help me if I need help	○	○	○	○	○
I believe that the robot system is interested in under- standing my needs and preferences	○	○	○	○	○
I think that robot system is competent and effective in assisting my task.	○	○	○	○	○
I think that the robot system performs its role as assistent very well	○	○	○	○	○

	1	2	3	4	5
I believe that the robot system has all the functionalities I would expect from	◯	◯	◯	◯	◯
When sharing something with the robot system I believe that I will get a response	◯	◯	◯	◯	◯
When sharing something with the robot system, I expect to get back a meaningful & knowledgeable response	◯	◯	◯	◯	◯

Nasa TLX

Please rate how you feel about the questions, from very (0) low to very high(20).

*

Please choose the appropriate response for each item:

	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Mental Demand - How mentally demanding was the task?	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○
Physical Demand - How physically demanding was the task?	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○
Temporal Demand - How hurried or rushed was the pace of the task?	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○
Performance - How successful were you in accomplishing what you were asked to do?	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○
Effort - How hard did you have to work to accomplish your level of performance?	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○
Frustration - How insecure, discouraged, irritated, stressed, and annoyed wereyou?	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○

If you have any feedback, comments or remarks, please share them here:

Please write your answer here:

Condition 2

Condition *

Only numbers may be entered in this field.

Please write your answer here:

I trusted the robot during the execution of the tasks.
(From 0 = trust totally to 5 = no trust at all) *

Please choose **only one** of the following:

- 1
- 2
- 3
- 4
- 5

I felt safe while executing the tasks.
(from 0 = not safe at all, to 5 = totally safe)
*

Please choose **only one** of the following:

- ◯ 1
- ◯ 2
- ◯ 3
- ◯ 4
- ◯ 5

System Usability Scale Please rate how you feel about the following statements from 0 = Strongly Agree, to 5 = Strongly Disagree *

Please choose the appropriate response for each item:

	1	2	3	4	5
I think that I would like to use this system frequently.	○	○	○	○	○
I found the system unnecessarily complex.	○	○	○	○	○
I thought the system was easy to use.	○	○	○	○	○
I think that I would need the support of a technical person to be able to use this system.	○	○	○	○	○
I found the various functions in this system were well integrated.	○	○	○	○	○
I thought there was too much inconsistency in this system.	○	○	○	○	○
I would imagine that most people would learn to use this system very quickly.	○	○	○	○	○
I found the system very cumbersome to use.	○	○	○	○	○
I felt very confident using the system.	○	○	○	○	○
I needed to learn a lot of things before I could get going with this system.	○	○	○	○	○

Human-Computer Trust Scale Please rate how you feel about the following statements from 0 = Strongly Agree, to 5 = Strongly Disagree *

Please choose the appropriate response for each item:

	1	2	3	4	5
I believe that there could be negative consequences when using the robot system.	○	○	○	○	○
I feel I must be cautious when using the robot system.	○	○	○	○	○
It is risky to interact with the robot system	○	○	○	○	○
I believe that the robot system will act in my best interest	○	○	○	○	○
I believe that the robot system will do its best to help me if I need help	○	○	○	○	○
I believe that the robot system is interested in under- standing my needs and preferences	○	○	○	○	○
I think that robot system is competent and effective in assisting my task.	○	○	○	○	○
I think that the robot system performs its role as assistent very well	○	○	○	○	○

	1	2	3	4	5
I believe that the robot system has all the functionalities I would expect from	◯	◯	◯	◯	◯
When sharing something with the robot system I believe that I will get a response	◯	◯	◯	◯	◯
When sharing something with the robot system, I expect to get back a meaningful & knowledgeable response	◯	◯	◯	◯	◯

Nasa TLX

Please rate how you feel about the questions, from very low(0) to very high.(0)

*

Please choose the appropriate response for each item:

	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Mental Demand - How mentally demanding was the task?	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○
Physical Demand - How physically demanding was the task?	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○
Temporal Demand - How hurried or rushed was the pace of the task?	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○
Performance - How successful were you in accomplishing what you were asked to do?	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○
Effort - How hard did you have to work to accomplish your level of performance?	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○
Frustration - How insecure, discouraged, irritated, stressed, and annoyed wereyou?	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○

If you have any feedback, comments or remarks, please share them here:

Please write your answer here:

Feedback

Do you have any more Feedback?

Please write your answer here:

07-17-2023 – 09:20

Submit your survey.

Thank you for completing this survey.

Privacy Information (Article 13 DS-GVO)

Regarding the collection of data in the study „ Increasing trust in Human-Robot Interaction through Data Visualization in Augmented Reality **“ of the Visualization Research Center of the University of Stuttgart (VISUS)**

Responsible body under data protection laws
University of Stuttgart
Keplerstraße 7
70174 Stuttgart
Germany
Phone: +49 711/685-0
E-Mail: poststelle@uni-stuttgart.de

Data protection officer
University of Stuttgart
Data protection officer
Breitscheidstr. 2
70174 Stuttgart
Tel: +49 711 685-83687
Fax: +49 711 685-83688
E-Mail: datenschutz@uni-stuttgart.de

Used and collected data

In the study we collect:
- The data from the respective questionnaires
- Data concerning the motions you make in the study tasks
- Video recording

Besides the data explicitly asked for in the survey, there will be data collected which is needed by the web servers of the university. For further information see here. https://www.uni-stuttgart.de/en/privacy-notice/

Usage Purpose of the Collected Data

- Conduction of the survey as part of a research project

At VISUS we are doing research regarding the development and design of visualizations, as well as Virtual and Augment Reality (VR and AR) applications. The study „ Increasing trust in Human-Robot Interaction through Data Visualization in Augmented Reality “ wants to investigate how visualization in AR can increase the trust towards an industrial robotic arm during collaborative tasks involving a human and a robot. For the results to be evaluated, the study procedure has to be completed. However, **the study can be cancelled at any time.** In this case, the incomplete results are deleted during evaluation and not considered further.

Further usage:
Usage of the data in consecutive research projects concerned with Augmented Reality at VISUS.

Usage of the data within the respective publications of the research.

By not agreeing to the data collection there will be no consequences. However, a participation in the study is not possible.

Legal Basis

1. Conduction of the survey as part of a research project

Art. 6 Paragraph. 1 lit. e together Art. 6 Paragraph. 3 Datenschutz-Grundverordnung (DS-GVO) together with § 13 Abs.1 Landesdatenschutzgesetz Baden-Württemberg, Art. 6 Paragraph. 1 lit. c in Verbindung mit §§ 70, 75 Landeshaushaltsordnung.

2 Optional Agreement to further usage
Art. 6 Paragraph. 1 lit. a DS-GVO

Data Recipients

- Evaluated Research Data: Worldwide readers /users of scientific publications.

- Raw Data within a repository: users that have been permitted to use the data within the university and the provider of the repository within the university. For reviewing processes for scientific publications the raw data could be passed to the reviewers and the publisher.

The data above can potentially also be processed outside the EU in countries, where there are no comparable data protection laws. These can mean potential restrictions of your rights.

- For receiving your compensation in cash, you have to sign a receipt and provide your address and full name. The internal accounting of the university will process this receipt.

Based on policies the University archive must be consulted before deletion of data. The archive then decides on whether or not to keep the data.

Duration of the Storage Period

- All research data are stored till 10 years after the completion of a research project.

Potentially, the concerned data will be transferred to the respective university archive, which can store it indefinitely.

Your rights

- You have the right to receive information from the university concerning the data saved in relation to your person and/or to have incorrectly saved data corrected.
- In addition, you have the right to deletion or to have the processing restricted or to object to the processing.

For this purpose, please contact the data protection officer of the University of Stuttgart via Email.

- You have the right to complain to the supervisory authority, should you be of the opinion that the processing of the personal data relating to you breaches legal regulations.

The competent supervisory authority is the State Data Protection and Freedom of Information Officer of Baden-Württemberg - Landesbeauftragte für den Datenschutz und die Informationsfreiheit Baden-Württemberg

Study Description

Description of the study "Increasing trust in Human-Robot Interaction through Data Visualization in Augmented Reality" of the Visualization Research Center of the University of Stuttgart (VISUS)

At VISUS we are doing research regarding the development and design of visualizations, as well as Virtual and Augmented Reality (VR and AR) applications. The study **Increasing trust in Human-Robot Interaction through Data Visualization in Augmented Reality"** wants to investigate how visualizations in AR and VR can help collaborative tasks involving humans and industrial robots. For the results to be evaluated, the study procedure has to be completed. **However, the study can be canceled at any time**. In this case, the incomplete results are deleted during evaluation and not considered further.

1. Procedure

- Before the task starts, you will be asked to fill a demographic form regarding yourself and experience with the technology used.
- Then you will put on the Microsoft Hololens 2 and get a short introduction to the device.
- Afterwards you will conduct simple tasks which involve carrying an object around the robotic arm and doing some drawing.
- This will be repeated three times. In each turn you will see a different visualization in the Hololens.
- After each trial is over, you will be asked to fill a questionnaire regarding your experience with the task.
- In total, the study will take up to 45 minutes.
- The study will be compensated with 12€ if you are not a university employee. You have to sign a receipt with your address and your name to get the payment.

2. General Conditions of Participation:

- You have no visual impairment (short or long-sightedness not included)
- You have no physical injury that impairs your movement.
- You are older 18 years old.

3. Data Usage and Processing

- Each questionnaire and recorded movement will be linked to a self-generated personal code to map the results together.
- We will record the data that you fill in the questionnaire, and we might also record video and image data of you doing the tasks. They will be used only for internal analysis and will not be used in publications.
- On the receipt you have to sign for your compensation, there will be no ID, so that the research data cannot be mapped to your person.

- Within publications, the data will be provided in an anonymized form.

4. Further usage of the data

The data will only be used in research purposes.

Point of Contact

In case of questions please contact:

Aimee Sousa Calepso
Visualization Research Center of the University of Stuttgart (VISUS)
Allmandring 19
70569 Stuttgart
Germany
E-Mail: aimeee.sousacalepso@visus.uni-stuttgart.de
Phone.: +49 (0) 711 685-88629

Form of Consent

Please read this form carefully. In case of questions, feel free to ask the present researcher.

- I have read the survey description and agree with the concerned data usage and processing.
- The agreement and participation is entirely voluntary. Not participating does not result in any kind of disadvantage.
- **I'm free to cancel the study at any point and thereby withdraw my consent.**
- Withdrawing the consent after completing the study is not possible, as the data from one specific person cannot be identified in retrospect.
- I have read the privacy information and agree to it.
- I have received a copy of the information sheets.

Location, date . . . .   Signature volunteer . . . .

Location, date . . . .   Signature investigator . . . .

Declaration

I hereby declare that the work presented in this thesis is entirely my own. I did not use any other sources and references than the listed ones. I have marked all direct or indirect statements from other sources contained therein as quotations. Neither this work nor significant parts of it were part of another examination procedure. I have not published this work in whole or in part before. The electronic copy is consistent with all submitted hard copies.

place, date, signature