Dissertation

Meet Your Robotic Work Colleague: Exploring Human-Robot Collaboration in a Virtual Reality based Research Platform

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Abstract

Autonomous robots, capable of collaborating with humans could benefit industrial production by supporting personnel in domains with tedious, repetitive, and dangerous tasks. To make this vision reality, Human-Robot Collaboration (HRC) has established itself as a research field. HRC researchers identified multiple challenges regarding the technical implementation such as enabling the robot to act autonomously, as well as human factors aspects, e.g., expectation conformity. These challenges prevent current realizations of industrial processes involving the collaboration between humans and robots to reach their full potential. Due to the variety of robot representations and shared task requirements, extensive research is needed to develop solutions to overcome these challenges. However, confronting these challenges in empirical studies is restricted due to safety concerns as exposing participants to prototypical implementations of robot collaboration setups either in full contact or close proximity can provoke hazardous situations.

To address this problem, this research presented here proposes a virtual reality (VR) application, where new concepts for HRC configurations can be explored and tested without causing harm to participants. Due to the nature of VR, the application can function as a sandbox, where a wide range of HRC settings can be portrayed without the need for expensive and elaborate setups involving real robots. The design and functionality of the VR application were developed in accordance with the state-of-the-art HRC research literature, established statutory norms, and remarks from industry representatives. The VR application offers several features, such as the implementation of machine learning agents in conjunction with an inverse kinematic system that allows the virtual representation of an autonomous robot to collaborate with a human participant on a designated shared task.

The versatility of the VR application allows for the creation of multiple forms of stimulus materials depending on the requirements of the study, ranging from interactive setups, where participants collaborated with the robot within the virtual environment, and passive media, such as videos and images. Additionally, every parameter within the virtual environment can be adjusted to fit the targeted scenario. By using this VR application, a series of three experimental studies with 80 participants addressed the challenges of HRC by exploring various effects of augmenting an autonomous robot with communication in collaboration scenarios. In addition, two qualitative studies were conducted to complement the research on positive and negative impressions of the robot. Considering that communication is a substantial contributor to the success of collaboration among humans, it is assumed that it benefits HRC as well. However, research is still open to finding an effective arrangement, due

to the countless variations of HRC setups that are difficult to recreate in a lab environment. In addition to the effect of the communication, derived from the challenges of HRC selected human factors variables, such as perceived stress as well as the overall perception of the robot as an intelligent system, were collected due to their potential to affect the collaboration process. To complement the subjective data from the questionnaire, the VR application collected objective data, e.g., the collision frequency and production quantity to investigate the safety and task allocation challenges of HRC.

The qualitative and quantitative results from the conducted empirical studies in this dissertation revealed several benefits regarding the usage of communication in HRC scenarios. The communication of contextual information in form of guidance for the shared task and explanation of the robot's actions, among other aspects, reduced the perceived stress, improved the overall perception of the robot, and induced the impression of the robot as an intelligent system.

While these studies merely confronted a fraction of the vast challenges of HRC, the results provide a foundation for future design decisions regarding the implementation of industrial HRC scenarios involving autonomous robots. In addition to the results of the empirical studies, a key contribution of this work is the VR application that can be used as a tool to investigate a wide variety of HRC scenarios. The VR application itself provides a platform that can be continuously expanded and used for future studies exploring HRC concepts difficult to evaluate otherwise. Through this VR application, the goal is to contribute to the efforts of the HRC research community to develop a common methodology for the collaboration between humans and robots in industrial environments.

Zusammenfassung

Autonom agierende Roboter, welche in der Lage sind, mit Menschen zusammenzuarbeiten, können die industrielle Produktion bereichern, indem sie das Personal bei mühsamen, sich wiederholenden und gefährlichen Aufgaben unterstützen. Um diese Vision Wirklichkeit werden zu lassen, hat sich die Mensch-Roboter-Kollaboration (MRK) als Forschungsgebiet etabliert. MRK-Forscherinnen und Forscher haben hierbei zahlreiche Herausforderungen bezüglich der technischen Umsetzung identifiziert, z. B. wie man einen Roboter befähigt, autonom zu handeln. Weitere Herausforderungen betreffen Aspekte menschlicher Faktoren (Human Factors), wie beispielsweise die Erwartungskonformität. Diese Herausforderungen verhindern derzeit, dass Industrieprozesse, in denen die Kollaboration zwischen Menschen und Robotern eingesetzt werden, ihr volles Potenzial ausschöpfen. Aufgrund der Vielfalt an Repräsentationen von Robotern und Kollaborativ-Aufgaben, welche durch MRK getätigt werden können, besteht ein hoher Forschungsbedarf, um Lösungen zur Bewältigung dieser Herausforderungen zu entwickeln. Die Entwicklung von Lösungen für diese Herausforderungen wird jedoch durch sicherheitsbedingte Restriktionen bei empirischen Studien eingeschränkt. Durch den direkten oder unmittelbaren Kontakt von prototypischen Umsetzungen von Roboter-Kollaborationsaufbauten mit Probandinnen und Probanden ergibt sich für diese ein nicht zu unterschätzendes Gefahrenpotenzial.

Um dieses Problem anzugehen, wird in der hier vorgestellten Forschungsarbeit eine Virtual Reality (VR) Anwendung präsentiert, mit der neue Konzepte für MRK-Konfigurationen erforscht und getestet werden können, ohne Probandinnen und Probanden einer Gefahr auszusetzen. Durch die Eigenschaften virtueller Realität kann die Anwendung als sogenannte "Sandbox" fungieren, in der ein breites Spektrum an MRK-Konstellationen dargestellt werden können, ohne dass teure und aufwendige Aufbauten mit echten Robotern erforderlich sind. Die Gestaltung und die Funktionalitäten der VR-Anwendung wurden in Übereinstimmung mit dem neuesten Stand der MRK-zentrierten Forschungsliteratur, etablierten gesetzlichen Normen und Befragungen von Industrievertreterinnen und Vertretern entwickelt. Hierdurch bietet die VR-Anwendung mehrere Funktionen, wie z. B. die Implementierung von Software-Agenten für den Einsatz von maschinellem Lernen. In Verbindung mit der integrierten inversen Kinematik ermöglicht diese, dass die virtuelle Darstellung des Roboters mit den menschlichen Probandinnen und Probanden eine Kollaborativ-Aufgabe tätigt.

Die Vielseitigkeit der VR-Anwendung ermöglicht je nach Anforderungen der Studie die Erstellung verschiedener Formen von Stimulus-Materialien. Angefangen bei interaktiven Szenarien, in denen Probandinnen und Probanden innerhalb der virtuellen Umgebung mit

dem Roboter zusammenarbeiten, bis hin zu passiven Medien wie Videos und Abbildungen. Darüber hinaus kann jeder Parameter innerhalb der virtuellen Umgebung an das gewünschte Szenario angepasst werden.

Diese VR-Anwendung wurde eingesetzt bei einer Reihe von drei Experimentalstudien mit jeweils 80 Probandinnen und Probanden, ergänzt durch zwei qualitative Studien. Abgeleitet von den Herausforderungen der MRK, untersuchten die Studien, welche Auswirkungen der Einsatz von Kommunikation in Kollaborationsszenarien mit autonom agierenden Robotern nach sich zieht. In Anbetracht der Tatsache, dass Kommunikation einen wesentlichen Faktor zum Erfolg der Kollaboration zwischen Menschen darstellt, ist davon auszugehen, dass diese auch für die Mensch-Roboter-Kollaboration von Vorteil ist. Aufgrund der zahllosen Variationen von MRK-Konfigurationen, die in einer Laborumgebung nur schwer nachgebildet werden können, ist die Erforschung jedoch nur bedingt möglich, um eine effektive Gestaltung zu untersuchen. Zusätzlich zur Kommunikation wurden, abgeleitet von den Herausforderungen der MRK, ausgewählte menschliche Faktoren wie wahrgenommener Stress sowie die allgemeine Wahrnehmung des Roboters als intelligentes System erhoben, da diese den Kollaborationsprozess beeinflussen können. Zur Ergänzung der subjektiven Daten aus dem Fragebogen erhob die VR-Anwendung zusätzlich objektive Daten, wie z. B. die Kollisionshäufigkeit und die Produktionsmenge, um die Herausforderungen der Sicherheit und der Aufgabenverteilung in einem MRK-Arbeitsprozess zu untersuchen. Die qualitativen und quantitativen Ergebnisse, welche in den empirischen Studien dieser Dissertation durchgeführt worden sind, zeigten mehrere Vorteile in Bezug auf den Einsatz von Kommunikation in MRK-Szenarien. Die Vermittlung von kontextsensitiven Informationen in Form von Hilfestellungen für die gemeinsame Aufgabe und Erklärungen, welche die Handlungen des Roboters erläuterten, verringerte unter anderem den empfundenen Stress. Darüber hinaus verbesserten diese die Gesamtwahrnehmung des Roboters und vermittelten den Eindruck, dass der Roboter ein intelligentes System ist.

Obwohl diese Studien nur einen Bruchteil der enormen Herausforderungen der MRK abdecken, bieten die Ergebnisse eine Grundlage für zukünftige Gestaltungsentscheidungen hinsichtlich der Implementierung von industriellen MRK-Szenarien mit autonomen Robotern. Neben den Ergebnissen der empirischen Studien ist ein wesentlicher Beitrag dieser Arbeit die VR-Anwendung, die als Werkzeug zur Untersuchung einer Vielzahl von MRK-Szenarien verwendet werden kann. Die VR-Anwendung selbst bietet eine Plattform, die kontinuierlich erweitert und für künftige Studien genutzt werden kann, in denen MRK-Konzepte erforscht werden können, die in herkömmlichen Laborstudien nur sehr schwer zu untersuchen sind. Ziel ist es, durch diese VR-Anwendung einen Beitrag zu den Bemühungen der MRK-Forschungsgemeinschaft zu leisten und eine gemeinsame Methodik für die Zusammenarbeit zwischen Menschen und Robotern in industriellen Umgebungen zu entwickeln.

List of Included Publications

Chapter 2
A. Arntz and S. C. Eimler, “Experiencing AI in VR: A Qualitative Study on Designing a Human-Machine Collaboration Scenario,” in *HCI International 2020 – Late Breaking Posters,* ser. Communications in Computer and Information Science, C. Stephanidis, M. Antona, and S. Ntoa, Eds. Cham: Springer International Publishing, 2020, vol. 1293, pp. 299–307.

Chapter 3
A. Arntz, S. C. Eimler, and H. U. Hoppe, “Augmenting the Human-Robot Communication Channel in Shared Task Environments,” in *Collaboration Technologies and Social Computing,* ser. Lecture Notes in Computer Science, A. Nolte, C. Alvarez, R. Hishiyama, I.-A. Chounta, M. J. Rodríguez-Triana, and T. Inoue, Eds. Cham: Springer International Publishing, 2020, vol. 12324, pp. 20–34.

Chapter 4
A. Arntz, S. C. Eimler, and H. U. Hoppe, ““The Robot-Arm Talks Back to Me” - Human Perception of Augmented Human-Robot Collaboration in Virtual Reality,” in *2020 IEEE International Conference on Artificial Intelligence and Virtual Reality (AIVR).* IEEE, 2020, pp. 307–312.

Chapter 5
A. Arntz, S. C. Eimler, C. Straßmann, and H. U. Hoppe, “On the Influence of Autonomy and Transparency on Blame and Credit in Flawed Human-Robot Collaboration,” in *Companion of the 2021 ACM/IEEE International Conference on Human-Robot Interaction,* C. Bethel, A. Paiva, E. Broadbent, D. Feil-Seifer, and D. Szafir, Eds. New York, NY, USA: ACM, 03082021, pp. 377–381.

Chapter 6
A. Arntz, S. C. Eimler, and H. U. Hoppe, “A Virtual Sandbox Approach to Studying the Effect of Augmented Commmunication on Human-Robot Collaboration,” *Frontiers in Robotics and AI,* vol. 8, p. 318, 2021. [Online]. Available: `https://www.frontiersin.org/article/10.3389/frobt.2021.728961`

Additional Works

The dissemination formats listed below describe works and publications that are adjacent to this thesis but are not included as dedicated chapters.

A. Arntz and S. C. Eimler, “Artificial Intelligence Driven Human-Machine Collaboration Scenarios in Virtual Reality,” Poster presented at the Intelligent Automation Symposium[1], 2018.

The research included in this dissertation was invited to the round table panel of the Science-Fiction vs. Science-Fiction 2020 conference[2], 2020.

A. Arntz and S. C. Eimler, “Den Arbeitsplatz von Morgen erleben - KI-basierte Mensch-Roboter-Kollaboration simuliert durch Virtual Reality,” Poster presented at the World Usability Day[3], 2020.

Several invited interdisciplinary talks and HRC workshops in the context of teaching for the study programs “Mensch-Technik-Interaktion” and “Soziale Robotik” at the University of Applied Sciences Ruhr West, “Master Innopreneurship” at the University of Duisburg-Essen, as well as “Computer Science” at the Babeş-Bolyai-University, Cluj-Napoca, Romania.

The VR application described in this thesis was nominated for the DIVR Science Award in the category **Best Tech** at the 2021 Places VR Festival[4], 2021.

A. Arntz, A. Di Dia, T. Riebner, and S. C. Eimler, “Machine Learning Concepts for Dual-Arm Robots within Virtual Reality,” in *2021 IEEE International Conference on Artificial Intelligence and Virtual Reality (AIVR)*. IEEE, 2021, pp. 168–172.
This publication was distinguished with the best presentation award (posters/demos)[5]

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[1] Intelligent Automation Symposium Website: `http://iasymposium.rwth-aachen.de/`

[2] SFSF 2020 Website: `https://sfsf.hs-rw.de/konferenzprogramm/`

[3] Ruhr WUD Website: `https://ruhrwud.de/2020/12/04/rueckblick-ruhrwud-2020/#more-553`

[4] Places VR Festival Website: `https://places-festival.de/divr-award-2021/`

[5] Best presentation award winners - October 15th, 2021: Machine Learning Concepts for Dual-Arm Robots within Virtual Reality by Alexander Arntz, Agostino Di Dia, Tim Riebner, and Sabrina Eimler - AIVR 2021 Website: `https://ieee-aivr.cs.nthu.edu.tw`

Contents

1. Introduction

Akin to Human-Robot Interaction, the term Human-Robot Collaboration (HRC) describes both the research discipline and the subject itself [1], [2]. HRC exceeds the mere interaction between humans and robots through the constellation of working together in close proximity towards a shared goal [3]. The concept derives from circumstances where some tasks are too complex to be solely conducted by robots or too costly to realize in full automation [4]. In such cases, robots can be used to support human personnel performing either repetitive, cumbersome, or dangerous tasks [5]. The ideal implementation for HRC regards both collaboration parties capable of intuitively recognizing each other's actions and adapting their current activity to facilitate mutual assistance [6]. The benefits of mutual support during collaborative tasks between humans and robots bear the potential to revolutionize a wide range of industrial domains [7].

Although many technological advancements have been made in the last decade, current implementations of HRC deviate enormously from this ambitious vision [8]. Industrial workplaces where HRC is deployed are dominated by robots operated by hand guiding where the human personnel actively controls the robots' movement or powered by predetermined programming [9], [10]. Both approaches represent a sub-optimal realization of HRC as the hand-guided control degrades the robot into a passive role during the shared task and the predetermined programming denies the robot the ability to react and adapt toward the humans' actions. Due to increasing product variants and shortening fabrication cycles paired with the increasing competitiveness in the market, these realizations of HRC are often not suited as a long-term solution to see widespread adoption in the industry [4], [11]. Advancements in machine learning fueled various concepts to enable collaboration robots with autonomous behavior [12–14]. This raises the question of how to design collaboration scenarios involving autonomous robots. Although HRC-related research has attempted to establish a taxonomy for the design and implementation of the collaboration concept between humans and robots [15], no guidelines for the general approach of HRC exist so far [16]. Combined with various challenges, among others in the field of safety, expectation conformity, communication, and task allocation, examining the optimal realization of optimized HRC setups is a difficult task. Empirical studies are only possible to a limited extent, as extensive safety restrictions deny the exposure of participants to unreliable prototype implementations of HRC. Another aspect that hampers the research in this area is the scope of possible robot and procedure configurations, demanding enormous resources to generate the appropriate setup for empirical studies. Since current research methods regarding HRC are elaborate and subject to many restrictions, new approaches are needed to explore concepts for the implementation of optimized HRC.

For this purpose this dissertation introduces a virtual reality (VR) application dedicated as a platform to conduct empirical studies with participants. Based on the experience with prior VR-related projects [17–19], the proposed VR application offers the latest VR mechanics and provides a safe and replicable environment to gain insights into the reactions, behavior, and performance of the participants while being confronted with an autonomous collaborating robot. In addition to avoiding safety hazards from exposing participants to prototype implementations of HRC, the VR application offers logistical, technical, and financial benefits. This is possible as the VR application contains a modular setup that allows the portrayal of any needed scenario as environments, assets, and functionality can be adjusted to fit the desired research objective. To achieve the representation of a wide variety of different robot models that can act autonomously and collaborate with the human partner, the VR application is equipped with an inverse kinematic system. To accommodate most industrial robots, the inverse kinematic system is structured in seven degrees of freedom (DoF) and allows the robot to move dynamically and independently of prefabricated animations. Powered through the usage of machine learning agents, the virtual robot is able to conduct different procedures and can adapt to certain behavior parameters during the unpredictable collaboration with a human partner. Complemented with refined interaction mechanics adapted from prior VR projects [17–19], participants can authentically conduct shared task procedures in conjunction with the respective collaboration robot.

This VR application was used as a sandbox to examine the aforementioned challenges of HRC, namely safety, expectation conformity, communication, and task allocation. By combining qualitative, quantitative, and objective measurements, a series of five empirical studies were conducted that addressed substantial research questions regarding the collaboration of humans with autonomous robots in industrial settings. Apart from the VR application itself as a research platform for future empiric studies in the field of HRC, the results of the included studies contribute toward design recommendations for upcoming industrial scenarios involving the collaboration between human personnel and autonomous robots.

The following Section 1.1 defines HRC by describing the different levels of interactions between humans and robots and the resulting challenges of HRC. Section 1.2 states the concrete research questions that motivated the empirical studies reported in this dissertation. In Section 1.3, supplementary to the information provided in the included publications, additional details regarding the VR application are described. A summary of the empirical studies from the included publications of Chapters 2–6 is provided in Section 1.4. Afterward, in Chapter 7, the contribution of this dissertation is concluded and complemented by describing the limitations of the VR approach and future research involving the presented VR application.

1.1. Background

This section outlines the definitions and describes the different levels of interaction between a human and a robot with a focus on industrial settings. The distinction is important to contextualize the presented HRC studies in the included publications (Chapters 2-6) since some terminologies are used synonymously by laymen, e.g., cooperation and collaboration. Afterward, the various challenges of HRC itself are being discussed in tandem with the difficulties to address these challenges in empirical studies.

1.1.1. Defining Human-Robot Collaboration

According to Schmidtler et al. [20], all forms of humans interacting with robots can be defined as Human-Robot Interaction. The level of interaction between humans and robots can be categorized through four criteria [21]. The first criterion is determined by whether or not the human and the robot overlap in the space they occupy [4]. The second criterion involves the time the human and the robot spend in their common space. The third one is the presence of a goal for the interaction. Both the human and the robot can enter the interaction with a goal. Both parties can either share their goal, pursue a different goal, or have an opposing goal in each case. The fourth criterion is the contact between the human and the robot. While sharing the same space at the same time, both parties can come into contact with each other. Either by accident, if the procedure is not intended to contain contact, or intentionally if contact is part of the interaction. Contact between the human and the robot can range from mere touch to the exchange of force between the two parties [22].

Based on these four criteria, the research field of Human-Robot Interaction can be categorized into three classifications: (1) Human-Robot Coexistence, (2) Human-Robot Cooperation, and (3) Human-Robot Collaboration.

Human-Robot Coexistence

Coexistence refers to humans and robots that are located within the same space without a shared task or common goal. It is therefore defined as the weakest form of Humans interacting with robots [20]. Since no common goal is present within the coexistence, no coordination of actions between the human and the robot is required [23]. The coexistence between humans and robots within industrial production is common [24], realized often by either caged robots in dedicated areas or proximity sensors [23]. Mutual contact is strictly avoided [4]. Since robots for the coexistence level are prohibited to operate with humans nearby, the detection of an individual through integrated proximity sensors results in the termination of any task execution of the robot in accordance with the *safety rated monitored* *stop* stated in ISO TS 15066[1] [26], [27].

Human-Robot Cooperation

Humans cooperating with robots elevates the complexity of the interaction. The cooperation involves both entities being present in the vicinity of each other at the same time. Roschelle and Teasley describe the cooperative procedure as the division of the individual working steps in which each party is responsible for an assigned segment of the task [28]. Although both parties share a common goal, due to the division of the labor, there is no dependency on each other to accomplish the assigned task [29]. Considering that the cooperation level involves no direct interaction between the human and the robot, no adjustments in the design of the robot are required. Since standard industrial robots adhere to the safety regulations of speed and separation monitoring described in ISO TS 15066 [26], [27], these robots are usable for the cooperation with humans [9].

Human-Robot Collaboration

The highest tier of interaction is designated as the collaboration between humans and robots. The collaboration can be differentiated into two distinct modalities of (1) contactless collaboration and (2) intentional contact [4]. The first modality of contactless collaboration omits physical interaction in any form [4]. The coordination of the procedure is therefore delegated to the human, who conducts the respective working steps where decision-making is involved. The robot in this case is assigned to tasks that require no human participation, such as repetitive, dangerous, or force demanding labor [20]. Contactless collaboration with a robot following a pre-determined pattern requires the human to intervene with direct input for alterations during the procedure. This type of collaboration is often used in procedures where the human personnel is required to attach an object to the robot's end-effector while the robot is inactive or place an object within the robot's area of influence [9]. A promising approach for contactless collaboration is the usage of robots controlled by software agents to provide a certain level of autonomy and a larger scope of possible procedures that can be executed by the robot [4], [30]. Contactless collaboration with a software agent-controlled robot requires direct or indirect communication channels for coordination exchange [4], [30]. However, current HRC research lacks sufficient empirical studies regarding the effective merger of communication channels with autonomous robots in a collaboration setup. To address this gap, the presented research of this dissertation aims to address the challenges (cf. 1.1.2) associated with this scenario in the included publications (cf. Chapters 2-6). To provide further insight into the subject of HRC, the following segment will describe the second modality of HRC, which involves physical contact. This is important further contextualize the studies

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[1] While ISO TS 15066 is developed and accepted by the majority of industry representatives and reflects the state of the art, a wide range of literature and regulations still refers to the previous specifications of ISO 10218 [25]

and the limitations of this dissertation (cf. Section 7.3)

The second modality of HRC contains intentional physical contact with exchanging forces between both parties [31]. According to the regulations found in ISO TS 15066 [26], HRC with physical contact between humans and robots is divided into two sub-categories: (1) *Hand guiding* describes the HRC process where the human collaboration partner can freely move the actuators of the robot without any exercise of force [9]. Without any external input, the robot remains in its current position, as the motion can only be initiated by the human operator. Robots used in this type of collaboration are equipped with sensor arrays monitoring external loads and forces influencing the robot. Additional safety is provided by an operator presence control. This ensures that the robot can only move and be moved if the human collaboration partner is pressing the dead man's switch [9]. Collaboration procedures involving hand-guided robots are often used to relieve staff of lifting heavy payloads and improving working ergonomics [20]. Apart from using hand-guided collaboration for coordinated semi-automated procedures, the guidance of motion is often also used during the robot's programming for pre-determined operations [9]. (2) The second sub-category for physical contact is the *power and force limiting* collaboration [9]. This type requires special robots, capable of measuring the forces emerging during the contact and adapting their torque to prevent harm to the human collaboration partner [32]. For this purpose, high-resolution sensory equipment is needed to continuously monitor the robot's position and velocity [33]. Tactile sensor hardware measures the electric current consumed by the actuators to calculate the forces and torque that are exerted on the robot [9]. Regulations demand immediate countermeasures if a collision is detected [26], requiring the robot to cease all motion to reduce the kinetic energy of the impact [9].

Both modalities of HRC requires that both human and robot be present in the same space at the same time. Compared to the cooperation level, collaboration requires the human and the robot to be participating throughout the entire procedure and work in dependence on each other towards the common goal [29]. The distribution of the respective sub-tasks is coordinated among the human and the robot during the collaboration process. Due to the requirements of tactile awareness and collision detection, the application of HRC necessitates special robots [4]. Colgate and Peshkin coined the term *"Cobots"*[2] for robotic systems designed with the purpose of collaborating with humans on a dedicated workstation [34]. Although collaboration-certified robots have been adopted by various industries, where they support personnel with the placement of heavy loads or executing precise operations, the design and application of HRC, independent of the modality of intentional contact or contactless collaboration, remains one of the most challenging problems in the field of industrial robotics [35]. In order to contribute to the research effort of investigating design recommendations for the design of HRC setups, it is important to consider the specific challenges of

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[2] "Cobots" - A portmanteau word formed from the two terms *collaborative* and *robotics* denotes a robotic system that has been explicitly designed for the purpose to interact through physical contact with a human partner within a shared workplace [4]

HRC.

1.1.2. Challenges of Human-Robot Collaboration

The collaboration between humans and robots is predominantly discussed for industrial applications. Therefore, collaborative robots must function in a complex working environment, while confronted with sophisticated procedures and unforeseen circumstances created by the human partner [4], [36]. The concept of HRC aims for a shared workspace, free of isolating fences around the robot, where both parties can work with the preserved abilities of each other [37]. Due to the direct contact between the human and the robot, safety measures to protect the operator from the forces created by the robot are important for the successful realization of this concept [38]. Not only is the movement of the robot a potentially hazardous factor for the human, but the tools and components wielded by the robot can also become a threat to nearby individuals [39].

Safety

The collision between the robot and the human collaboration partner has been identified as the most frequent type of accident in industries where both entities share their workspace [40]. The HRC-related research has explored multiple concepts to approach this problem. Santis and Siciliano proposed three distinct categories to improve collision safety during HRC [41]. (1) The first category contains actions related to intrinsic safety. (2) The second category attempts to avert collisions (pre-collision measures) and (3) the third category deals with strategies to enhance safety in case a collision has occurred (post-collision measures) [4]. Research regarding the intrinsic safety of industrial robotic systems investigates concepts to improve the reliability of the mechanical design of the actuators [42]. The idea is to develop a mechanical structure that enables the actuators of the robot to better absorb the kinetic energy when a collision with a foreign object occurs [43]. In addition to this, new materials for the joints and the body of the robot are anticipated to aid safety by reducing weight, resulting in less kinetic energy [44]. Since unplanned collisions between humans and robots bear a high risk for injuries, pre-collision measures helping to prevent inappropriate and forceful contact, are a top priority for HRC research [23]. The capability to actively prevent collisions requires that the robot can detect its surrounding objects and individuals. For this purpose, the majority of HRC-related research explores various sensor implementations with the aim of detecting obstacles that are crossing the current trajectory of the robot [45–47]. However, the implementation of a safe and rigid system that maintains the full capabilities of both collaboration parties, has yet to arrive [4], [37]. Apart from technical aspects that can improve safety, the human factor can not be neglected. Misinterpretations of the robot's actions due to insufficient communication can lead to flawed interactions (cf. Section 1.1.2), increasing the potential for accidents (cf. Chapter 6) [4]. However, no common metrics exist as methods to analyze flawed collaborative interactions with industrial robots are limited, considering that confronting participants with these systems is too dangerous [48]. This opens up the need to find new and innovative ways to explore the usage of communication as a means to improve safety during the collaboration between humans and robots. Also, psychological safety during the collaboration process has to be considered, as the perception of an unsafe interaction with the robot can result in discomfort or stress, diminishing the effectiveness and actual safety of the shared task procedure [49]. Galin and Meshcheryakov state that studies regarding the perceived safety of robots in collaboration setups are limited for the formation of common design guidelines due to the complexity of different parameters [50]. In addition to the variety of different workplace setups, again the exposure of participants to experience the perceived safety firsthand in HRC environments for controlled empirical studies is restricted (cf. Chapter 6) [51]. Since the safety aspect of HRC remains an unsolved problem, an alternative that enables controlled studies for objective and psychological safety would provide not only a way to confront this gap in research but also contribute to the overall safety in HRC [50]. To address this challenge, the experimental study described in Chapter 6 used the HRC VR application to explore objective and subjective safety aspects.

Autonomy and Competence

Although, the definition for HRC as described in Section 1.1.1, states that the human and the robot work in a shared space on a common goal, no natural collaboration as it can be found within human group collaboration is as of yet apparent [15]. Current implementations of HRC use hand-guided trajectories described in Section 1.1.1 or pre-packaged actions that are required to be programmed specifically for the respective use-case [10]. Since the personnel involved in HRC are not necessarily experts in programming robots, the approach of hand guiding trajectories in combination with programmed actions can become a time-consuming and cost-ineffective process [52]. According to Rußwinkel, the major challenges for HRC research are to identify the demands for an autonomous and competent collaboration between human and robot, where both parties are enabled to estimate the intentions of the other and the robot can anticipate and adapt to the actions of the human partner [53]. A promising approach to realizing adaptive robots for collaboration scenarios is the usage of machine learning (ML) to cope with the dimensional and computational complexity [12]. It is anticipated that future HRC setups will use machine learning to supervise incoming real-time multi-modal sensory information to process the working procedure, determining the behavior of the robot while simultaneously learning from the human input for future adaption [14]. The goal is to continuously expand the robot's functionality for the required procedures of the respective shared tasks and enhance its effectiveness to collaborate with the human partner [54]. To approach this goal the research community has developed a vast array of different implementations, all specialized for a different aspect of robot autonomy. For example, Zakka et al. used ML technology to enable the robot to learn and recognize the shape of objects, a feature needed for the adaptation to new assembling policies [13]. Other HRC research focuses on the ML implementation of the hybrid force and position control of the robot [55], anomaly detection [14], pathfinding and collision avoidance [12]. While all of these works regarding the use of various ML concepts are prolific in their technical achievements, they often neglect the impact of these trained behaviors on the human collaboration partner (cf. Chapter 5). Although the need for explainable autonomous systems has been recognized [56], evaluations exposing the various ML implementations that seek to equip the robot with adaptive capabilities to participants are restricted. In addition to the potential risks stated in Section 1.1.2, an autonomous robot could show unforeseen, incorrect, or erratic behavioral patterns during experimental setups. This can be caused by problems in the algorithmic implementation, resulting in a failed prediction of the human trajectory [57], or interference in the gathered sensor data that feed the respective agents of the robotic systems with information about the environment. Since an intelligent robot that is able to act independently of the control of the human operator should make its actions transparent, predictable, and instantaneously understandable for the human collaboration partner (cf. Section 1.1.2) [58], the challenge of HRC arises to conduct the testing of these automated systems for controlled empirical studies that ensures that the ML trained skills and behavior meet the expectations of the human collaboration partner (cf. Section 1.1.2 and Chapter 2) and the ramification the impression of intelligence from the automated behavior has on the humans and the collaboration relationship (cf. Chapter 5).

Expectation Conformity

Compared to non-collaborative robots, an autonomous collaborative robot must contribute to a shared task in conjunction with a human partner. This setup creates a social condition similar to the collaboration among humans where both parties interact with active decision-making that involves the respective other [59]. However, Bütepage and Kragic state that HRC research with autonomous robots mostly focuses on the perspective of the agent within the collaboration, neglecting the human representation [60]. This can lead to ineffective and flawed realizations of HRC, as the implementation of autonomous behavior for the robot without including the human perspective omits half of the collaboration team. Studies regarding the interaction between humans indicate that people expect that the partner adheres to certain proximity during the collaboration process based on the individual relationship both parties have [61], [62]. It can be argued that with a sophisticated level of automation, these robots will be perceived as more intelligent (cf. Chapter 5), thus raising the expectation of these systems to follow social norms such as respecting the proxemics of an individual. Introducing an autonomous robot in an HRC environment that fails to meet such expectations might be rejected (cf. Chapter 2), resulting in a sub-optimal performance for shared tasks [63]. Charalambous et al. found that a vast array of human factors such as mental workload and perceived stress can influence the outcome of a successful collaboration between a human and robot in an industrial setting (cf. Chapter 3 and Chapter 6) [64], [65]. However, most case studies regarding the expectation conformity of robots in HRC scenarios are narrow in their scope of workplace arrangements they can cover. As already described in Section 1.1.2 the restrictions of HRC-based empirical studies limits the range of setups where participants can respond to behavioral characteristics of an autonomous robot [4]. Considering the wide variety of robot representations in terms of appearance and behavior in conjunction with the current setting in which the robot is deployed, can affect the human factors and contribute to the user's impression and expectation (cf. Chapter 2 and Chapter 4) [59], HRC research is faced with the challenge to find new ways that allow the exploration of a wide variety of different workplace arrangements and representations of autonomous robot behavior with the goal to develop generalized guidelines for the design of HRC to meet the expectation conformity. A major factor for the formulation of guidelines regarding user expectation conformity is to explore the various characteristics of a collaborative robot and how they are perceived by the users across different cultures [66]. Considering that current experimental approaches are limited in the number of different robot models that they can incorporate due to budget or logistics constraints, the use of a research platform that can present a variety of different robot models in a controlled and comparable setup could help to address this.

Communication

The exchange of information between the human and the robot remains one of the significant challenges of industrial HRC [4]. While the metrics of communication with social robots are extensively researched in the field of Human-Robot Interaction, the principles regarding communication are quite different for industrial robots [67]. Compared to robots used in social fields, industrial robots lack the ability for visual cues that are designed to convey the intention of the robot [67]. Combined with the ambition to make industrial robots more autonomous and adaptive, a misinterpretation of the robot's actions can result in potentially hazardous situations (cf. Section 1.1.2) [4]. This makes a reliable implementation of communication paramount, as unsuitable realizations of the communication can affect the safety of the respective HRC setup [68], [69]. The most important research questions regarding HRC-related communication are stated by Kaupp et al. [70], as (1) *What type of information should be communicated?* (2) *When should communication occur?* (3) *Who should communicate with whom?* and (4) *What medium should be used for communication?*. The HRC research community has tried to address these questions with a variety of different concepts. The most preferred communication channel is the exchange of information with the robot in natural language [4]. Apart from the social aspect observed within the group collaboration among humans [71], the ability to communicate through vocal language bears several key advantages, as it is fast and demands a short acclimation for the user [4], [72]. In recent years, many technical and conceptual approaches for the implementation of natural language-based communication in HRC have surfaced [69], [73]. While vocal-based commands are rated as an effective way to communicate in scenarios where participants encounter the robot in a lab environment [73], the use of verbal communication can be limited in an industrial soundscape to comfortably exchange information with the robot [68]. Visual and gesture-based communication channels are discussed in HRC research as alternative ways to convey information from the robot to the human collaboration partner [4]. Same as in the collaborative relationship between humans, the way communication is represented exceeds the mere exchange of information by affecting additional impressions gained from the robot, e.g., trust and intelligence (cf. Chapter 5) [73], [74]. Human-Robot Interaction research indicated that the communication of the robot can also affect a person's emotional response towards the robot and the way a person interacts with it [75], [76]. Elprama et al. confirmed the importance of communication cues in settings where people interact with industrial robots [77]. However, communication in collaborative settings among humans is not restricted to one dedicated communication channel alone (cf. Chapter 3). Research indicates that people prefer when robots convey themselves through multiple channels, resulting in the need to explore the effectiveness of allowing the robot to express itself through several channels [78]. However, due to the number of different constellations between the representation of collaboration robots, shared tasks, and communication channels, the exploration of optimized solutions requires an enormous effort in terms of technical implementation, logistics, and funding.

Considering the significant role communication for the exchange of information has during the collaboration process between human individuals on the reduction of uncertainty (cf. Chapter 3), it is paramount to investigate the potential ramifications of using communication on human factors aspects, e.g., perceived stress and perceived safety (cf. Chapter 3). However, due to the number of different constellations between the representation of collaboration robots, shared tasks, and communication channels, the exploration of optimized solutions requires an enormous effort in terms of technical implementation, logistics, and funding (cf. Section 7.2).

Task Allocation

The concept of combining the individual strength of humans and robots can create a major benefit for certain production scenarios. However, these benefits can only be realized if the individual sub-tasks within a shared task are distributed effectively [79]. The challenge is to facilitate the coordination between both parties to improve the efficiency of the collaboration process and enhance the production output [80]. Several methods have been developed to plan the allocation of assignments in a sequential shared task between a human and a robot [4]. A commonly used method in HRC is the master-slave principle in which the human and the robot interact in an asymmetric setup where one party acts as the dominant partner and the other as the subordinate [81]. Research indicates that this constellation can result in a relationship where the robot is seen as a mere tool that assists in the task completion [60]. While the master-slave principle is often applied due to a lack of autonomy of the robot, it is uncertain how the usage of autonomous robots affects that relationship. This is especially important in the task coordination between both collaboration partners, as an autonomous robot can claim tasks previously exclusive to the human operator. This might evoke a negative attitude towards the robot as people perceive this as an intrusion of their position [82]. Exploring ways to examine the ramifications of increased autonomy by the robot and strategies to facilitate the coordination between both parties during the collaboration is essential [83]. As mentioned in Section 1.1.2, communication could provide a potential benefit for the collaboration process, as the provision of information could ease the coordination and task allocation. However, no prior research has confronted the challenge of exploring the usage of communication for the purpose of increasing coordination, therefore, improving the productivity in industrial HRC scenarios (cf. Chapter 6).

1.2. Research Questions

As described in Section 1.1.2 researching HRC faces various challenges, which need to be explored in empirical studies. However, as previously explained in Section 1.1.2, HRC-related empirical studies are restricted in the settings and scope they can explore, due to safety concerns and elaborate setups among other things. The objective of this thesis is to provide a safe and replicable method to conduct empirical studies with participants by using the HRC VR application. In doing this, the VR application is used to explore gaps in research regarding the effective collaboration with autonomous robots in consideration of human factors aspects, such as perceived stress. Derived from stated challenges, open issues that are crucial for the success and the acceptance of HRC will be addressed in experimental studies conducted with the HRC VR application. The versatility of the VR application allows it to not only be used for experimental studies but also to serve as stimulus material in context and interplay with other methods, e.g., qualitative approaches and online studies. This ability to function as a foundation to explore through a combination of different methods the challenges of HRC (cf. Section 1.1.2) was used for the here presented research. The aforementioned key issues of HRC are formulated as the following four research questions (RQ) to provide an overarching guideline for the objective, design, and implementation of the studies presented in Chapters 2-6 (see Figure **1-5**):

- **RQ1** - What are the general expectations towards a collaborative industrial robot and which aspects will be perceived as positive or negative?
- **RQ2** - How does the use of an autonomous robot augmented with communication channels affect the human collaboration partner in terms of perceived stress, perceived safety, and positive emotions?

- **RQ3** - Which aspects cause people to consider the autonomous robot as intelligent and what are the effects of this perceived intelligence on the collaboration relationship?
- **RQ4** - Can communication contribute to improving productivity and safety during the collaboration between a human and a robot?

1.3. The Virtual Reality Application

This section contains the description of the components of the virtual reality application, which was developed within the context of this thesis. It further contextualizes the stated information of the included publications in Chapters 2-6 and provides additional detail on the functionality of the virtual reality application. First, the contemporary usage of virtual reality in the HRC community is outlined. Second, the virtual reality application as a sandbox platform to conduct HRC-themed empirical studies is described.

1.3.1. Virtual Simulation in Context of HRC

Virtual reality technology enables the development and depiction of artificial environments, where users can experience and interact with objects generated through computer graphics [84]. The benefit of using these immersive environments to expose users to situations that are dangerous, elaborate, or impossible under normal circumstances has been recognized in various fields, such as learning applications [85], medical fields [86], and biochemical engineering [87]. The capabilities of virtual reality have also been used in HRC-related projects as a flexible tool to enhance the interaction with industrial robots [88]. With the goal of improving safety in HRC settings, Vogel et al. introduced the concept of using projectors that throw a virtual depiction of visualized safe zones onto the workplace, based on the inputs of several optical sensory devices and a tactile floor [89]. Human personnel working with the robot can use these projected safe zones, displayed in a similar manner to a virtual cave, as guidance to collaborate with high payload robots [89]. Another concept regarding the improvement of safety conditions for HRC was proposed by Hernoux et al. using virtual reality and spatial detection through motion capture to locate the human operator in relation to the industrial robot [90]. The gathered data were used for real-time detection during the collaboration procedure and the development of algorithms enhancing the pre-collision capabilities of the robot [90]. Guhl et al. used virtual reality technology to enable operators to interact with industrial robots and other cyber-physical systems [91]. The approach was to use virtual reality as an interface for a distributed control system that allows safe interaction with industrial robots [91]. Apart from the safety during the actual collaboration procedure, virtual reality can also help to prepare personnel for the interaction with industrial robots. For this purpose, the virtual reality training system was developed by Matsas and Vosniakos [92]. This application trains users to conduct simple manufacturing tasks in cooperation with a robot and provides feedback for possible misconduct [92]. A similar approach was chosen by Di Gironimo et al., using virtual reality to plan collision-free trajectories for multiple robots to improve the training of the staff that cooperated with the industrial robots [93]. Another virtual reality application for the cooperation between humans and robots was developed by Gammieri et. al. The authors simulated multiple cooperation scenarios to recreate a safe behavior for the real robot counterpart while simultaneously providing training for the human operators [88]. A proof of concept for a virtual reality application created by Giorgio et al. simulates the characteristics of industrial robots that are intended for collaboration scenarios [94]. Additional projects using virtual representations of the interaction with industrial robots can be found in the realm of mixed reality and augmented reality, respectively. A common theme for these projects is the goal to confront the challenges of safety or to optimize the interaction procedure with additional information provided through the head-mounted display. Green et al. proposed an augmented reality interface that aims to increase users' awareness of the robot during the collaboration procedure by feeding them a live cast of the robot's perspective in the view [95]. Another research project was presented by Wang et al. where the authors used augmented reality to simulate the cooperation with a robot to examine human factors aspects and the ergonomic design of the assembly cell [96]. While the authors extended the interaction capabilities of the used augmented reality device with optical finger tracking based on Leap Motion [96], the implemented interaction mechanics can not match the scope of dedicated virtual reality devices that are equipped with haptic motion controller [84].

Although the aforementioned VR-related projects pursue a wide range of objectives, none of them are utilized for the exploration and research of new and versatile HRC concepts and approaches in empirical studies. This opens up the need for a VR application equipped with sophisticated interaction mechanics that enable the portrayal of authentic collaboration procedures with autonomous robots. Such VR application could serve as a dedicated platform to cover a wide variety of different collaboration scenarios where participants are exposed to different representations of industrial robots, difficult to realize in empirical studies. The approach of using VR for empirical studies in the context of HRC raises the question of the suitability of this technology to acquire authentic results of an individual's behavior and reaction exposed to virtual representations of industrial robots and shared tasks. This question is covered in the next section.

1.3.2. The Virtual Reality Application as a Research Platform

The opportunity to confront participants of an empirical study with a nearly limitless amount of possible scenarios as a stimulus material would be a powerful tool. The potential technology that could deliver this opportunity for research in the fields of psychology, education, and usability was recognized with the emergence of consumer graded virtual reality hardware [97]. Affordable hardware and accessible development tools allowed researchers to not only recreate existing experimental setups but also to come up with new ideas, which were hardly possible without the use of virtual reality technology. Van Loon et al. used the immersiveness of the virtual reality technology for perspective-taking studies, where participants assumed the role of a different individual [98]. This concept, while difficult to realize otherwise, proved effective in evoking an increase in cognitive empathy [98]. Multiple studies adopted the idea of confronting participants with new identities, roles, situations, and social norms, with the research indicating that the virtual stimulus can facilitate response in participants, dubbed as the Proteus effect [99–101]. Results showed that the exposure to the virtual reality stimulus material can grant insight into people's reaction and behavior towards certain situations inside the virtual application but can also affect behavior and mental conditions after exiting the virtual environment [102], [103]. The precondition of virtual reality to evoke such a strong response was coined by Burdea and Coiffet as *"the three I's"* [104]. (1) The first *"I"* refers to the *imagination* and describes the user's willingness to seclude completely from reality and experience virtual reality as their current environment [104]. (2) Second is the *interaction*, where user can manipulate their surroundings at will and experience a direct response to their actions based on consistent rules established within the virtual world [104]. (3) Third is the *immersion*, where the information is passed onto the user through multimodal channels that allow experiencing and exploring of the displayed virtual setting [104]. The isolation from reality paired with the audiovisual representation of an artificial setting that can be interacted with at will can trigger the same emotional and behavioral patterns as their respective counterpart stimulus, a phenomenon used actively in virtual reality-based fear confrontational studies [105]. This suggests that virtual reality can be used to explore the various challenges of HRC described in Section 1.1.2 in empirical studies to investigate participants' reactions toward the collaboration with an autonomous robot. Since existing HRC-related virtual reality applications are not dedicated to functioning as a distinct tool for empirical studies (cf. Section 1.3.1), a new virtual reality application was required to be conceptualized and developed.

1.3.3. Prior Works Influencing the Design of the Platform

In order to make use of lessons learned and best practices acquired from several prior and adjacent projects involving virtual reality-based education and learning applications, design principles and tried and tested mechanics were adopted for the HRC VR application. The origin of the HRC VR application can be rooted back in a virtual classroom application, where users attended a fully rendered and animated lecture held by a virtual tutor. By combining a questionnaire with Electroencephalography (EEG) data, the influence of changing lighting conditions on the recall of the learning material was examined [106]. While the application provided merely a passive experience with minimal interaction, valuable knowledge was gained for the usage of virtual reality in empirical studies.

A successor project to the virtual classroom examined the effectiveness of mixed reality for teaching practical tasks. Comparing the practical skills of assembling computer hardware through virtual and augmented reality against the real condition, required the development of interaction mechanics that closely mimicked the real actions such as tightening a screw or plugging in a circuit board [17]. Together with the visual fidelity of the virtual components, the interaction mechanics aimed at facilitating the association with real components and actions to trigger a recall. Results confirmed the effort as users indicated a higher recall of the learning content [17]. The experience from this application was used to develop the HRC VR application with the same goal of merging visual fidelity with authentic interaction mechanics to generate a scenario where participants can immerse themselves into the shared task in collaboration with a (virtual) robot (cf. Chapter 6 (Section 3.2)).

These interaction mechanics were extended and increased in precision for the development of a virtual reality application that teaches students about the basic handling of a milling machine. The application contained the recreation of a Hermle C40U milling machine together with extended interaction mechanics and the emulation of the machine's user interface to recreate the milling process [19]. The best practices such as the legible portrayal of user interfaces within the virtual environment acquired for the recreation of the milling machines' information panel were applied for the implementation of the text panel communication channel found in the HRC VR application (cf. Chapter 2 (Section 3.2) and Chapter 6 (Section 3.2.4)).

Additional influences came from a prototype gallery application where users were able to inspect and interact with various diversity-themed exhibits, ambulate freely within the virtual world and access integrated content, e.g. a station where participants can exercise their motor skills while challenged by a tremor in their hands [107], [108]. Due to the variety of the different exhibitions in theme and mechanics such as the interaction with kinematic objects and multimedia content, it was necessary to design and implement them as interchangeable modular components, laying the foundation of the modular design of the HRC VR application presented in this thesis.

Developed in parallel to the HRC VR application was an application that teaches students about the functionality of photovoltaic systems [18], [109]. By combining an authentic virtual recreation of an existing photovoltaic installation with a network interface that allows receiving data generated by its real counterpart on the rooftop of the university building, students were invited to experiment with the array in a fault-tolerant environment. A weather simulation fed by real weather data contextualized the current energy output adequately. Again the interaction mechanics fit the actions of the real installation and enabled the students to place and manipulate the individual components at will using the same basis implemented in the HRC VR application to control the Pin-Back Button press (cf. Chapter 6 (Section 3.2.1)).

Additional projects that helped to validate concepts and technical approaches for this dissertation involved a virtual reality application that confronts participants with environmental pollution to raise awareness [110], [111] and a VR-based relaxation application [103], where the additional experience was gained to optimize the performance of the HRC VR application to ensure a stable frame rate over 90Hz [84]. Further knowledge regarding the design and implementation of real-world items into virtual simulations was acquired during the development of an augmented reality-based indoor navigation application for industrial usage [112] and a mixed reality application to explain to students the functionality of heating, venting and air conditioning systems [113].

An amalgamation of the experience and skills gained from these aforementioned research and development projects contributed to the design and creation of the HRC VR application. The VR application is further described in Chapter 3 (Section 3), Chapter 4 (Section IV. A), and Chapter 6 (Section 3.2) and is complemented by the following section, containing descriptions of the interaction mechanics (Section 1.3.4), the inverse kinematic system (Section 1.3.5), and the machine learning agent (Section 1.3.6).

1.3.4. Interaction Mechanics of the VR application

After the prior section outlined the gained experiences and best practices from prior projects that were used to conceptualize a virtual reality application that is dedicated to being used for HRC-related empirical studies with an autonomous robot. In order to portray a wide range of possible shared tasks to be explorable in empirical studies, the VR application was equipped with a library of interaction mechanics that mimicked the practical activities found in real manufacturing procedures. The core interaction functionality of the Oculus Integration SDK provided prefabricated scripts for gripping a virtual object with the dedicated touch controller and binding it to the physics model of Unity 3D [114]. However, the replication of complex manufacturing tasks required more than simply grabbing objects. For this purpose, the VR application was equipped with a library of modular handlers, which provided action mechanics such as customizable hinges, rotators, and joints as well as pull and push forces (cf. Chapter 6 (Section 3.2.1)). Prior conducted projects have shown the significance of consistent interaction rules to evoke the portrayal of an immersive experience [18], [19]. To provide mechanics that are consistent throughout the interaction, every call to the Oculus SDK is bound to the Rigidbody parameter of the respective object and receives from there the values for mass, angular drag, and the kinetic drag [114], [115]. This system ensures that every interaction calculates with the same properties while being expandable with other third-party SDKs such as OpenXR and the virtual reality toolkit [116], [117]. This allowed the realization of a variety of different actions to be conducted by the user while collaborating on the shared tasks with the virtual robot. Due to the missing ability of VR to portray touching an object (cf. Section 7.3), haptic force feedback was used as a substitute to signal the user whenever a contact has occurred. By factoring in the intensity of the contact based on the current velocity of the two colliding objects, the respective interaction mechanics provided the appropriate amount of haptic force feedback. Prior VR-related projects validated this approach as an effective way to notify users of contact with a virtual object [18], [19].

Together with the methods described in Chapter 3 (Section 3) and Chapter 6 (Section 3.2) to ensure the audiovisual fidelity of the virtual environment, the haptic force feedback contributed to the immersion of the VR experience.
Besides the interaction mechanics, the VR application required components to portray the virtual robot as an autonomous collaboration partner. To accommodate a variety of different robot models, the HRC VR application contained an inverse kinematics system, which is described in the next section, and the machine learning agents, explained in Section 1.3.6, as essential modular components to enable the autonomy of the robot.

1.3.5. Inverse Kinematic System

Industrial robots used in collaboration setups are required to conduct complex tasks and move in a crowded space occupied by multiple obstacles while simultaneously confronted with unexpected actions from the human partner [4]. To grant the robot the capability to move within such an environment, operate tools, or manipulate other items and evade collisions, the majority of industrial robots designed for collaboration are equipped with either one or multiple arms in seven DoF [36]. To enable compatibility with the majority of industrial robots, a seven DoF inverse kinematic system following a spherical-rotation-spherical structure derived from the KUKA LBR iiwa R800 series robot was integrated into the HRC VR application [88], [118–120]. Based on the works by Artemiadis, a closed-form solution for the inverse kinematic was used, as it provided a more performant approach compared to a numeric solution [121]. Faria et al. recommended that to ensure a closed-form solution, the design of the respective robot is required in their alignment of the axes to contain as many α_i or ±90° as possible [118], [122]. The authors stated that the closed-form is calculated by a polynomial where the highest permissible degree is four [118], [122]. The foundation of the calculation of the inverse kinematic in seven DoF was delivered by the Denavit-Hartenberg parameter [118], [122] (Table **1-1**). Used through the parenting mechanic of the Unity 3D engine, where child GameObjects inherit rotation, scale, and the position of their respective parent, the Denavit-Hartenberg parameters in conjunction with a homogeneous transformation matrix, which converted the coordinate system from *i - 1* to *i* (Equation 1-1) [118], [123], delivered forward kinematics starting from the basis of the robot arm (Equation 1-2) [118], [123].

$$T_i^{i-1} = \begin{bmatrix} cos(0_i) & -sin(0_i)cos(\alpha_i) & sin(0_i)sin(\alpha_i) & \alpha_i cos(0_i) \\ sin(0_i) & cos(0_i)cos(\alpha_i) & -cos(0_i)sin(\alpha_i) & \alpha_i sin(0_i) \\ 0 & sin(\alpha_i) & cos(\alpha_i) & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{1-1}$$

$$P'_w =^0_7 T \cdot P_w =^0_1 T(0_1)^1_2T(0_2)^2_3T(0_3)^3_4T(0_4)^4_5T(0_5)^5_6T(0_6)^6_7T(0_7) \cdot [X, Y, Z, 1]^T_w \tag{1-2}$$

Table **1-1**.: The Denavit-Hartenberg parameters for seven-DoF with the values d_{bs}, d_{se}, d_{ew} and d_{wf} inserted for the KUKA LBR iiwa R800 that was used [118], [122], [124].

i	$\boldsymbol{\alpha_i}$	$\boldsymbol{d_i}$	$\boldsymbol{\alpha_i}$	$\mathbf{0}_{\boldsymbol{i}}$
1	$-\frac{\pi}{2}$	340mm	0	0_1
2	$\frac{\pi}{2}$	0	0	0_2
3	$\frac{\pi}{2}$	400mm	0	0_3
4	$-\frac{\pi}{2}$	0	0	0_4
5	$-\frac{\pi}{2}$	400mm	0	0_5
6	$\frac{\pi}{2}$	0	0	0_6
7	0	126mm	0	0_7

Based on the works of Singh and Claassens [118], [125], [126], the spatial coordinates of the elbow position (X,Y,Z) in relation to base (B) of the robot arm (Equation 1-3) allows the inverse kinematic the calculation of the joint angles 0_1 (Equation 1-4) and 0_2 (Equation 1-5) of the virtual robot arm [118], [125], [126].

$$P^B_{elbow} = A^B_3 P^3_{elbow} = A^B_1 A^1_2 A^2_3 P^3_{elbow} \tag{1-3}$$

$$0_1 = atan2(P^B_{elbow} \cdot y, P^B_{elbow} \cdot x) \tag{1-4}$$

$$0_2 = arcos(\frac{P^B_{elbow} \cdot z - d_{bs}}{d_{se}}) \tag{1-5}$$

The same approach proposed by Liu et al. is used, starting from the base (B) of the robot arm (Equation 1-6) enables the inverse kinematic the calculation of the joint angles 0_3 (Equation 1-7) and 0_4 (Equation 1-8), which form the elbow section [118], [126].

$$P^B_{elbow} = A^B_5 P^5_{wrist} = A^B_1 A^1_2 A^2_3 A^3_4 A^4_5 A^5_{wrist} \tag{1-6}$$

$$0_3 = atan2(n, m) \tag{1-7}$$

$$0_4 = acos\frac{p - d_{se}}{d_{ew}} \tag{1-8}$$

The following equation (Equation 1-9) formulated by Liu et al. allows the inverse kinematic system of the VR application to calculate the joint angles for 0_5 (Equation 1-10) and 0_6 (Equation 1-11), that determine the wrist section of the robot arm [118], [126].

$$P^B_{target} = A^B_7 P^5_{target} = A^B_1 A^1_2 A^2_3 A^3_4 A^4_5 A^5_6 A^6_7 A^7_{target} \tag{1-9}$$

$$0_5 = atan2(n, m) \tag{1-10}$$

$$0_6 = arcos(\frac{p - d_{ew}}{d_{wf}}) \tag{1-11}$$

The motion of 0_7 as described by Liu et al. (Equation 1-12) is used by the Unity implementation of the inverse kinematic as a rotation along the Z-axis, which results in the following equation [118], [126].

$$0_7 = atan2(m, n) \tag{1-12}$$

In addition to these equations that form the inverse kinematic system that was used in the HRC VR application, additional variables for the range of angles that the respective joints can cover and the maximum velocity at which the joints are allowed to move were present. This was required to prevent the robot from moving through its own body. The respective angles restrictions are derived from the robot model that uses the inverse kinematic system and are described here on the basis of the LBR iiwa series of industrial robots (Table **1-2**) [127].

Table **1-2**.: The movement characteristics of the virtual robot arm adopted from the manual of the LBR iiwa 7 R800 CR [127].

Axis	**Motion range**	**Max. Torque**	**Max. Velocity**
Axis 1 (A1)	±170°	176Nm	98°/s
Axis 2 (A2)	±120°	176Nm	98°/s
Axis 3 (A3)	±170°	110Nm	100°/s
Axis 4 (A4)	±120°	110Nm	130°/s
Axis 5 (A5)	±170°	110Nm	140°/s
Axis 6 (A6)	±120°	40Nm	180°/s
Axis 7 (A7)	±175°	40Nm	180°/s

Although the basis of the inverse kinematics system followed the structure of the LBR iiwa series manufactured by KUKA [119], [120], the general approach is applicable to most robots that operate with seven DoF [128]. This allows the inverse kinematics system used within the HRC VR application to be adopted with minor adjustments to a wide variety of industrial robots, which then can be represented as a virtual counterpart to serve within HRC empirical studies. This has been successfully applied to a successor project of this thesis, where a virtual representation of a YuMi-IRB 14000 dual-arm robot was equipped with the inverse kinematics system (cf. Section 7.4) [129].

1.3.6. Autonomy of the Robot

The collaboration between two entities bears the potential for unexpected circumstances. As described in Section 1.1.2, the ambition of HRC research is to enable industrial robots with the capabilities to react to the individual actions of their human collaboration partner while executing their specific allocated tasks. Machine learning is the most promising approach to realizing this ambition [12]. Therefore, the evaluation of industrial robots tasked with autonomously collaborating with human personnel required the usage of a machine learning approach. For this purpose, the Unity ML-Agents toolkit, an open-source project based on PyTorch[3] [131], was implemented into the HRC VR application. By using the ML-Agents toolkit, various machine learning techniques can be applied within the Unity 3D engine and allow to simulate learned behavior patterns with virtual objects [132]. In the context of the HRC VR application, a specific shared task procedure can be learned by the respective agents which assume control of the virtual robots and control the robot's movements through the inverse kinematic system. This is achieved by using the ML-Agents toolkit to train a neural network through the process of reinforcement learning on the basis of a reward and penalty policy [132], [133]. The training process itself can be adjusted through several configuration options within the ML-agents framework, e.g. the number of nodes in the neural network or the entropy can be set [131]. The training performance of the agents can be monitored by the Tensorflow utilities that can be accessed through Unity by the provided application programming interfaces (APIs) of the ML-agents toolkit (Figure **1-1**).

Since the goal of the HRC VR application is to provide a versatile environment for a wide variety of different collaboration setups, the implementation was required to be applied independently of a determined manufacturing procedure. However, due to the differences between the virtual setting where the position of an object within 3D space can be accurately determined and a real collaboration setup that is dependent on the interpretation of sensor data, none of the machine learning approaches presented in Section 1.1.2 were appropriate. Therefore, using the ML-agents toolkit required an approach specifically suited for a virtual setup. For this purpose, the finite state machine pattern proposed by Kyaw was used [134]. The finite state machine pattern consists of multiple states that can be chained together [134]. Each state contains a set of conditions that trigger and interrupt the actions of the respective state and the designated event that causes the state to resume. This allows a specific state to react towards specific interventions and return to the previous state if necessary. Conditions, roles, and events within a state a determined by the Relational Action process adopted from Toussaint et al. which is further described in Chapter 6 (Section 3.2.3) [135]. Additional abstraction layers can be added to continuously expand the finite state pattern with new states, conditions, roles, and events. The information regarding the different states can be delegated to the respective agents to adjust the requirements of the model that is trained.

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[3] PyTorch is a machine learning program library that provides high-level functionality for tensor computation and deep neural networks [130].

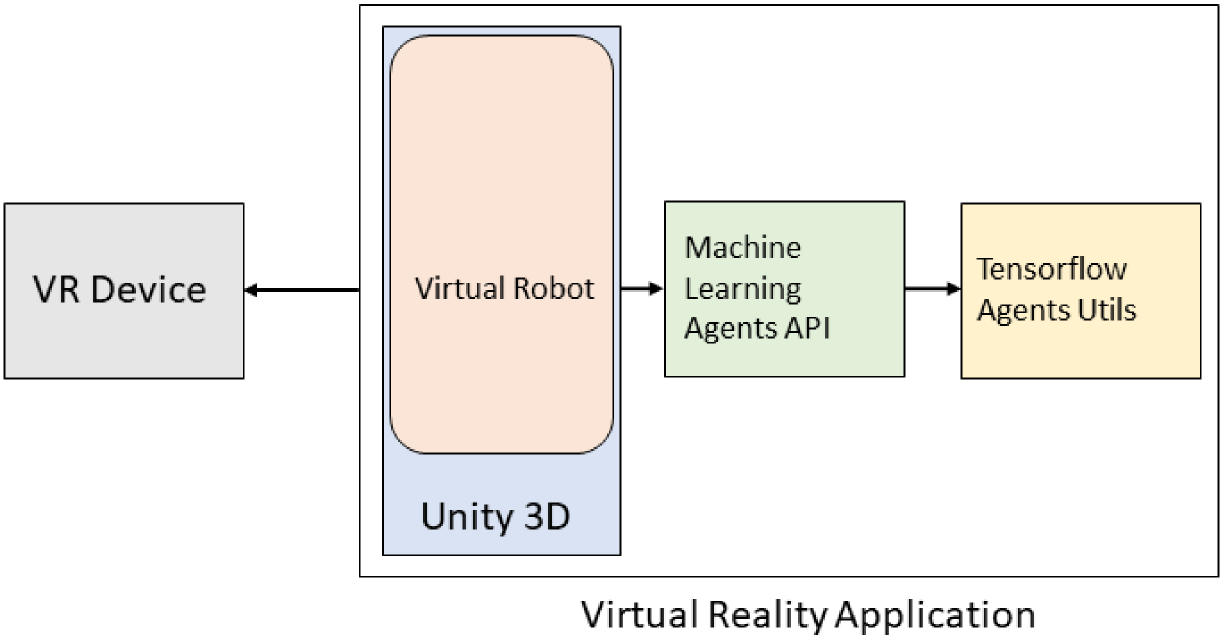


Figure **1-1**.: Overview of the architecture of the VR application.

This approach enables the robots that are represented within the HRC VR application to train various shared tasks following different procedures and execution parameters. This was used to implement a conceptualized shared task for use within the empirical studies and is further described in Chapter 3 (Section 3.1), Chapter 4 (Section IV. C), and Chapter 6 (Section 3.2.1).

Independent of the actual procedure of the shared task, four essential elements are required for the agents to learn. First is the position of the user's avatar which is represented by both the right and the left hand (see Chapter 3, Section 3.1, Fig. 1) as well as the head. This is important as the robot needs to know the current location of the users' head and hands to track their trajectory. Second is the position of the individual components that are used within the collaboration procedure in conjunction with the conditions defined from the respective state (Figure **1-2**). In addition to the components, the position of tools that are needed to be operated by the robot is required to be learned. Again operation procedures are derived from the respective state from the finite state pattern [134]. The fourth is the position of the robot's gripper point. This is necessary as the robot needs to learn its own position in relation to the other items. The spatial coordinates of the individual objects are represented as vectors that are being measured with each iteration of the robot's movement using the gripper point as a reference. By calculating the distance between the gripper point ($\vec{G}$) and the position of the requested item ($\vec{T}$), the reward was distributed in accordance with the distance (Equation 1-13) [129].

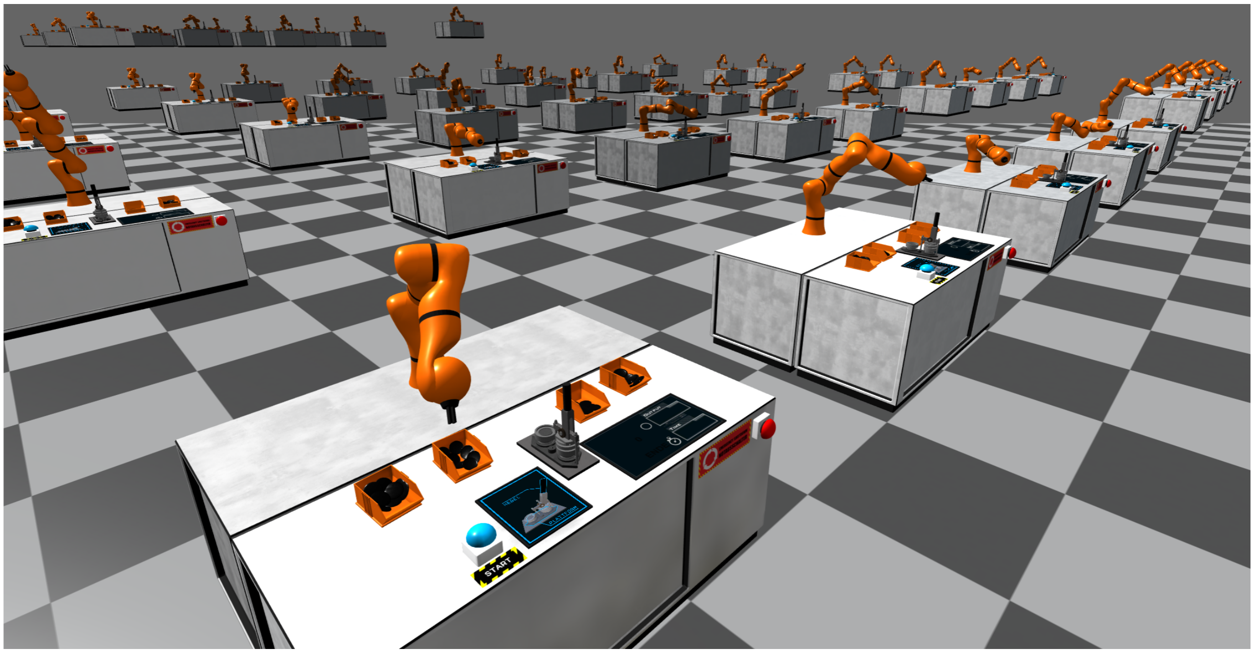


Figure **1-2**.: The learning setup where the agents of 60 individual robots trained simultaneously the targeting of the respective components necessary for the collaboration procedure.

$$0.8 \geq |\vec{T}\vec{G}| \Rightarrow \text{Reward: } + 1.0 \tag{1-13}$$

A penalty was awarded to the agent if the distance of the gripper point increased in comparison to the previous iteration of the training sequence (Equation 1-14) [129].

$$oldDistance \leq newDistance \Rightarrow \text{Penalty: } - 0.1 \tag{1-14}$$

By distributing a penalty if the agent increases the distance between the robot gripper point and the requested target by the finite state machine pattern, the agent is encouraged to adjust its trajectory to the target's direction. To provide the agents with additional information about the environment, the Mesh Collider system of the Unity 3D engine was incorporated as a trigger for the event conditions of the various agents and increasing the precision of the vector distance [136]. Each asset within the virtual environment received a Mesh Collider component, which established a bounding box around the respective 3D model (Figure **1-3**). To increase the precision of the trajectory anticipation, the virtual avatar of the user was equipped with three additional boundary zones in different distance gradations. Rewards for entering distinct boundary zones were distributed based on the conditions and scripted events of the respective state. Undesired intrusions of the robot into a boundary zone resulted in a penalty. The approach resulted in a training model that indicated a tendency to converge over time (Figure **1-4**a). This assumption is supported by a decrease in the episode length (Figure **1-4**b). The here-stated approach was refined in a successor project with the goal to equip the YuMi-IRB 14000 dual-arm robot with machine learning capabilities within the HRC VR application (see Section 7.4) [129], [137].

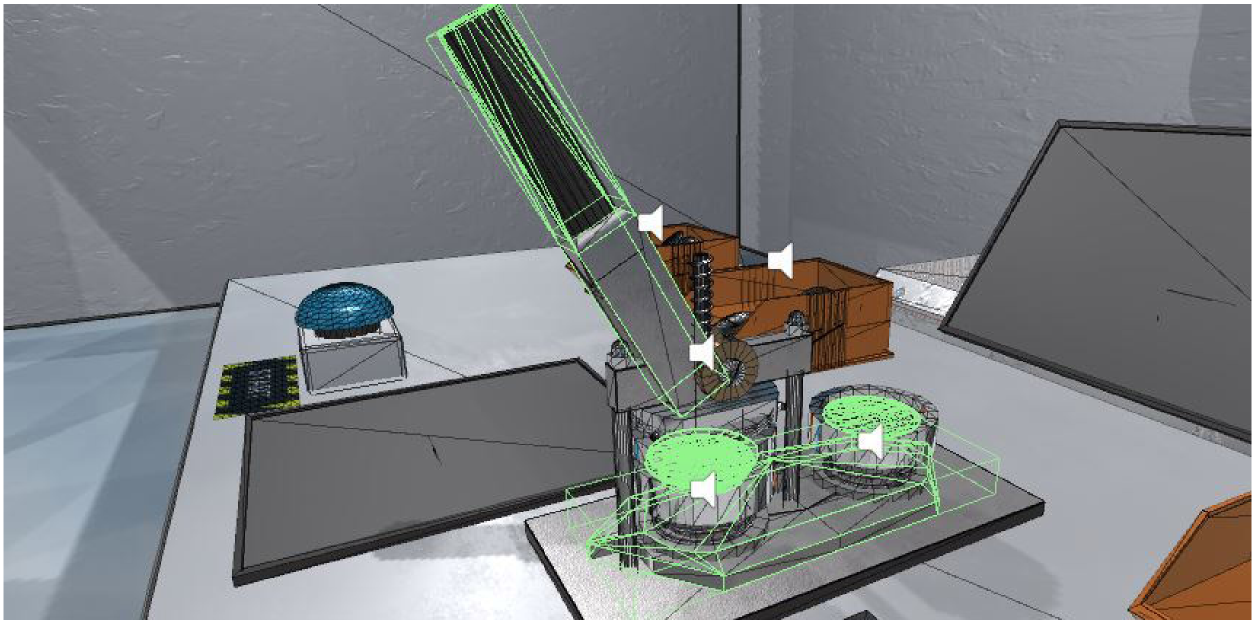
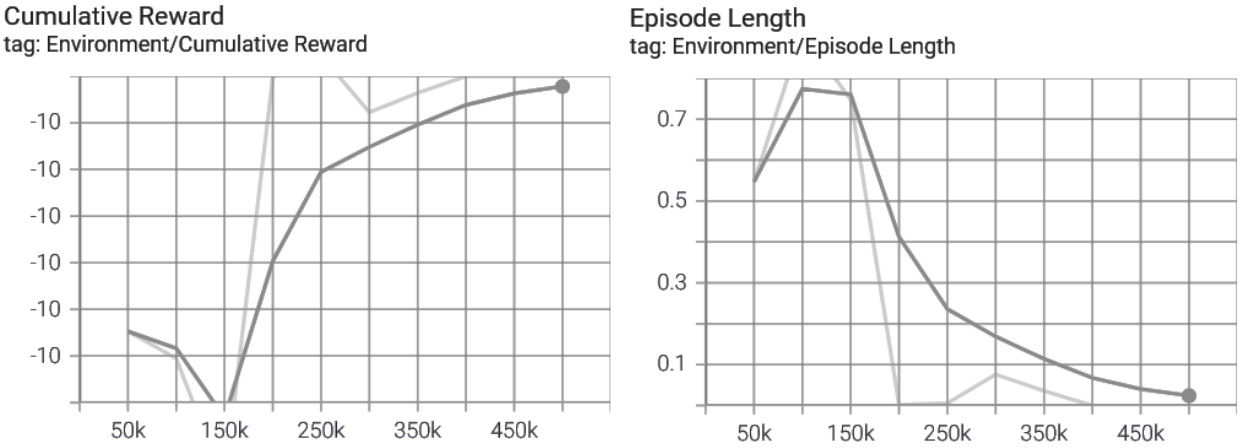


Figure **1-3**.: Based on the example of the pin-back button press, the various boundary zones displayed as green lines around specific objects relevant for agents to be monitored are illustrated [136], [138].



(a) Reward function of the training model on the Y-Axis and training iterations on the X-axis.

(b) Episode length of the training model on the Y-Axis and training iterations on the X-axis.

Figure **1-4**.: The two graphs from the Tensorflow console illustrate the appropriate training model that is used for the shared task of the empirical studies described in Chapters 3-6.

The described implementation of the ML-Agents in conjunction with the inverse kinematic systems explained in Section 1.3.5 enabled the robot to act and react autonomously and conduct the steps of the shared task (cf. Chapter 3 (Section 3.1) and Chapter 6 (Section 3.2.1)) defined in the state machine pattern in collaboration with a human partner. The resulting autonomous behavior of the robot was used in the five empirical studies included in this dissertation to investigate the overarching research questions established in Section 1.2, further described in the following synopsis.

1.4. Synopsis of the Included Publications

While the prior chapters have described in detail the definition and challenges of HRC along with the explanation of various aspects regarding the HRC VR application, this section contains the contributions of this dissertation, which are presented in the following chapters. The selected contributions follow the previously established research questions (Figure **1-6**) and are outlined in their key topics and dependencies in Figure **1-5**. The first segment contains the qualitative results of the preliminary study described in Chapter 2 and explores the general expectation of the collaboration with a robot [139]. In addition to this, the positive and negative aspects of the collaboration robot presented in Chapter 4 will be discussed [140]. The second segment deals with the communication augmentations and their effect on subjective measures such as perceived stress and emotions as outlined in Chapter 3 and the perceived safety reported in Chapter 6 [141], [142]. The third segment examines the association of the autonomous robot as an intelligent system derived from the results in Chapter 2 and reviews the effects of the intelligence attribution on the collaboration, which is reported in Chapter 5 [143]. The last segment summarizes Chapter 6 and contains the impact of communication on the production quantity and collision rate.

1.4.1. Expectations and Characteristics of the Collaborative Robot

This section summarizes the included publications dedicated to the general expectations towards the collaboration with industrial robots and the perceived negative and positive aspects during such collaboration. Explained in this section are the results of the research and the approach that was used to explore *RQ1* (*"What are the general expectations towards a collaborative industrial robot and which aspects will be perceived as positive or negative?"*.

Chapter 2: Preliminary-Study

Chapter 2 describes a preliminary study where the first iteration of the HRC VR application was used to explore the expectations that participants have towards the collaboration robot. As previously stated in Section 1.1.2, it is generally assumed that an autonomous collaboration robot that diverts in behavior and characteristics from the expectation of the human

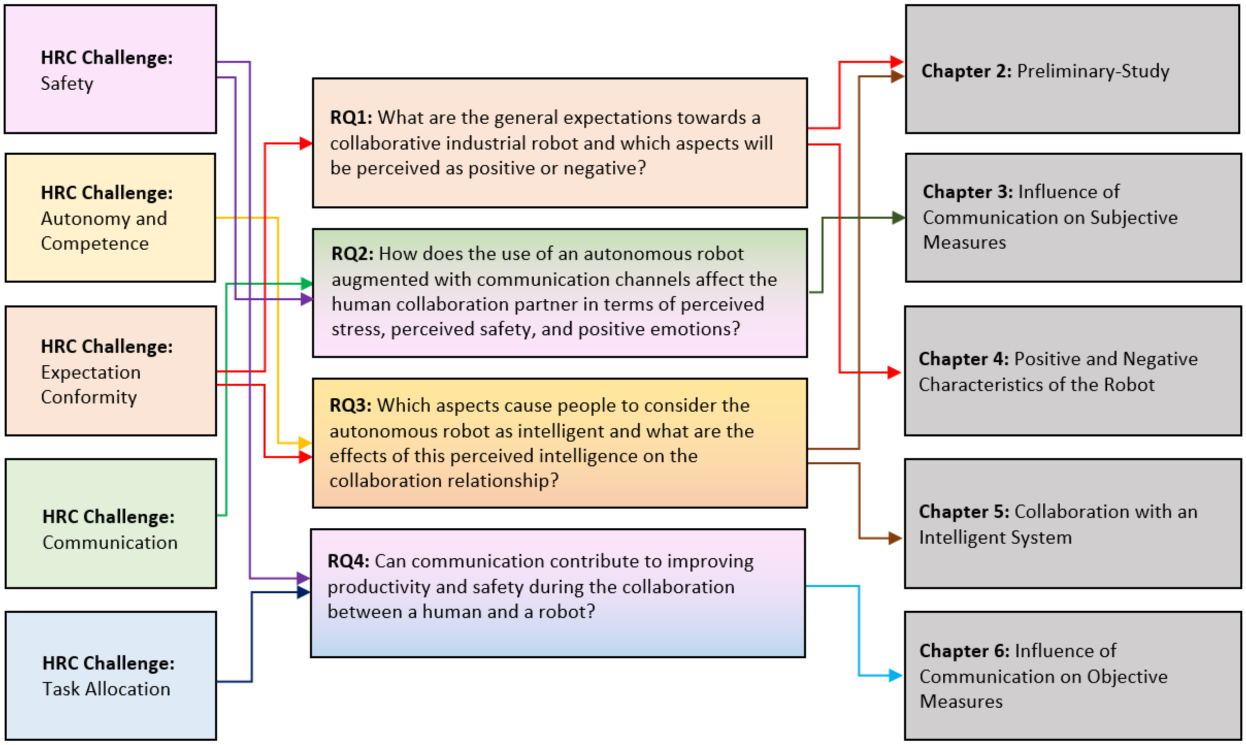


Figure **1-5**.: The assignment of the challenges to the respective research questions and the corresponding chapters.

operator can cause aversion that results in a diminished collaboration performance [63]. This is especially important, considering the widespread unfavorable opinion industrial personnel have towards automation systems [144]. Motivated by the necessity to investigate the general expectation toward collaborative robots, a qualitative approach with guided questions (cf. Appendix C) was used to collect answers from the participants after they were exposed to the VR application. Divided into three conditions (generic instructions vs. personalized instructions vs. gestures), participants were asked a set of seven prepared questions. The answers given in Chapter 2 revealed that the participants valued the competence, reliability, and trust of the robot as an important expectation. Further answers favored the condition with personalized instruction communication, where the robot addressed the participants through context-sensitive text messages formulated in natural sentences. The strong tendency of the participants to favor personalized instructions influenced the design of the text-panel communication channel in the succeeding studies described in Chapters 3-6. To optimize the representation of the robots' communication further, participants were asked to state additional communication methods that allow the robot to express itself, to accommodate the previously established research questions regarding communication in HRC settings formulated by Kaupp et al. (cf. Section 1.1.2) [70]. Answers indicated that the participants did not associate the text panel instructions with the robot. This led to a change in the design and representation of the text panel closer to the robot to elicit a stronger connection between the communication and the robot which is further described in Chapter 3 (Section 3.2) and validated in Chapter 5 (Section 4). An additional communication channel that was suggested by the participants was to equip the robot with light signals, similar to a traffic light. This suggestion has been adopted in the subsequent studies and is further explained in Chapter 3 (Section 3.2) and Chapter 6 (Section 3.2.4).

Chapter 4: Positive and Negative Characteristics of the Robot

To follow up on the collected impressions gained from the participants in Chapter 2, a qualitative study was conducted to investigate the positive and negative aspects of the robot in a refined version of the VR application. By using the elaborate study setup that is also used in Chapters 3 and 6, participants stated their opinion on the potential benefits of working with the robot and characteristics that they deemed adverse. The study contained a major contribution to the HRC research effort in identifying themes where users recognized the positive aspects of the collaboration with the robot. Across the communication and non-communication conditions, participants stated that the work in conjunction with the robot can improve the overall task efficiency. Another beneficial aspect that was attributed to the robot was the assistance with repetitive tasks. An important theme that emerged in the participants' answers was the relationship with the robot. Answers differed depending on the condition. While participants from the communication setup perceived the robot as more predictable and attributed more human behavioral characteristics, participants from the non-communication condition stated that they were required to better adapt to the robot. These themes contribute to the general perceived relationship within HRC settings and how distinct characteristics of the robots can influence this relationship as described in Section 1.1.2. In opposition to the potentially beneficial aspects were the negative characteristics lamented by the participants. Participants stated that the robot was too slow in its movement. This is a major aspect, as the current safety regulations mentioned in Section 1.1.2 that dictate the robots' speed limitations can prevent the effective coordination between both parties and influence further aspects such as expectation conformity (cf. Section 1.1.2) and task allocation (cf. Section 1.1.2). Another theme was the communication channels and their absence. Participants from the non-communication condition expressed uncertainty as they had difficulties comprehending the robots' actions. These findings emphasized the necessity of communication channels in collaboration to prevent uncertainty (cf. Chapter 3). Another negative aspect that is important for the challenges of HRC regarding the design of suitable collaboration robots is the unpleasant noise noted by the participants.

1.4.2. Influences of the Communicative Robot on Human Factors

The study presented in Chapter 3 examined human factors aspects, such as perceived stress and attributed emotions during the collaboration affected by the communication channels of the autonomous robot is reviewed in this section. The aim of the study from Chapter 3 aligns with *RQ2* (*"How does the use of an autonomous robot with augmented communication channels affect the human collaboration partner in terms of perceived stress, perceived safety, and positive emotions?´´*) and reports results that have implications for the use of communication channels in HRC workplace arrangements to improve the well-being of the respective personnel.

Chapter 3: Influence of Communication on Subjective Measures

As described in Section 1.1.2, communication is an essential aspect of HRC and collaboration settings among humans in general. However, as stated in Chapter 3, no common approach to the use of communication channels in HRC and their effect on the personnel exists. The role of communication in collaboration scenarios is widely accepted as the exchange of information to enable the formation of a common mental model about an individual's role and actions. Insufficient awareness about these aspects can increase the uncertainty during the collaboration, resulting in increased perceived stress [145], which can result in a negative emotional connotation of the collaboration experience. This can influence a person's willingness to perform during the collaboration, emphasizing the importance of this subject being investigated to ensure a successful implementation of upcoming HRC concepts. Based on the works of Cramton [146], Chapter 3 argues that a robot, capable of communicating its actions, could reduce a persons' mental load required to coordinate with the robot and contribute to the comprehensiveness of the system. Based on this, the study in Chapter 3 formulates hypotheses that state that the communication channels evoke less perceived stress and negative emotions in the participants. Furthermore, the expressiveness of the robot through the communication channel strengthens the perception of the robot as a (social) presence. To investigate this, the VR application was used in Chapter 3 to portray a shared task with an autonomous robot. By using a between-subjects design with two conditions (communication vs. non-communication) the influence of the communication channels on people's perceived stress was measured (cf. Appendix A). The design presented was also applied to the studies presented in Chapters 4 and 6. Results from Chapter 3 support the hypothesis that augmented condition induces less perceived stress in participants. The study discusses that participants from the non-communication condition were prevented from the formation of a workflow due to the absence of communication, resulting in higher perceived stress to perform the task. The outcome presented in Chapter 3 contains important implications for the design of the upcoming HRC settings, as the hereby presented combination of the three communication channels was able to reduce the perceived stress. Along with perceived stress, the experimental study reported investigated the effect of the communication channels on the users' emotions. Results indicate that participants felt more positive emotions after the collaboration with the augmented collaboration robot compared to their peers. This result has important implications as an HRC setup that produces negative emotions can diminish people's willingness to work with the robots, thus negatively affecting the collaboration effectiveness. The third aspect that that examined was if the communication channels elicit an increased (social) presence of the robot. Participants stated a more intense feeling of presence in the communication conditions, which supports the hypothesis and is in line with findings from Heerink et al. [147]. This outcome contributes to the research of the relationship between a human and robot during a collaboration setup, which is already described as a challenge in Section 1.1.2

1.4.3. The Robot as an Intelligent System

This section reviews the perception of the autonomous robot as an intelligent system and its influence on the collaboration relationship derived from *RQ3* (*"Which aspects cause people to consider the autonomous robot as intelligent and what are the effects of this perceived intelligence on the collaboration relationship?"*). The introduction of autonomous robots in collaboration scenarios shifts the robot's role from a tool that is operated by the human to an active element that contributes toward the collaboration. The presented studies examined the aspects that are required on the side of the robot to induce the impression of an intelligent system and how the perception of intelligence and agency affect the attribution of certain characteristics.

Chapter 2: Preliminary-Study

The preliminary study described in Chapter 2 explored the characteristics that participants expect from an intelligent system. Due to the efforts of HRC research to equip robots with autonomous behavior, it is important to explore the human perspective to align such a system with the user's expectations. The themes that emerged in the qualitative answers revealed that participants expect that an intelligent system is able to adapt to the current situation while remaining predictable in its actions. Another aspect stated by the participants was the execution of self-determined actions which enable the intelligent system the expression of agency. The third theme was the display of spontaneous behavior. These results supply HRC research with directives to design the autonomous behavior of the robot in accordance with the user expectation of an intelligent system.

Chapter 5: Collaboration with an Intelligent System

This chapter shifts the scope regarding the research of attributed intelligence from a qualitative approach in Chapter 2 to a study using the refined virtual setup. The online study was designed along with a 2 (augmented communication vs. non-augmented condition) x 2 (AI-narrative vs. non-AI-narrative) between-subjects structure and presented participants with a recording of the collaboration procedure lifted from the prior empirical studies (Chapter 2-4). The recording contained intentional mistakes and deviations from the collaboration procedure made by the human representative and the autonomous robot. Participants from the AI-narrative were explicitly briefed about the artificial intelligence of the robot (cf. Appendix B). A strong focus of Chapter 5 is the effect of expected autonomy. Based on the assumption that a more intelligent system elicits more human-like characteristics and personalized behavior [83], the study examined which characteristics are associated with the autonomous robot. This is important as positive and negative attributes can shape the collaborative relationship between the robot and the human personnel. While the results indicated no significant difference between the condition with the AI-narrative and the non-AI-narrative in terms of perceived intelligence, participants from the AI-narrative condition rated the robot as more independent and cooperative. Also, the ability to perceive and interpret was rated higher in the AI-narrative.

The relationship between humans and autonomous robots can develop an interesting dynamic in a work environment where mistakes can have serious ramifications. Considering that the autonomy of the robot reduces the humans' control of the system, the question emerges which party is to blame for incorrect action. The question of the responsibility for mistakes made by the autonomous system and on the contrary the credit for successful tasks can have major effects on the effectiveness of HRC [148]. The results of the study indicate no significant difference in the attribution of blame and credit between the AI-related conditions. The research work, therefore, provides the HRC community a first indicator regarding the dedication of responsibility in collaboration settings involving autonomous robots.

Another aspect that was covered in Chapter 5 was the effect of communication and transparency in HRC settings. Based on the findings of Chapter 3 where the communicating robot was attributed with a higher (social) presence, it was of interest to investigate which additional human characteristics participants attributed to the robot augmented with communication channels. The outcome of the study indicates that participants perceived the robot from the communication condition as a better collaboration partner and attributed this condition a higher collaboration success. In terms of human characteristics, participants rated the communicating robot as more dominant. Chapter 5, therefore, completes the results regarding the perception of the robot equipped with the communication channels from Chapter 3.

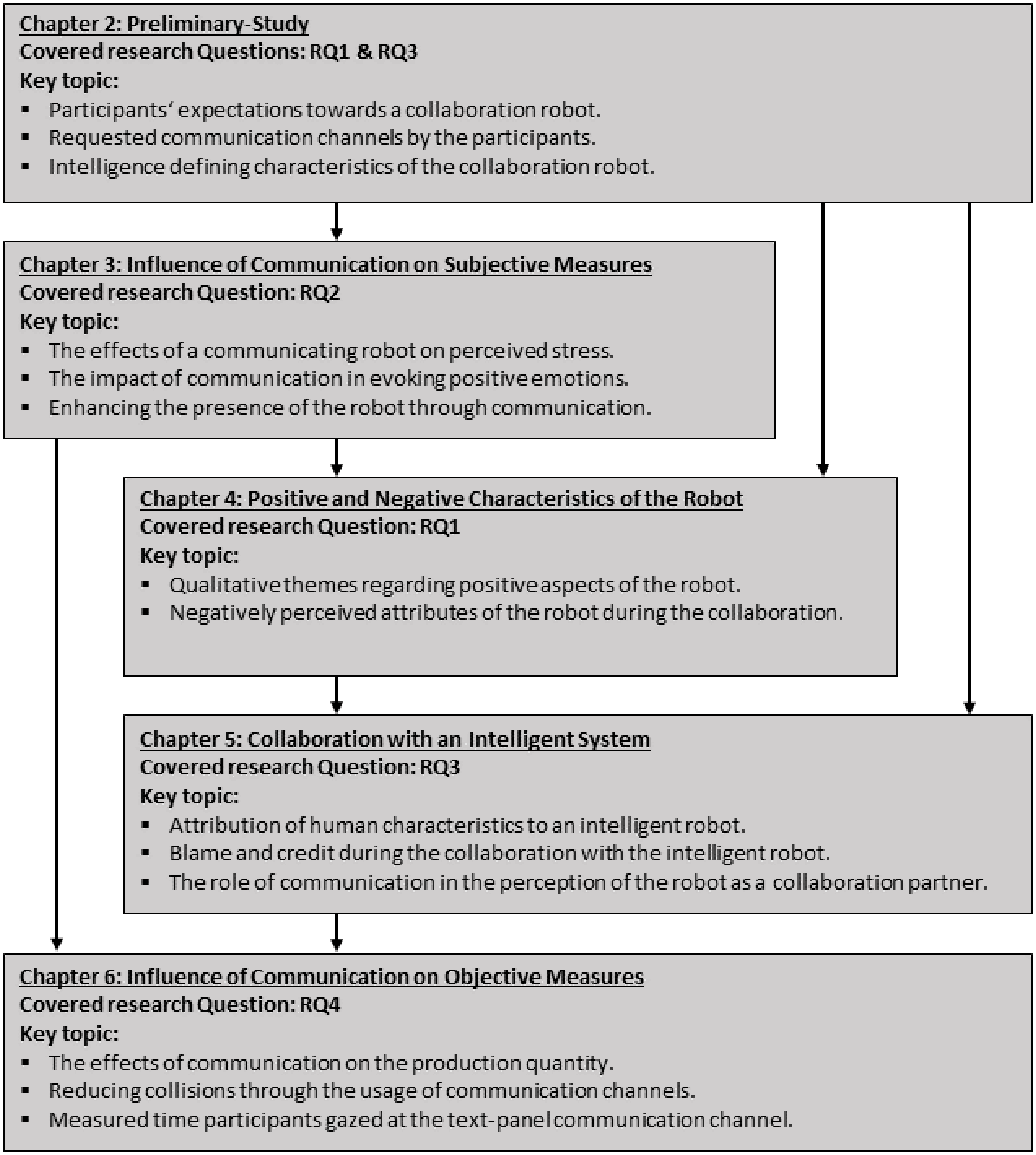
1.4.4. Effects of Augmented Communication on Objective Measures

In this section, the research work of Chapter 6 is discussed. In accordance with *RQ4* (*"Can communication contribute to improving productivity and safety during the collaboration between a human and a robot?"*) the hereby reported study examined the effect of augmenting the robot with communication channels on two objective measures, production rate, and collision frequency during the collaboration. The results of the research contribute to the improvement of HRC as both objective measures are important aspects regarding production effectiveness and safety.

Chapter 6: Influence of Communication on Objective Measures

The positive effects of the communication channels observed on subjective measures in Chapter 3 prompted the interest in whether the use of augmented communication can provide benefits for objective measures as well. As already stated, HRC research is confronted with various challenges in the implementation of safety precautions (cf. Section 1.1.2). Chapter 6 addressed these challenges by examining methods that could provide enhanced safety but at the same time preserve the full spectrum of the collaboration abilities for both parties. The approach was using the communication channels (text-panel, multi-colored light signals, and gestures) to notify participants the robot detected an imminent collision while simultaneously initiating countermeasures. To test the effectiveness of this approach, the study in Chapter 6 used the same between-subjects design (communication vs. non-communication) as the studies reported in Chapters 3 and 4. Participants divided into two conditions with gender parity were then tasked to assemble pin-back button components in collaboration with the robot. Results showed statistically significant less frequently detected collisions in the communication condition compared to the non-communication variant. This finding of Chapter 6 not only contributes to the efforts of research in the field of HRC through the indication that the communication of the robot notified participants to react more appropriately towards the imminent collision but also through the effectiveness of the communication channel composition (text-panel, multi-colored light signals and gestures). Although not an objective measure, adjacent to the interest in enhancing the actual safety was the effect of the communication channels on the perceived safety (cf. Appendix A). Again the results indicated a contribution of the communication channels towards a stronger perceived safety. This is discussed in Chapter 6 by arguing that the communication expressed by the robot reinforced the perception of safety by lowering the uncertainty felt by the participants during the shared task. The outcome reported in this study can help to further optimize the configuration of HRC workplace arrangements in terms of safety with the inclusion of human factors aspects.

Chapter 6 also investigates the use of communication channels to improve the production rate. Although the effectiveness of HRC plays a major role in its widespread adoption throughout various industries, the aspect of investigating measures to increase production rate is often neglected in HRC-related studies. Same as with the collision rate, participants from the communication condition outperformed their peers from the non-communication condition in terms of the number of produced pin-back buttons. Chapter 6 argues that the communication channels, specifically designed to provide guidance and explanation for the collaboration procedure assisted participants in the formation of a mental model of the required task. Participants who did not receive the guidance and explanation were on their own to acclimate to the collaboration procedure, resulting in a slower production rate. The implications for *RQ4* gained from these results are that upcoming HRC workplace arrangements can benefit from the augmentation of the robot with communication channels as they allow for collaboration to be more effectively resulting in more produced goods and less frequent collisions in conjunction with a higher perception of the HRC-setup as a safe system.



Chapter 2: Preliminary-Study
Covered research Questions: RQ1 & RQ3
Key topic:
- Participants' expectations towards a collaboration robot.
- Requested communication channels by the participants.
- Intelligence defining characteristics of the collaboration robot.

Chapter 3: Influence of Communication on Subjective Measures
Covered research Question: RQ2
Key topic:
- The effects of a communicating robot on perceived stress.
- The impact of communication in evoking positive emotions.
- Enhancing the presence of the robot through communication.

Chapter 4: Positive and Negative Characteristics of the Robot
Covered research Question: RQ1
Key topic:
- Qualitative themes regarding positive aspects of the robot.
- Negatively perceived attributes of the robot during the collaboration.

Chapter 5: Collaboration with an Intelligent System
Covered research Question: RQ3
Key topic:
- Attribution of human characteristics to an intelligent robot.
- Blame and credit during the collaboration with the intelligent robot.
- The role of communication in the perception of the robot as a collaboration partner.

Chapter 6: Influence of Communication on Objective Measures
Covered research Question: RQ4
Key topic:
- The effects of communication on the production quantity.
- Reducing collisions through the usage of communication channels.
- Measured time participants gazed at the text-panel communication channel.

Figure **1-6**.: The organizational structure, main theme, key topics, order and the dependencies of the included publications.

2. Experiencing AI in VR: A Qualitative Study on Designing a Human-Machine Collaboration Scenario

This publication was accepted and presented in 7/2020 at the 22nd International Conference on Human-Computer Interaction (HCI International 2020)[1]. The conference aims to deliver an international format for the exchange of innovative scientific research on theoretical and applied fields of Human-Computer Interaction and their auxiliary categories.

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Author	**Contribution**	**%**
Alexander Arntz	- Conceptualization of the approach - Implementation of the VR-application - Qualitative Study - Altering the VR-application based on the results	85%
Sabrina C. Eimler	- Supervision - General advice for the study design	15%

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[1] 1HCI International 2020 Website: https://2020.hci.international/

Experiencing AI in VR: A Qualitative Study on Designing a Human-Machine Collaboration Scenario

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Abstract. This paper describes the setup and results of a qualitative interview study, in which participants were given the opportunity to interact with an AI-based representation of a robotic-arm in a virtual reality environment. Nine participants were asked to jointly assemble a product with their robotic partner. The different aspects of their experiences, expectations and preferences towards the interaction with the AI-based industrial collaboration partner were assessed. Results of this study help to inform the design of future studies exploring working arrangements and communication between individuals and robots in collaborating together.

Keywords: Human-machine collaboration · Artificial intelligence · Virtual reality · Qualitative study

1 Introduction

Recent advancements in Artificial Intelligence (AI) and industrial robotics enabled the first step towards true Human-Machine Collaboration (HMC), which allows for new concepts of industrial production [14]. Envisioning these upcoming production scenarios in the age of digitalization is a major advantage for creating optimized and efficient workplaces [7]. Virtual Reality (VR) delivers the tool to validate concepts for production processes of the future before they become reality [4]. This allows to explore how individuals behave, when confronted with AI-enhanced industrial robots in a safe and controlled virtual environment, that can be adjusted for any scenario or robot manifestation or behavior. One of the key aspects of HMC is that a human and a robot entity work as equal parties together to accomplish a task [9]. Apart from the technical implementation of the machine, the human factor should not be neglected. One of the major problems is the outward appearance of the robot, considering that a robot in such a scenario is not antropomorphic but embodied as an industrial robot-arm. The lack of verbal communication paired with the absence of body language hampers the interpretation of the machine's intention [2]. This is critical as an autonomously

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acting machine, that is unpredictable in terms of communicated behavior, might induce aversion [11]. In addition, according to a study by the European Union, the disdain against autonomous machines and AI-systems is already widespread among the industrial workforce [12]. These unfavorable opinions, currently aimed towards the fear of being replaced and loss of the job, might be fueled by poorly designed HMC workplaces, thus leading to a fail of the concept. This renders the need for investigating how AI-enhanced robots in such scenarios should behave and communicate. This paper presents results from an exploratory qualitative study, in which 9 participants from different levels of prior experiences with robotics interacted with an AI-driven robot-arm in a virtual reality workspace environment. A qualitative method was used to gain insights into users' feelings, expectations and thoughts in pursuing a joint construction task with the AI-driven robotic-arm. The following parts describe research questions, scenario description and methods used. Results and implications are discussed.

1.1 Research Questions

The projected VR-experimental approach demands to design the robot-arm with a comprehensible interface that communicates the robot's action to the participants enabling an efficient collaboration process. As outlined earlier, it is especially important to determine which expectations people have towards an AI-enhanced collaborative robot-arm, in which ways they want to communicate with the system and which characteristics evoke participants feeling of an intelligent robot. Therefore, the interview was guided by the following research questions:

- **RQ1:** What are participant's expectations towards a collaborative robot-arm?
- **RQ2:** Which communication methods are requested by the participants?
- **RQ3:** Which characteristics make the robot-arm appear as an intelligent system?

2 Study Setup and Procedure

The study involved 9 participants, with 3 assigned for each of the 3 conditions. Every condition consisted of 2 males and 1 female participant. All of them were students recruited from the University of Applied Sciences Ruhr West (Bottrop, Germany). A purposive sampling was chosen according to preselected criteria e.g. age, gender, experience with robots, technical expertise and previous knowledge in manufacturing work. Each condition contained a virtual software agent driven robot-arm, capable of autonomously reacting to the participant's input and collaborating with them. The conditions differed only in the way the virtual robot communicated its actions to the participants, based on suggestions found in prior Human-Robot interaction related studies [3,8,13]. The first condition contained generic text instructions (e.g. “component is removed”, “task successful”) placed right next to the user (Fig. 1(A)). The second used instructions written in first person (e.g. "I am now placing the component into the container"), adapted from the natural communication pattern established by voice assistants (Fig. 1(B)). In the third condition the robot merely relied on gestures to communicate its intentions to the user (Fig. 1(C)). Participants were given 10 minutes to collaborate with the robot in an assembling task, self-determining working speed, procedure and coordination with their robot partner. Afterwards, each participant received a debriefing and was interviewed.

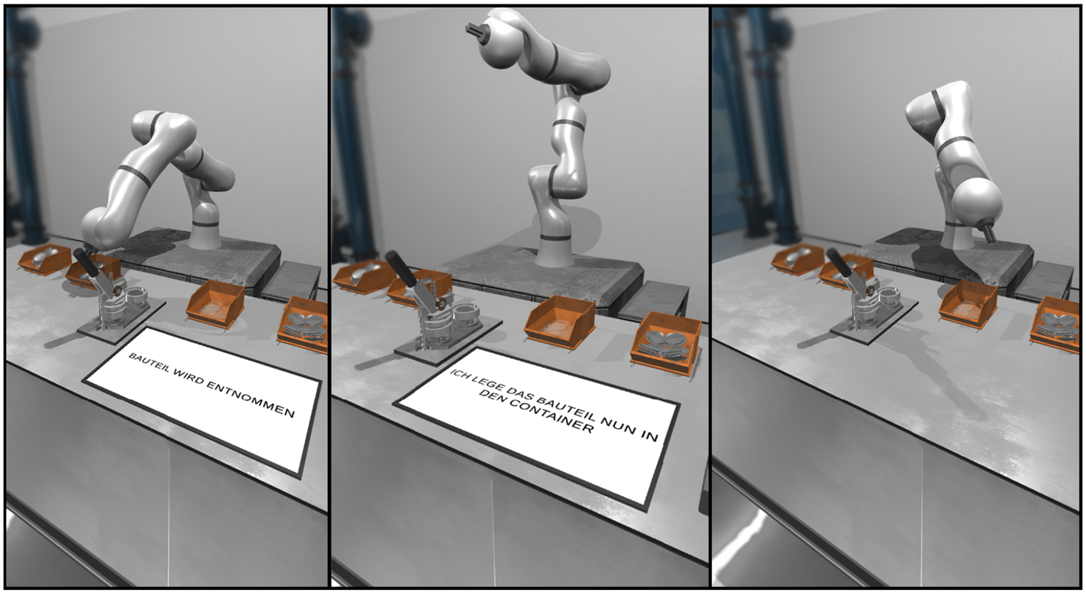

Fig. 1. The 3 conditions from left to right: (A) generic instructions condition, (B) personalized instructions condition, (C) gestures condition

The interviews were conducted with each participant individually after the interaction with the system. The interviews took place in a prepared seating area, enabling participants a more comfortable environment for the interrogation. A total of 7 predefined questions helped to structure the interview (Table 1). The questions were derived from the already stated research questions. During the interview, participants were encouraged to voice their thoughts and explain their answers in detail. For analyzing purposes, all interviews were audio recorded and transcribed. On average, the time spend with the participants was about 20 minutes. The interview language was German, thus all quotes were translated for this paper. Transcribed answers were categorized along the research questions.

3 Findings

This section presents the main themes which emerged during the conducted interviews and the subsequent data analysis.

Table 1. Questions asked in the qualitative interview.

No.	Question
1	How did you feel about the cooperation with the robot?
2	What expectations towards a robot do you have, if you have to work with it?
3	Which forms of communication of the robot did you perceive?
4	What additional forms of communication would you wish for, if you had to work with the system?
5	What characteristics would you assign to the robot?
6	Which aspects of the robot did you find unpleasant?
7	Which characteristics would the robot have to have for you to perceive it as an intelligent system?

3.1 RQ1: What Are Participant's Expectations Towards a Collaborative Robot-Arm?

Across all conditions, participants from both genders stated that the competence (the robot knows its task and knows what to do) of the robot-arm is a crucial factor for a successful collaboration. Also, they referred to aspects of uncertainty avoidance, in highlighting the importance of a) reliability (no need to control the robot, it reliably does its job) and b) trust (does not hurt people). The ability to work independently is a recurring theme stated by the participants.

"That he does the tasks he's supposed to do, that I don't have to work beyond my assigned tasks. Above all, he must be competent and reliable, so that I don't have to constantly keep an eye on if the tasks were being completed. I have to know that I only have to do my part"

(female participant no. 2, gestures condition)

"I expect that I can trust the robot to do his job competently. Also that he can work independently"

(male participant no. 2, personalized instructions condition)

"So the main criteria is that I can trust the robot to do its job. But also that it can work independently. That he doesn't hurt me and that everything is working smoothly".

(male participant no. 1, generic instructions condition)

Further quotes gathered from other participants corroborate the shared expectation of a robot-arm that is capable to conduct the instructed task, minimize or prevents failures and decreases workload for the person that is collaborating with it. The theme of competence was put forward by all participants, independent of the condition or prior exposure with robots. One aspect on the perceived competence that is associated with the robot is the communication, covered by the second research question.

3.2 RQ2: Which Communication Methods Are Requested by the Participants?

Although participants exposed to the condition with the personalized text output (condition B) stating the robot's intentions) rated the collaboration process more favourably than participants from other conditions, additional ways for the robot to express itself such as light signals were recommended.

"I only recognized the text output as a communication form there and that he also waits for me if I haven't done something yet. I would like to have a color signal, a light or something similar, directly on the robot. I always had to look back and forth between the text field and the moving robot. The robot and the text was not in my field of vision and forced me to look back and forth between them. A control lamp, like a traffic light on the robot, yellow, green, red, so that you know the next step is due. Then I would find it easier to work with the robot".

(male participant no. 3, generic instructions condition)

In addition to criticising the monitors' location that forced participants to continuously shift their view between the robot-arm and the text, participants commented that the monitor displaying the text should be placed in vicinity of the robot-arm.

"I had not associated the text instructions directly to the robot. I think it would help if the text was written as if it came from the robot itself. For example, I do this and that instead of the robot does this and that. Also the monitor should be directly in front of the robot, so you can see both at the same time. Then it also looks like the statement is coming directly from the robot"

(male participant no. 2, generic instructions condition)

The implementation of gesture based communication (condition C) turned out unfavourably as no consensus in the interpretation of the meaning emerged among participants. The only gesture that was uniformly recognized was the termination of motion, once the robot-arm detects that the participant approximates to close for safe operations.

"I wasn't paying attention directly at it. But there were certain movements where he didn't go directly to the component but hinted at something. But I can't tell you exactly what it meant.

(male participant no. 3, gestures condition)

"I could not recognize gestures. I only noticed sometimes that the robot came unnecessarily far forward, what that means I don't know. But what was clear was that I should not get too close to the robot".

(male participant no. 1, gestures condition)

"I did not really notice any gestures apart from that I just tested if it would stop when I put my hand in its way and it did. So when you put yourself in danger, that it stops and waits. If you take your hand away, it continues".

(female participant no. 2, gestures condition)

3.3 RQ3: Which Characteristics Make the Robot-Arm Appear as an Intelligent System?

Independent of the condition, most participants stated that the robot-arm adapting to actions outside of the procedure is the greatest indicator for intelligence. The variety of descriptions of intelligent behaviors ranged from a) adaptation, in the sense of compliance with predefined rules, b) a reflection-based reaction and self-determined selection of behavior and c) showing signs of spontaneous behavior outside of parameters.

"The robot must be able to cope with unforeseen events. That would be a form of intelligence for me. But just that it can tell when you get too close and it stops, shows a representation of logic. That the robot not stubbornly does something, but that it constantly evaluates its environment and acts according to it".

(male participant no. 2, personalized instructions condition)

"For me to call the robot intelligent it would have to show some form of spontaneity. Spontaneity in the sense that the robot does not work with predetermined steps but can react to new situations"

(male participant no. 1, personalized instructions condition)

Occasionally, participants were unsure whether or not the robot-arm needs some sort of intelligence. While others stated that the impression of intelligence is linked to human like characteristics such as the presence of a face. Thus, the perception of the robot-arm as an intelligent system can be evoked by adjusting the way it communicates.

"An intelligent system, mmmh difficult question. Well, I couldn't say at this point if the robot is intelligent or not. Overall, it did the tasks it was designed to do. I don't think there's any need for more intelligence".

(male participant no. 1, generic instructions condition)

"Sounds a bit cliché, but maybe the robot should have a face. Of course, in terms of an industrial scenario, I don't know. I got the instruction through this text box. Maybe it just needs to be designed differently to relate better to the robot. That probably changes the perception of intelligence as well".

(female participant no. 3, generic instructions condition).

4 Discussion

The gathered data from the qualitative interviews delivered valuable insights in the expectations people might have for a HMC scenario involving AI-enhanced industrial robots and was a first step for determining the communication design of the robot, which was at that time under development. It also shows the diverse requirements for such a system to be faced in order to be accepted by people. Minute aspects in the communication design determine the perception of the robot and can possibly repell people, fueling existing negative attitudes towards the robot. This is especially prevalent in non anthropomorphic robot representations, which are generally perceived as more cool and dismissive compared to their android counterparts [10]. A major factor for the concept of HMC is the execution of the work by both parties as equal partners. For this reason it was necessary to investigate, at what degree the participant would qualify the system a form of intelligence. A convergence can be made on spontaneous reactivity, as the majority of participants valued it, apart from the actual competence on the task, as the highest indicator of a intelligent system. Although such high expectations a difficult to meet in terms of technical implementation, the impression of such reactivity can be made by adding more and refined communication interfaces (i.e. the light signals, visual feedback along the text output). Apart from safety precautions for collision avoidance, the usage of gestures turned out not effective enough as a communication basis in such a scenario. However, there are some limitations to the results, the limitations of the study are needed to be acknowledged. As previously stated, the majority of participants that formed the sample consisted of students recruited from the University of Applied Sciences Ruhr West. Even tough, the sample does not represent the overall population, the composition of the sample was cast from diverse technical backgrounds, offering wide range from no prior exposure and knowledge of robotics and AI-systems to expert level. Also, the sample size is small and, although this could lead to inadequate depth for collecting data, the interviews indicated repeating concepts without new emerging themes. Additional HMC scenarios with a diverse range of tasks remain to be explored in further studies and should help continuously refine the communication capabilities of the robot in order to meet user expectation and supplying an effective way for collaborative work.

5 Conclusion

The ongoing digitalization of the industrial working environment is in full motion [5]. It is expected that this will have a major influence on the workforce, as it is not only introducing new production processes but also new concepts of how employees interact with machinery such as robots [6]. Through continuous advancements in artificial intelligence and machine learning algorithms, the concept of equal collaboration between human workers and robotic entities is not some far-fetched vision of the future anymore [1]. However, the implications that such a major shift in sociotechnical systems will bring, have to be investigated. Results of this exploratory interview study will be taken into account, i.e. adding light signals and shifting the communications display in vicinity of the robot, to enhance future VR-based HMC studies that will explore different working arrangements.

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References

1. Arntz, A., Eimler, S., Handmann, U.: Artificial intelligence driven human-machine collaboration scenarios in virtual reality (poster) (2018). http://www.handmann.net/pdf/IA-Poster-ArnEimHan2018.pdf
2. Embgen, S., Luber, M., Becker-Asano, C., Ragni, M., Evers, V., Arras, K.: Robot-specific social cues in emotional body language. In: Proceedings - IEEE International Workshop on Robot and Human Interactive Communication, pp. 1019–1025, September 2012. https://doi.org/10.1109/ROMAN.2012.6343883
3. Ende, T., Haddadin, S., Parusel, S., Wüsthoff, T., Hassenzahl, M., Albu-Schäeffer, A.: A human-centered approach to robot gesture based communication within collaborative working processes, pp. 3367–3374, September 2011. https://doi.org/10.1109/IROS.2011.6094592
4. de Giorgio, A., Romero, M., Onori, M., Wang, L.: Human-machine collaboration in virtual reality for adaptive production engineering. Proc. Manuf. **11**, 1279–1287 (2017). https://doi.org/10.1016/j.promfg.2017.07.255
5. Hermann, M., Pentek, T., Otto, B.: Design principles for industrie 4.0 scenarios: a literature review, January 2015. https://doi.org/10.13140/RG.2.2.29269.22248
6. Kirschner, D., Velik, R., Yahyanejad, S., Brandstötter, M., Hofbaur, M.: YuMi, come and play with me! A collaborative robot for piecing together a tangram puzzle. In: Ronzhin, A., Rigoll, G., Meshcheryakov, R. (eds.) ICR 2016. LNCS (LNAI), vol. 9812, pp. 243–251. Springer, Cham (2016). https://doi.org/10.1007/978-3-319-43955-6_29
7. Mueller-Abdelrazeq, S.L., Stiehm, S., Haberstroh, M., Hees, F.: Perceived effects of cycle time in human-robot-interaction. In: 2018 IEEE Workshop on Advanced Robotics and its Social Impacts (ARSO), pp. 25–30. IEEE (2018). (27092018–29092018). https://doi.org/10.1109/ARSO.2018.8625819
8. Scheunemann, M.M., Salge, C., Dautenhahn, K.: Intrinsically motivated autonomy in human-robot interaction: human perception of predictive information in robots. In: Althoefer, K., Konstantinova, J., Zhang, K. (eds.) TAROS 2019. LNCS (LNAI), vol. 11649, pp. 325–337. Springer, Cham (2019). https://doi.org/10.1007/978-3-030-23807-0_27
9. Shah, J., Wiken, J., Williams, B., Breazeal, C.: Improved human-robot team performance using chaski, a human-inspired plan execution system. In: Billard, A., Kahn, P., Adams, J.A., Trafton, G. (eds.) Proceedings of the 6th International Conference on Human-Robot Interaction - HRI 2011, p. 29. ACM Press, New York (2011). https://doi.org/10.1145/1957656.1957668
10. Straßmann, C.: All eyes on the agent's appearance?!: Investigation of target-group-related social effects of a virtual agent's appearance in longitudinal human-agent interactions. Ph.D. thesis, June 2018
11. Straßmann, C., von der Pütten, A.R., Yaghoubzadeh, R., Kaminski, R., Krämer, N.: The effect of an intelligent virtual agent's nonverbal behavior with regard to dominance and cooperativity. In: Traum, D., Swartout, W., Khooshabeh, P., Kopp, S., Scherer, S., Leuski, A. (eds.) IVA 2016. LNCS (LNAI), vol. 10011, pp. 15–28. Springer, Cham (2016). https://doi.org/10.1007/978-3-319-47665-0_2
12. European Union: Special eurobarometer 382: public attitudes towards robots (2014). https://data.europa.eu/euodp/de/data/dataset/S1044_77_1_EBS382. Accessed 13 Mar 2020

13. Yanco, H., Drury, J.: A taxonomy for human-robot interaction, pp. 111–119, December 2002
14. Zheng, P., Sang, Z., Zhong, R., Liu, Y.: Manufacturing systems for industry 4.0: conceptual framework, scenarios and future perspectives. Front. Mech. Eng. **13**, 137–150 (2018)

3. Augmenting the Human-Robot Communication Channel in Shared Task Environments

This paper was accepted and presented in 9/2020 at the 26th International Conference on Collaboration Technologies and Social Computing (Collabtech 2020). With a competitive acceptance rate for a full paper of 10 out of 25 submissions for the 2020 rendition, the CollabTech conference format provides a forum for academics and practitioners to share experiences regarding the development of collaboration technologies. The majority of accepted publications contain innovative technological, conceptual, or organizational approaches to extend the support of collaboration. Presented works are the result of diverse backgrounds from various disciplines in computer science, cognitive science, management science, and social science. Due to the wide range of collaborative applications and their accompanying technologies, research in this field is validated through multiple processes including experimental studies, fieldwork, prototyping, and empirical tests.

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Author	**Contribution**	%
Alexander Arntz	- Conceptualization of the approach - Implementation of the VR application - Conduct of the experimental study	70%
Sabrina C. Eimler	- Supervision - General advice for the study design	15%
H. Ulrich Hoppe	- General supervision	15%

Augmenting the Human-Robot Communication Channel in Shared Task Environments

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Abstract. Adaptive robots that collaborate with humans in shared task environments are expected to enhance production efficiency and flexibility in a near future. In this context, the question of acceptance of such a collaboration by human workers is essential for a successful implementation. Augmenting the robot-to-human communication channel with situation-specific and explanatory information might increase the workers' willingness to collaborate with artificial counterparts, as a robot that provides guidance and explanation might be perceived as more cooperative in a social sense. However, the effects of using different augmentation strategies and parameters have not yet been sufficiently explored. This paper examines the usage of augmenting industrial robots involved in shared task environments by conducting an evaluation in a virtual reality (VR) setting. The results provide a first step towards an iterative design process aiming to facilitate and enhance the collaboration between human's and robot's in industrial contexts.

Keywords: Human-Robot Collaboration · Virtual reality · Augmentation · Shared task

1 Introduction

Human-Robot Collaboration (HRC) is a promising approach for future industrial production [6] with settings in which human workers and robots work together to achieve a common goal, e.g. an assembling task. The idea is to make production cycles more adaptive, as HRC combines the precision and endurance of industrial robots with the intuition and experience-based decision-making of human workers [22]. While current implementations of this concept delegate the control over the robot to the employee, it is anticipated that robots will be able to act in more adaptive and autonomous ways. This shifts the working relationship from the human operating the robot as a tool, to a shared task

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environment where both parties act collaboratively and contribute specialized skills [8]. However, there are currently no established concepts how these shared task environments involving autonomous robots can be augmented to ensure the acceptance and willingness to collaborate with them. It is assumed that a robot augmented with the capabilities to explain its actions and guide through objectives can diminish the level of uncertainty and contribute to the prevention of stress [23]. Results from a preceding study revealed three augmentation channels desired by the participants: Text-panel, light signals and gestures. Related studies omit the aspect of augmentation channels to inform the human about its characteristics [21,25] and an effective concept to reduce the occurrence of uncertainty and subsequently stress has yet to be explored. This paper evaluated the implementation of augmentation channels for communicating the behavior of an autonomous robot in an authentic VR simulated shared task environment to explore its effects on stress, emotion, presence and acceptance.

1.1 Shared Tasks in Virtual Reality

Involving autonomously acting and adapting robots in a real world shared task environment requires the elaboration of setups that consider restrictive safety precautions to prevent potential harm for participants. The usage of VR provides an alternative approach for evaluating these scenarios as a risk free and cost effective setup in which every parameter can be adjusted to fit the context. Due to this, evaluations involving shared task environments with robots can be standardized in their procedure while monitoring and recording data. Therefore, a VR simulated HRC-centered work-place was created allowing the exploration of human behavior towards collaborative robots and (dis)advantages of certain workplace arrangements in a controlled and replicable setup. Virtual reality has been used in research of industrial working arrangements [21,24], as it allows the representation of any environment, object or context. Nevertheless, the usage of VR in experimental studies requires an appropriate implementation of the interaction and locomotion mechanics as well as a sufficient visual quality to ensure the immersion of the participants, which is necessary to receive accurate behavioral data. To ensure this, the application utilized in this experimental study, used the established recommendations and guidelines for VR.

2 Related Work

Studies investigating the collaboration between human individuals have identified group cognition as an essential criterion for success [13]. The term, proposed by Wegner [34], describes a transactive memory system that contains the shared and organized knowledge of a group of collaborating individuals. Research indicates [29] that the formation of a common mental model, developed through exchange of information, can reduce uncertainty in the decision-making process, as it improves the understanding of individual roles, responsibilities and task distribution [5]. Additionally, findings indicate that the insufficient or inappropriate addressing of information in a collaborative context reduces the likelihood of comprehension about the current context of the task or situation [10], leading to an increased mental workload that can be perceived as stress [1]. Applied to the human-robot interaction, the necessity to explain the robot's current behavior to the human in order to establish a mental model has been recognized [16]. This is amplified when the interaction is conducted with a robot of non-anthropomorphic appearance [11]. Most applications involving automation related shared task environments will make use of industrial robots following an expedient non-anthropomorphic design, so that the individual's ability to recognize the robot's agency becomes more important. This is reinforced by participants' interview statements in a preceding study, suggesting that augmentations by interfaces providing guidance and explanation of the robot's behavior might mitigate stress. Actions of the robot might become more predictable and allow the human to intervene accordingly to ensure accomplishing the goal of the shared task [2]. The robot's ability to provide explanation and guidance is not only beneficial for conveying its current behavior, research exploring human-robot interaction indicates that it also lowers the barrier for individuals to perceive it as a social presence [15]. The social presence has been identified as a direct contributor to a person's enjoyment of interacting with a robot. The experience of less stress, combined with the increased likelihood of perceived social presence should lead to more positive emotions or lower levels of negative emotions (frustration, insecurity) evoked by the robot respectively.

Working steps that are processed in shared task environments can be either divided, overlapping or interdependent, resulting in the human employee to relying on the capabilities of the robot partner for a successful completion. This dependency forms a social structure, which can be either be accepted or rejected by the human. Prior research has shown the influence of the robot's presence for human willingness to interact with it in social contexts [4]. Presence in this context is defined as the "sense of being with another" [28] and, according to Biocca, manifests itself as "the access to the intelligence, intentions, and sensory impressions of another" [7]. While the robot's presence is determined by several factors, its representation mediated through behavior and appearance contributes the most. Non-anthropomorphic designs commonly found in HRC related industrial environments evoke less presence than their anthropomorphic counterparts [17]. However, it has been shown that the influence of physical appearance is mitigated when personified communication channels are applied, as even systems without physical manifestation can be perceived as a social actor [26]. However, the influence of augmentation with explanation and guidance capabilities in shared task environments has yet to be explored.

2.1 Hypotheses and Research Question

To further explore the effect of explanatory and guiding augmentation in shared task environments with non-anthropomorphic robots, the following hypotheses and research question were formed:

- **H1:** The shared task procedure involving the augmented robot-arm is perceived as less stress inducing compared to the condition without augmentation.

- **H2:** The shared task with the augmented robot-arm evokes more positively associated emotions compared to the condition without augmentation.
- **H3:** The augmentation with explanation and guidance channels increase the (social) presence of a robot-arm deployed in a shared task environment.

3 The VR Implementation

The VR-application that serves for the conducted experiment was developed with the goal to replicate a HRC centric workplace as close as possible. It is based on arrangements found in the industry, scientific articles [30] as well as findings acquired in a preceding study [2]. Remarks made by various representatives of enterprises that either use or anticipate to use HRC work-spaces were also incorporated into the design of the environment, i.e. the arrangement of the robot-arm or the ambient soundscape. The VR-application was rendered on an Oculus Rift S and developed with Unity 3D (2018.4.11f1). The robot-arm for the collaboration with the participants was represented by the virtual recreation of a LBR iiwa 7 R800 CR. The behaviour of the robot-arm was determined by an implementation of the Unity Machine Learning-Agents Toolkit, enabling the execution of the work procedure and adaptation to the participant's actions with appropriate reactions in accordance with the ISO TS 15066 guidelines for collaborative robots. Apart from adjusting to the individual work-pace of the participant, this included safety precautions, such as the detection of imminent collisions with the virtual hands of the participant, which resulted in the robot-arm either slowing down and adapt its movement to avoid a potential collision. If the collision is deemed unavoidable, the robot-arm will cease its current motion to protect its human collaboration partner. Although the protection of the human partner is regarded as the highest priority, the latter option is only considered if no alternative evasion is possible. This was implemented to mimic the desire to prevent unnecessary wear on the axis of real industrial robots, due to absorbing the momentum of sudden deceleration. This adaptive movement system prevented the usage of predefined animations, instead the robot-arm used an inverse kinematic system and was able to conduct every action of its real counterpart in terms of speed and movement in seven degrees of freedom, enabling an authentic depiction in virtual reality.

3.1 The Shared Task

The task to be performed in collaboration with the robot-arm involved the manufacturing of pin-back buttons through a Badgematic Flexi Type 900 (59 mm) Button-press, which was accurately recreated for VR in terms of scale and interactive functionality (Fig. 1). This setup provided a shared task that demanded the coordination between the participant and the robot with distinguished roles as well as an inter-dependency for both parties on each other to accomplish the objective. Simultaneously the relative simplicity of the task allowed even participant's without prior knowledge to establish a workflow based on the guidance

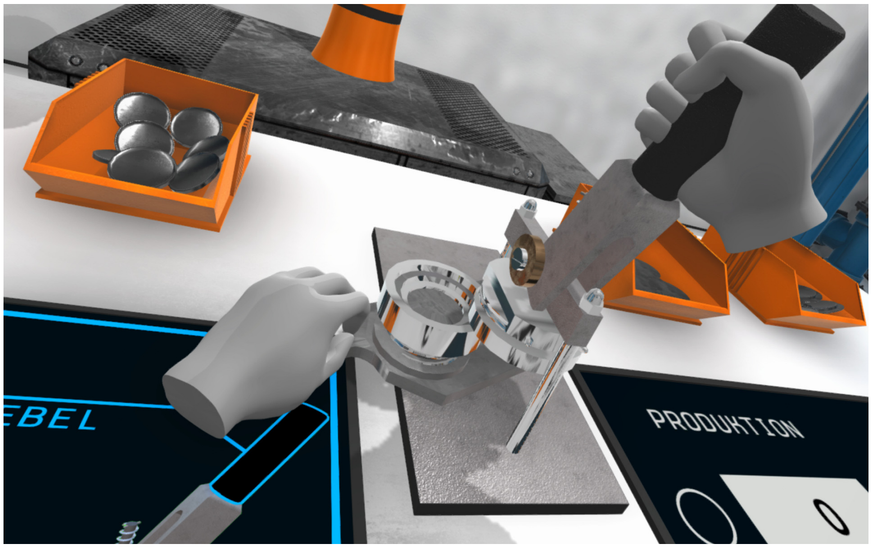


Fig. 1. The Badgematic button-press Flexi Type 900 (59 mm) that was used as the basis for the collaboration task

Fig. 2. The robot-arm extracts a component from one of the storage container while stating: "I pick up the first component"

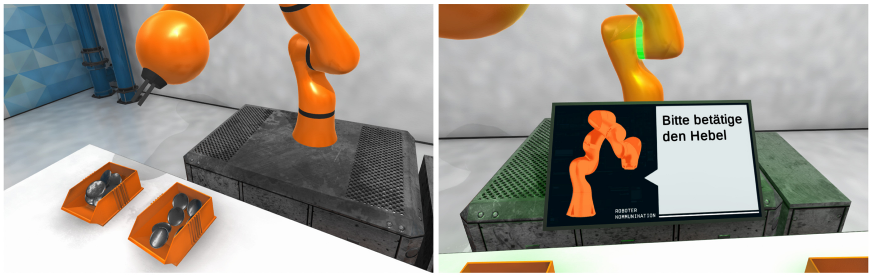
provided by the robot's augmentation channel. The assembling process of the pin-back buttons itself required nine individual working steps (Table 1), which are divided in five procedures executed by the participants and four by the autonomously working robot-arm (Fig. 2).

Table 1. The collaboration procedure used in the experimental setup.

Working procedure of the participant	Work step
Participant rotate and lock the press platform	2
Participant operate the press lever	3
Participant rotate and lock the press platform	6
Participant operate the press lever	7
Participant rotate and lock the press platform	9
Working procedure of the robot-arm	Work step
Robot extract component 1 from its container and inserts into the press	1
Robot extract component 2 from its container and inserts into the press	4
Robot extract component 3 from its container and inserts into the press	5
Robot extract product from the press into the designated container	8

3.2 Augmentation Channels of the Robot-Arm

To explain its actions and provide guidance to the participants, the robot-arm was equipped with three communication interfaces: A text-panel, light-signals and gestures. All three augmentation channels were implemented based on findings from a prior study [2] (Fig. 3(a)). The primary channel was a text-panel, serving both as medium for the robot-arm to explain its actions as well as to provide guidance for the collaboration partner regarding the working procedure. The statements were phrased as a text in natural language, e.g. "I'm gonna put component two in the press now". This implementation follows the recommendations stated in the Guidelines for Human-AI Interaction and allowed the robot-arm to express a variety of comprehensible context-based statements. The phrasing in first-person form was derived from the speech pattern of several voice assistants, such as Amazon Alexa, emulating a personality to reinforce the social presence of the robot-arm. The display containing the text-panel was placed directly in front of the robot to strengthen the association of the statements to the robot-arm. This was emphasized through an illustration of the robot-arm adjacent to a speech-bubble, containing the text-messages (Fig. 3(b)). An additional display was placed right next to button-press, indicating warning signs for imminent collision (Fig. 4(a)) or movement (Fig. 4(b)) and production related information such as production output and remaining time. To complement the augmentation of the display, the robot-arm was equipped with light-signals. Besides being a frequently requested communication method by individuals participating in a preceding study [2], light-signal see usage in almost every industrial environment, e.g. as lamps that light up in case of malfunctions or warnings. These light-signals can be found as augmentation in vicinity of real industrial robots as well, explaining the state of the robot at a glance. A green light indicates that the robot is ready for operation, whereas a red light indicates possible malfunctions. This concept was projected onto the robot-arm which signalled a green light (Fig. 5(a)) when operational for the next task and red (Fig. 5(b)) if the robot detected an imminent collision or error in the working procedure (Fig. 4). Another augmentation, that enabled the robot-arm to explain itself, was the usage of three gestures: standby, action initiating, action termination. The design of gestures followed recommendations stated by [12], after a first self designed implementation was rated to ambiguous by participants [2]. The standby gesture made the robot-arm take a retracted posture, signaling the human collaboration partner that the robot-arm has accomplished its previous task and is now awaiting the human to proceed. In case the human partner ceases to continue the procedure, the robot-arm conducts an action initiating gesture and points towards the object that is required to be operated for the next working step. The opposite of this is an action terminating gesture, in which the robot-arm rotates its head joint to mimic a negating hand gesture with its clamps. These gestures were absent in the condition with no augmentation, in which the robot-arm merely moved and took an arbitrary position based on calculations of the inverse kinematic for the current task instead. The purpose of the gestures was to enable the robot-arm to fit its movement in accordance to social norms, regarding personal space and conformity [19], preventing abrupt movement that was deemed threatening in a prior rendition.

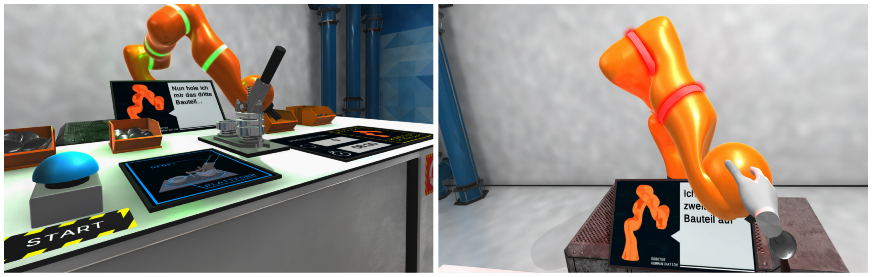


(a) (b)

Fig. 3. A comparison between the two conditions: (a) The robot-arm without augmentation, (b) The guidance provided by the robot-arm: please use the lever!

(a) (b)

Fig. 4. Display with additional explanation: (a) Attention! Robot too close, (b) Caution! Robot is moving



(a) (b)

Fig. 5. The light-signal on the robot-arm: (a) green for operational, (b) red for collision or malfunction (Color figure online)

4 Evaluation

In an experiment, reactions by participants and the evaluation of the augmented, adaptive version of the robot-arm, were compared with a non-augmented, adaptive version of the robot-arm. Participants were tasked to assemble pin-back button components in collaboration with the robot-arm. In the experimental condition the robot-arm was augmented with a text-panel, light signals, and gestures, giving guidance and explanations to the human collaboration partner about its actions, whereas in the second condition, the communicative augmentation of the robot was absent.

4.1 Measures and Procedure

Participants were invited to take part in a lab experiment. Upon arrival, they signed an informed-consent declaration after going through a briefing about the experiments' purpose. Participants were then asked to fill in the a pre-questionnaire including the Negative Attitudes Towards Robots Scale [27].

The scale contains 3 subscales measured on a 7-point Likert scale (1 = strongly agree, 7 = strongly disagree): "situations and interactions" (5 items, $\alpha = .633$; e.g. "I would feel nervous operating a robot in front of other people."), "social influence" (5 items; $\alpha = .781$; "I feel that if I depend on robots too much, something bad might happen."); "emotions in interaction" (3 items; $\alpha = .859$; e.g. "I feel comforted being with robots that have emotions."). Since prior experience with industrial robots showed to be important in other studies, it was also assessed with 1 item here ("Do you have experience with robotic systems").

After completion, they were introduced to the VR-hardware: The industrial environment with the robot-arm absent was loaded to allow participants a first orientation in the virtual environment and get accommodated to the VR-experience. The scene switched then to the work bench with the robot-arm, which began the procedure at participant's will.

Once the collaboration task was finished, the experimental supervisor released the participant from the VR-hardware and promoted him/her to proceed to the post-questionnaire. The post-questionnaire contained Cohen's Perceived Stress Scale (10 items; $\alpha = 0.827$) [9] (H1). Participants rated their emotional state using the respective question on the intensity of their frustration ("How insecure, discouraged, irritated, stressed, and annoyed were you?") from the NASA Task Load Index (H2) after they were exposed to the shared task scenario (H2) [14].

To evaluate the robot's presence in a the "sense of being there" (H3), 14 items from the Witmer and Singer's Presence Scale were used [35]. Using a 5-point Likert scale (1 = does not apply at all, 5 = does apply completely), the scale asks into different aspects of presence, e.g. realism, possibility to act, quality of interface and possibility to examine ($\alpha = .636$). Social presence, in the sense of "being with one another" (H3) was operationalized by self-constructed items assessing participants' evaluation of the quality of the augmentation channels (4 items, $\alpha = .853$; e.g. "The robot's light-signals were...") and mutuality in interaction (3 items; $\alpha = .836$). All items were measured on a 5-point Likert scale (1 = very bad; 5= very good).

The experiment closed with a short debriefing that provided participants with additional information regarding the study and thanked them for their participation.

4.2 Results

The sample consisted of $N = 80$ (40 female), with 40 participants assigned to each of the two conditions. Both conditions consisted of 20 male and 20 female participants. On average, participants were 25 years old ($M = 25.31$, $SD = 6.1$). The majority of participants were students from the University of Applied Sciences Ruhr West, 6 of them received course credit for participating in the study. Data were analyzed using SPSS by IBM.

In order to test whether the participants allocated into the different experimental conditions differed in their attitude towards robots before taking the experiment, a t-test was used to investigate the difference in Negative Attitude

Towards Robots. No significant difference was found. Also, participants in the conditions did not report significantly different levels of prior experience with robots.

Hypothesis 1: The shared task procedure involving the augmented robot-arm is perceived as less stress inducing compared to the condition without augmentation.

In order to test H1, an ANCOVA was conducted, using the conditions as independent variable, the Perceived Stress Scale as dependent variable and the mutuality and communication quality as covariates. Significant differences between the conditions emerged ($F(3{,}78) = 14.93$, $p < 0.01$, $\eta_p^2 = 0.37$), showing that in the augmented condition ($M = 2.15$, $SD = 0.70$) participants experienced less stress than in the non-augmented condition ($M = 2.86$, $SD = 0.6$). Thus, H1 is supported.

Hypothesis 2: The shared task with the augmented robot-arm evokes more positively associated emotions compared to the condition without augmentation.

To investigate H2, the difference between the conditions regarding the frustration (i.e. insecure, discouraged, irritated, stressed, and annoyed) after collaborating with the system was calculated in a t-test. This revealed significant differences $t(78) = -3.396$, $p = .001$), indicating more negative emotions after being exposed to the robot-arm without augmentation ($M = 9.9$, $SD = 5.28$), compared to the augmented condition ($M = 6.05$, $SD = 4.85$). Thus H2 is supported.

Hypothesis 3: Does the augmentation with explanation and guidance channels increase the (social) presence of a robot-arm deployed in a shared task environment?

An ANOVA showed that presence in the "sense of being there" in the environment differed significantly between the conditions ($F(1{,}37) = 6.07$, $p < 0.02$, $\eta_p^2 = 0.08$). The feeling of presence was higher in the condition with the augmented robot-arm ($M = 4.73$, $SD = 0.55$) compared to the robot-arm without augmentation ($M = 4.34$, $SD = 0.66$). To explore potential differences in the social presence feeling ("sense of being with another"), a MANOVA was conducted including the conditions as independent and perceived quality of communication and mutuality in interaction as dependent variables. The perceived quality of communication differed significantly between the conditions ($F(1{,}77) = 55.06$, $p < 0.01$, $\eta_p^2 = 0.41$)) and was higher in the augmented version ($M = 3.86$, $SD = 0.65$) compared to condition without augmentation ($M = 2.54$, $SD = 0.91$). Also, mutuality was perceived significantly different ($F(1{,}77) = 14.41$, $p < 0.01$ $\eta_p^2 = 0.16$) and higher in the condition with the augmented interaction ($M = 4.89$, $SD = 1.3$) than without ($M = 3.74$, $SD = 1.39$). Thus, H3 is supported.

5 Discussion

The importance of communication in collaboration setups between human individuals is already established [33]. This experimental study explores the influence of communicative augmentation in HRC. Results indicate that communication in this context is essential as well and can lead to an increased (social) presence in interacting with the robot-arm, a less stressful working experience and more positive emotions. This can be attributed to the robot-arm informing its intention unambiguously coded via multiple channels, thus supporting the formation of a clear mental model in the recipient [32]. The latter is then able to process the situation and can adapt to the working step conducted by the robot-arm. In contrast, participants of the condition without the augmentation were left to their own interpretation of the situation, due to the lack of the communication interface. This introduces a level of uncertainty into the collaboration process that can lead to stress. Since the majority of participants had no previous experience with industrial-robots, let alone HRC, which might lead to a longer learning process on the capabilities of the robot-arm and the procedure. It can be argued that this delayed or, in some cases, prevented the emergence of a work-flow, resulting in the likelihood of unpleasant feelings and a lower willingness to collaborate with the robot-arm. This coincides with the qualitative data reported in an adjacent study [2]. Although it can be argued that the differences between the conditions are due to the first exposure to a robot-arm, thus denying the necessity of augmentation in HRC for skilled workers in a corresponding situation. Despite the building of a working routine in learned working procedures certainly will help to estimate the behavior of a collaborative robot, the use of AI techniques for adaptation introduces an element of unpredictability. Although more presence was attributed to the robot, the additional layer of presence from the virtual reality has to be considered. Especially novice users tend to experience a greater sense of presence during their first exposure, independent of the content. However, both groups were comparable in their prior experience with VR-devices and participants still attributed more presence in the augmented condition. While an argument can be made that the effects are caused by the selected conditions representing two opposite extremes (all vs. none) of a spectrum of gradual augmentation, it is to mention that the current guidelines used in HRC environments dictate the usage of warning and information channels that are coded through multiple channels [18]. However, a more granular approach, testing the augmentation step wise, could be of interest in future studies. The current guidelines might adjust with technological progress as the introduction of artificial intelligence should equip robots deployed in shared task environments with sophisticated safety procedures, making current regulations obsolete. All in all, future studies will also need to explore long-term effects, e.g. whether workers will get used to text panels, light signals and gestures and might disregard them.

5.1 Limitations

Finally, some limitations need to be mentioned. While a great effort was made, to create an authentic virtual application for the HRC setup, its simulation is only an approximation of a real industrial collaboration scenario. However, related studies made use of virtual simulations in similar cases [21]. Research in the tradition of the Media Equation Theory allows the assumption that humans respond to virtual environments in a way that is comparable to real life situations [31]. Also, VR is accepted as a tool to assess participants' reactions and emotions by exposing them to simulated scenarios [3]. The task used in the experimental study can be seen as a limitation as well, considering that it does not represent a procedure found in a real industrial context. Although, this task is not applicable to all aspects found in shared task environments, alternative considerations, e.g. the assembly of a spring-loaded safety valve, based on the API 526 series [20], have shown to be too complex for many people as they require too much previous knowledge and therefore are not suitable for a first approach of this kind. To get a general evaluation of the collaboration with the augmented robot-arm, a task was selected that allowed the participation of individuals regardless of expertise. This approach can be found in other HRC related studies as well [25]. Another limitation is the composition of the sample. Since most participants were students at the University of Applied Sciences Ruhr West, an affinity towards engineering can be assumed that might be higher than that of the general population. Although these students are currently not occupied in industries prone for HRC, some of them are likely to become exposed to HRC in the future or to be active in designing such scenarios. This makes it valuable to collect their assessment for the design of upcoming HRC setups, to meet the expectations towards such systems.

6 Conclusion

The augmentation of industrial production processes with digital systems is in full motion. It is expected that this will have a major influence on the workforce, as it is not only introducing new production processes but also new concepts of how employees interact with machinery such as robots. Through continuous advancements in artificial intelligence, the concept of equal collaboration between human workers and robotic entities is not some far-fetched vision of the future anymore. The results support the necessity for augmentation with communication channels in these adaptive HRC setups, as they allow for a decreased perceived stress and frustration when collaborating with the robot and contribute to the feeling of working together with the robotic collaboration partner. The implication for the industry is to design future work-arrangements involving HRC with communication based augmentation in mind. Future studies will need to explore further augmentation methods, levels and modalities of augmentation and their influence on productivity and safety. This will contribute to an integrative iterative design process, with the goal to reduce unfit work-place arrangements involving HRC in future production processes.

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References

1. Alsuraykh, N.H., Wilson, M.L., Tennent, P., Sharples, S.: How stress and mental workload are connected. In: Mayora, O., Forti, S., Meyer, J., Mamykina, L. (eds.) Proceedings of the 13th EAI International Conference on Pervasive Computing Technologies for Healthcare, pp. 371–376. ACM, New York (2019). https://doi.org/10.1145/3329189.3329235
2. Arntz, A., Eimler, S.C.: Experiencing AI in VR: a qualitative study on designing a human-machine collaboration scenario. In: HCI INTERNATIONAL 2020–22nd International Conference on Human-Computer Interaction, Copenhagen, Denmark (2020)
3. Bailenson, J., Blascovich, J., Beall, A.: Interpersonal distance in immersive virtual environments. Pers. Soc. Psychol. Bull. **29**, 819–833 (2003). https://doi.org/10.1177/014616720302900700210.1177/0146167203029007002
4. Bainbridge, W., Hart, J., Kim, E., Scassellati, B.: The effect of presence on human-robot interaction, pp. 701–706 (2008). https://doi.org/10.1109/ROMAN.2008.4600749
5. Banks, A., Millward, L.: Distributed mental models: mental models in distributed cognitive systems. J. Mind Behav. **30**, 249–266 (2009)
6. Bauer, A., Wollherr, D., Buss, M.: Human-robot collaboration: a survey. Int. J. Humanoid Rob. **5**, 47–66 (2008). https://doi.org/10.1142/S0219843608001303
7. Biocca, F.: The cyborg's dilemma: progressive embodiment in virtual environments [1]. J. Comput.-Mediated Commun. **3**(2) (1997). https://doi.org/10.1111/j.1083-6101.1997.tb00070.x
8. Bruemmer, D.J., Few, D.A., Boring, R.L., Marble, J.L., Walton, M.C., Nielsen, C.W.: Shared understanding for collaborative control. IEEE Trans. Syst. Man Cybern. Part A Syst. Hum. **35**(4), 494–504 (2005). https://doi.org/10.1109/TSMCA.2005.850599
9. Chan, S.F., La Greca, A.M.: Perceived stress scale (PSS). In: Gellman, M.D., Turner, J.R. (eds.) Encyclopedia of Behavioral Medicine, pp. 1454–1455. Springer, New York (2013). https://doi.org/10.1007/978-1-4419-1005-9_773
10. Cramton, C.D.: The mutual knowledge problem and its consequences for dispersed collaboration. Organ. Sci. **12**(3), 346–371 (2001). https://doi.org/10.1287/orsc.12.3.346.10098
11. Daugherty, P.R., Wilson, H.J.: Human + Machine: Reimagining Work in the Age of AI. Harvard Business Review Press, La Vergne (2018). https://ebookcentral.proquest.com/lib/gbv/detail.action?docID=5180063
12. Ende, T., Haddadin, S., Parusel, S., Wüsthoff, T., Hassenzahl, M., Albu-Schäeffer, A.: A human-centered approach to robot gesture based communication within collaborative working processes, pp. 3367–3374, September 2011. https://doi.org/10.1109/IROS.2011.6094592
13. Grand, J.A., Braun, M.T., Kuljanin, G., Kozlowski, S.W.J., Chao, G.T.: The dynamics of team cognition: a process-oriented theory of knowledge emergence in teams. J. Appl. Psychol. **101**(10), 1353–1385 (2016). https://doi.org/10.1037/apl0000136
14. Hart, S.G., Staveland, L.E.: Development of NASA-TLX (task load index): results of empirical and theoretical research. In: Human Mental Workload, Advances in Psychology, vol. 52, pp. 139–183. Elsevier (1988). https://doi.org/10.1016/S0166-4115(08)62386-9

15. Heerink, M., Krose, B., Evers, V., Wielinga, B.: Influence of social presence on acceptance of an assistive social robot and screen agent by elderly users. Adv. Robot. **23**, 1909–1923 (2009). https://doi.org/10.1163/016918609X12518783330289
16. Hellström, T., Bensch, S.: Understandable robots. Paladyn J. Behav. Robot. **9**, 110–123 (2018). https://doi.org/10.1515/pjbr-2018-0009
17. Hoffman, G., et al.: Robot presence and human honesty: experimental evidence, vol. 2015, March 2015. https://doi.org/10.1145/2696454.2696487
18. ISO: Iso 10218–1:2011 (2011). https://www.iso.org/standard/51330.html. Accessed 13 Mar 2020
19. Koay, K.L., et al.: Initial design, implementation and technical evaluation of a context-aware proxemics planner for a social robot. In: Kheddar, A., et al. (eds.) Social Robotics. Lecture Notes in Computer Science, vol. 10652, pp. 12–22. Springer, Cham (2017). https://doi.org/10.1007/978-3-319-70022-9_2
20. Leser: Safety valve (2020). https://www.leser.com/de-de/produkte/api/type-526/. Accessed 28 Mar 2020
21. Matsas, E., Vosniakos, G.-C.: Design of a virtual reality training system for human–robot collaboration in manufacturing tasks. Int. J. Interact. Des. Manuf. (IJIDeM) **11**(2), 139–153 (2015). https://doi.org/10.1007/s12008-015-0259-2
22. Müller-Abdelrazeq, S.L., Schönefeld, K., Haberstroh, M., Hees, F.: Interacting with collaborative robots—a study on attitudes and acceptance in industrial contexts. In: Korn, O. (ed.) Social Robots: Technological, Societal and Ethical Aspects of Human-Robot Interaction. HIS, pp. 101–117. Springer, Cham (2019). https://doi.org/10.1007/978-3-030-17107-0_6
23. Mumm, J., Mutlu, B.: Human-robot proxemics. In: Billard, A., Kahn, P., Adams, J.A., Trafton, G. (eds.) Proceedings of the 6th international conference on Human-robot interaction - HRI 2011, p. 331. ACM Press, New York (2011). https://doi.org/10.1145/1957656.1957786
24. Müller, S.L., Schröder, S., Jeschke, S., Richert, A.: Design of a robotic workmate. In: Duffy, V.G. (ed.) DHM 2017. LNCS, vol. 10286, pp. 447–456. Springer, Cham (2017). https://doi.org/10.1007/978-3-319-58463-8_37
25. Müller-Abdelrazeq, S.L., Stiehm, S., Haberstroh, M., Hees, F.: Perceived effects of cycle time in human-robot-interaction. In: 2018 IEEE Workshop on Advanced Robotics and its Social Impacts (ARSO), pp. 25–30. IEEE (27092018–29092018). https://doi.org/10.1109/ARSO.2018.8625819
26. Nijholt, A.: Disappearing computers, social actors and embodied agents. In: Sourin, A., Soon, S.H., Kunii, T. (eds.) 2003 International Conference on Cyberworlds, pp. 128–134. IEEE Computer Society, Los Alamitos (2003). https://doi.org/10.1109/CYBER.2003.1253445
27. Nomura, T., Suzuki, T., Kanda, T., Kato, K.: Measurement of negative attitudes toward robots. Interact. Stud. **7**(3), 437–454 (2006)
28. Oh, C.S., Bailenson, J.N., Welch, G.F.: A systematic review of social presence: definition, antecedents, and implications. Front. Robot. AI **5** (2018). https://doi.org/10.3389/frobt.2018.00114
29. Peltokorpi, V., Hood, A.C.: Communication in theory and research on transactive memory systems: a literature review. Top. Cogn. Sci. **11**(4), 644–667 (2019). https://doi.org/10.1111/tops.12359
30. Philipsen, M., Rehm, M., Moeslund, T.: Industrial human-robot collaboration, pp. 35–38, July 2018. https://doi.org/10.21437/AI-MHRI.2018-9

31. Reeves, B., Nass, C.: The Media Equation: How People Treat Computers, Television, and New Media Like Real People and PLA. Bibliovault OAI Repository. The University of Chicago Press, Chicago (1996)
32. Schmidtler, J., Hoelzel, C., Knott, V., Bengler, K.: Human centered assistance applications for production. In: 5th International Conference on Applied Human Factors and Ergonomics, Krakow, Poland, July 2014. https://doi.org/10.13140/RG.2.1.1608.7203
33. Shah, J., Wiken, J., Williams, B., Breazeal, C.: Improved human-robot team performance using chaski, a human-inspired plan execution system. In: Billard, A., Kahn, P., Adams, J.A., Trafton, G. (eds.) Proceedings of the 6th International Conference on Human-Robot Interaction - HRI 2011, p. 29. ACM Press, New York (2011). https://doi.org/10.1145/1957656.1957668
34. Wegner, D.M., Erber, R., Raymond, P.: Transactive memory in close relationships. J. Pers. Soc. Psychol. **61**, 923–929 (1991)
35. Witmer, B.G., Jerome, C.J., Singer, M.J.: The factor structure of the presence questionnaire. Presence Teleoperators Virtual Environ. **14**(3), 298–312 (2005). https://doi.org/10.1162/105474605323384654

4. “The Robot-Arm Talks Back to Me” - Human Perception of Augmented Human-Robot Collaboration in Virtual Reality

This publication was invited, accepted and presented in 12/2020 at the 3rd International Conference on Artificial Intelligence & Virtual Reality (IEEE AIVR 2020). With a competitive acceptance rate of 27.3% for the technical paper track (including full and short papers), the IEEE AIVR conference addressed researchers and industry representatives from every domain of artificial intelligence as well as Virtual, Augmented, and Mixed Reality. This publication was distinguished with the best presentation award (posters/demos)[1].

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Author	**Contribution**	**%**
Alexander Arntz	- Conceptualization of the approach - Design and implementation of the VR application - Conduct of the qualitative study	80%
Sabrina C. Eimler	- Supervision - General advice and support for the study design	10%
H. Ulrich Hoppe	- General supervision	10%

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[1] Best presentation award winners - December 15th 2020: The Robot-Arm Talks Back to Me - Human Perception of Augmented Human-Robot Collaboration in Virtual Reality by Alexander Arntz, Sabrina Eimler, and Ulrich Hoppe - https://aivr.science.uu.nl/2020/

2020 IEEE International Conference on Artificial Intelligence and Virtual Reality (AIVR)

“The Robot-Arm Talks Back to Me” - Human Perception of Augmented Human-Robot Collaboration in Virtual Reality

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***Abstract*—The usage of AI enhanced robots in shared task environments is likely to become more and more common with the increase of digitalization in different industrial sectors. To take up this new challenge, research on the design of Human-Robot-Collaboration (HRC) involving AI-based systems has yet to establish common targets and guidelines. This paper presents results from an explorative qualitative study. Participants ($N = 80$) were either exposed to a virtual representation of an industrial robot-arm equipped with several augmentation channels for communication with the human operator (lights, textual statements about intentions, etc.) or one with no communicative functions at all. Across all conditions, participants recognized the benefit of collaborating with robots in industrial scenarios regarding work efficiency and alleviation of working conditions. However, a communication channel from the robot to the human is crucial for achieving these benefits. Participants interacting with the non-communicative robot expressed dissatisfaction about the workflow. In both conditions we found remarks about the insufficient speed of the robot-arm for an efficient collaborative process. Our results indicate a wider spectrum of questions to be further explored in the design of collaborative experiences with intelligent technological counterparts considering efficiency, safety, economic success and well-being.**

***Index Terms*—Human-Robot Collaboration, Virtual Reality, Augmented Communication, Shared Task, Artificial Intelligence**

I. INTRODUCTION

The increasing digitalization of industrial production processes lays the foundation for the intertwining of highly automated manufacturing procedures and personnel. With the intention to make these processes as economical and efficient as possible, AI-based systems will be widely used [1]. Among many concepts for the usage of AI in production scenarios is the implementation of Human-Robot Collaboration (HRC) [2]. In contrast to the approach of full automation, the concept of HRC does not intend for the machine to replace the employees but to supplement their abilities, relieve them of stressful or heavy work or to enable them to carry out work, which they could not do on their own [3]. The goal of HRC is to combine the experience and intuition of the human personnel with the precision and performance of the robot. This requires the capability of the robot to adapt to the actions of the human, e.g. adjusting the speed to ensuring a seamless workflow. Additionally, the intention and coordination indicated by the robot have to be communicated to the human collaboration partner [4], especially by robots with a non-anthropomorphic appearance [5]. While prior research presented augmentation channels for communication [6], e.g. gestures [7], enabling a robot to state its intention, the assessment of autonomously acting industrial robots augmented with multiple communication channels in shared task environments has not been addressed in research. However, the media equation principle [8] indicates that the collaboration process with the robot provokes an intuitive social reaction of the human, which should be considered in the system design process by providing corresponding communicative elements. Although HRC is a growing research field, a general conceptional basis on how to approach collaboration scenarios in industrial contexts has yet to be established [9]. This is in part due to the complexity of such collaboration arrangements, requiring expensive robots, sophisticated sensory and extensive safety precautions. With the intention to create a reproducible setup for experimental studies, the simulation of a shared task-centered workplace was developed and presented in virtual reality (VR). Based on the results of a predecessor study [10], a virtual representation of an autonomous industrial robot-arm, capable of communication (text messages, light-signals and gestures) was developed and compared against its non-communicating counterpart. In addition to the augmentation

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channels, the autonomous robot-arm was capable of adapting to the work pace of the participants through the usage of the Unity Machine Learning Framework [11]. This paper presents qualitative data assessed in the context of a larger experimental study. Participants reported their personal impression - along a number of trigger questions - of an interaction with the collaborative robot-arm in a shared task scenario represented through VR.

II. WORKPLACE ARRANGEMENTS IN VIRTUAL REALITY

The usage of virtual simulations for the purpose of industrial workplace assessment and HRC is already established in research [12], [13], [14]. Due to the complex technological requirements of HRC related studies and the potential safety hazards for participants, VR offers a safe and reproducible alternative in exploring human reactions towards collaborating robots and their (dis)advantages. This is necessary, as the introduction of AI-based robots for shared tasks environments will influence the socio-technical structure of work-places and production processes. To prevent unforeseeable effects accompanying the usage of these systems, VR-based studies can contribute to an iterative design process, assisting in optimizing the behavior and procedures of robots used for HRC [15]. Another advantage is the ability to quickly and cost effectively evaluate different representations and behavior of the robot in various (industrial) environments. Important aspects to be considered are the proper implementation of the VR-mechanics, as cumbersome interaction and insufficient visual appeal will hamper the quality of participants' ability to assess the robot and the collaboration experience.

III. OBJECTIVE

While the assessment of robots in personal and recreational contexts is an established research field known as Human-Robot Interaction [16], the challenges of designing HRC, especially in work related environments still persist [17]. Although several studies in this research field were already conducted [18], [13], no common methodology for approaching the design of these systems has yet emerged. Publications addressing the design of industrial robots omit evaluations in the form of empirical studies in most cases [19], while research that contains empirical evaluation lacks the work-related context [20]. This study investigates expectations and evaluations of participants collaborating with the virtual representation of the industrial robot-arm. As stated before, the behavior in conjunction with the communication method is a crucial influence on a person's perception of the robot-arm. It is therefore necessary to investigate which different benefits and negative aspects are associated with the respective renditions of the robot-arm featured in the experimental conditions. This leads to the following research questions:

- **RQ1:** Which benefits and positive aspects do participants perceive while collaborating with the robot-arm in the shared task scenario?
- **RQ2:** Which aspects and behavior of the robot-arm do participants consider negative during the shared task scenario?

IV. STUDY

To evaluate participant's assessment of a collaborative robot-arm, two different conditions were compared. The first condition contained the autonomously acting robot-arm, which communicated its intentions and activities through several communication methods. In the control condition, while using the same setup of the working environment, the robot-arm did not have any communication capabilities.

A. Environment

The VR-application was developed using Unity 3D (2018.4.11f1) and presented by an Oculus Rift S head-mounted display. The application contains a fully modelled environment of a fictitious factory building. For immersion purposes, ambient industrial sounds and a variety of appropriate props for this setting were placed into the scene. The collaborative work-space, where participants interacted with the robot-arm, is placed in the center and based on HRC work arrangements found in manufacturing plants, literature [21] and data gathered from a pre-study [10], as well as comments made by industry representatives with experience in HRC.

The condition in which the robot was augmented with communication interfaces, featured two additional displays: One containing personalized text messages ("I am now picking up the first component") placed in front of the robot-arm, to strengthen the association of the texts as statements from the robot. The second informed the participants about objectives and safety related topics, such as collision prevention ("Heads up! Robot is too close"). Additional red and green light signals on the robot complemented the warning signs. These communication methods were chosen based on statements made by participants from a pre-study and validated through literature [10], [6].

B. Sample and Procedure

The collection of qualitative data to answer the research questions was integrated into a larger experimental study in which, on a quantitative level, a number of interaction-related variables were explored [22]. The overall procedure is outlined below. This paper, however, focuses on the qualitative results only. In total, 80 participants completed the study and 63 (79%) of them gave qualitative statements regarding their experience with shared task involving the robot-arm. Distribution between genders was equal with 40 male and 40 female participants with an average age of 25 (*M* = 25.31, *SD* = 6.1). The majority of participants were students. Six participants received course credits for their participation in the study.

Upon arrival in the lab, participants signed a declaration of consent and were briefed on the procedure. Afterwards, they filled in a pre-questionnaire containing demographic variables, prior experience with robots and the attitude towards robots. Subsequently, participants were introduced to the VR-equipment, where they received instructions on how to control the application. To enhance the hygiene for each session, disposable masks were given to the participants, reducing direct contact with the hardware. Once participants put on the VR-device, the same virtual industrial area albeit with the robot absent, was loaded. This was done to give participants time to accommodate the VR-experience and get accustomed the controls and mechanics. As soon as the individual participant' felt ready, the stimulus material containing the collaborating robot-arm was launched. A blue button with a start label activated the robot-arm. From there on, participants received the instruction from a virtual display next to the press, to manufacture as many components as they can in collaboration with the robot-arm. A timer displayed a ten-minute time limit. As soon as the time expired, participants were asked to take off the VR-device and continue with the post-questionnaire. As part of the post-questionnaire, participants provided assessments for the following questions via open text boxes: *In your opinion, what benefits does the collaboration with the robot have in this shared task context?* and *Which aspects of the robot do you consider negative?*

C. Assembling Task

For the purpose of creating a collaboration between the human participant and the virtual robot-arm, it was necessary to create a task with enough complexity where both shared a dependency on the collaboration partner to succeed. At the same time it was required that the task was uncomplicated enough to be conducted by the autonomous robot-arm in VR as well as without taxing inexperienced participants with real industry assembling procedures. To provide comprehensible task for novice participants, the authentic depiction of a virtual pin-back button press was used. The functionality of the press was realized through a custom hinge joint, which simulated the lever functionality. A simulated resistance for the lever was added, that changed its intensity based on a threshold angle to mimic the necessary force for the participants to operate the press. The rotary table of the press was implemented through a rotator hinge and included a snap force for the table to lock in place and a custom friction script implementation that used the built-in physics system of Unity 3D. The task required the sequential execution of 9 working steps [22], of which five were performed by the robot and four by the human and orientated its procedure along similar HRC studies [23], [24]. The concept of this approach is to enable participants to establish a workflow with the robot-arm through the sequential process, while simultaneously containing enough leeway for both the human and robot-arm to make mistakes that can be potentially recognized and corrected by both parties.

V. The Robotic Collaboration Partner

The virtual industrial environment was outfitted with a three-dimensional representation of a LBR iiwa 7 R800 CR, manufactured by KUKA. The decision of depicting this model in the VR-application was taken because of its common usage in industrial assembly processes involving robots and personnel. In order to ensure an authentic representation of the robot-arm in VR, every characteristic was recreated in detail according to the manual and the reference model. This includes the audio and visual depiction of the robot, using recorded sounds from the real model, as well as a true to scale 3D-model. The robot-arm was placed on a table in front of the simulated work place with a range of 800mm, allowing it to reach every necessary item for executing the collaboration task.

Performing tasks and responding to human input required the robot-arm to be capable of movement. Although the rigged 3D-model could be outfitted with an animation controller, predefined animations were no option. Due to the necessity of an adaptive movement system that enables the robot to react to user actions in order to accomplish tasks in the collaborative process, an inverse kinematic was implemented based on the characteristics of the robot-arm [25]. The inverse kinematic was written in C# to be usable in Unity 3D and was designed with all the capabilities and limitations of the real robot-arm considered, allowing a close depiction of the movement of the real robot-arm, equipped with 7 degrees of freedom. Same as its real counterpart, the virtual depiction of the robot-arm follows the safety of machinery guidelines described in EN ISO 13849 and the safety requirements for industrial robots found in EN ISO 10218-1 [26], [27]. In addition, the autonomous behavior of the robot-arm, corresponds with the ISO TS 15066 regulations for collaborative robots [28] and is determined by a set of predefined rules and an implementation of the Unity Machine Learning-Agents (ML-Agents) Toolkit [29].

VI. The Communication Augmentations of the Robot-Arm

With the intention to improve the collaboration process within the shared task setup, the autonomous actions conducted by the robot-arm were required to be conveyed to the participants. In order to provide guidance for the shared task and explanation for the behavior of the robot-arm, the latter was augmented with three communication interfaces based on finding from a proceeding study as well as an adjacent study [22]. The first consisted of a text-panel, which displayed in first person language from the point of view of the robot-arm the current action and the necessary user input to proceed the shared task. The direct placement of the text-panel in vicinity of the robot-arm was done, based on a prior study that revealed that this arrangement strengthens the impression that these statements coming from the robot-arm as an entity itself [10]. The second interface were light-signals emitted by the robot-arm, in order to provide an affirmative response or warning at a glance. This was realized a simple color coding that can be found in real industries as well, with green indicating a nominal procedure and red signaling a malfunction (Fig. 1).

The last augmentation for communication purposes were three gestures: one to indicate that action by human collaboration partner is required to proceed, the second gesture is

Fig. 1. The green light-signal emitted by the robot-arm indicating a correct operation. Below the text-panel where the robot-arm provides guidance and explanation to the participant.

designed to urge the participant to cease their current action and the last one involved a retracted position. This gesture is designed to communicate that the robot-arm has finished its previous task and makes room for the human to commence their imposed task. This was absent in the experimental control condition, instead the robot-arm stayed at its current position until the procedure required further actions by the robot-arm to proceed. In addition to the missing gestures, the experimental control condition lacked the functionality of the light-signal and text-panel augmentation channels as well.

VII. FINDINGS

In order to analyze the qualitative data, statements made by the participants were examined for recurring keywords. This allowed to explore remarks and impressions from the participants in much more detail compared to mere quantitative based results [22]. Congruent keywords were then combined into categories, allowing the identification of emerging themes across the participants.The established categories allowed to measure the quantity of certain themes within the conditions.

A. ***RQ1:*** *Which benefits and positive aspects do participants perceive while collaborating with the robot-arm in the shared task scenario?*

Efficiency

Across all conditions, participants stated that collaborating with the robot can increase precision and speed in which production processes can be executed, thus enabling to work more efficient. The statements are presented by gender followed by participant number followed by condition (C for communication condition, NC for no communication condition) i.e. M1C (gender, participant number, communication condition).

“Increase of precision in the production of components.”(M1C)

“Making the job faster and more efficient.”(F48C)

“In my opinion, robots carry out work precisely and quickly.”(M38NC)

“It allows to work faster and safer, compensating human weakness.”(F80NC)

Assistance

An additional theme expressed by participants from all conditions is the relief that the robot can provide during monotone, repetitive or cumbersome tasks. Also, participants expressed that the robot can carry out tasks that could be dangerous for the human to perform.

“Support for repetitive boring work processes”(M1C)

“Activities that are repetitive and require a lot of strength could be performed by such robots.”(F3C)

“I think that it can do many ”mindless” or ”monotonous” jobs.”(M54NC)

“Recurring tasks could be taken over to make people work other necessary tasks. Dangerous tasks could be taken over by robots to reduce the risk of injury.”(F63NC)

Relationship

Themes regarding the relationship with the robot differed dependent on the condition. While participants assigned to the communication condition, stated that the robot behaves within a range of predictability due to the constant communication of its intention. Even with the personalized communication messages, a more humanized behavior is suggested for the work relationship. Comments made by participants from the condition with the communication methods absent remarked the need for the human to adapt to the machine. Although the usefulness of the robot is still recognized, the desire for controlling the robot instead of accepting it as collaboration partner is predominant in the *no communication* condition.

“If the robot became more humane, this could also increase work morale. On the one hand, the robot helps and is very precise, on the other hand, one could humanize its behavior, so that the worker would not feel left behind.”(M12C)

“Recurring tasks are taken off your hands because you have a team partner and the robot behaves in a controlled manner so that nothing goes wrong - and yet the task is in my hands.”(F51C)

“In this situation, the human has to learn to interact with the machine because direct communication is not possible.”(M17NC)

“For some tasks it is certainly useful to work with a robot, but the robot should always be under human control.”(F50NC)

B. ***RQ2:*** *Which aspects and behavior of the robot-arm do participants consider negative during the shared task scenario?*

Analyzing the qualitative answers regarding **RQ2** was done in the same way as with **RQ1**. Repeating keywords in the statements were categorized, allowing the formation of themes.

Competence

The most criticized characteristic of the robot-arm was its speed. Almost every participant, independent of condition or gender, mentioned in some way or another, that the robot-arm was too slow. Some participants even suggested that they would prefer a human collaboration partner because of this. Additional remarks were made regarding the reaction time in which the robot-arm recognized actions conducted by the participants.

"The robot was relatively slow. If you put a skilled worker, who had done this work many times before, at the table, he would do this work with the same precision, but faster."(M12C)

"Movement too slow"(F46C)

"A little too slow to react to my actions."(M17NC)

"I found the robot too slow for this kind of task. A human partner would probably be faster for this kind of work."(F63NC)

Communication

While participants from the communication condition criticized some communication related aspects like the placement of text and signals or that the robot obscured the messages occasionally, participants from the control condition in which the robot did not use text of light signals, expressed frustration about the lack of information, rendering them clueless about the robot-arm's intention.

"Text notes too far away from the attention area of the worker."(M39C)

"Instructions could not be read behind the robot-arm. Optical signals on the right should be placed elsewhere."(F49C)

"I didn't know what he wanted to do next or what he wanted me to do."(M27NC)

"I didn't know what the robot was doing. The components were moved back and forth but sometimes I had no idea why and how the robot was now making a movement or waiting."(F50NC)

Attributes

A recurring remark by the participants, predominantly found in the condition without communication interfaces, was the unpleasant noise emitting from the robot. Only one female participant from the communication condition made a remark about the working condition, as she expressed that the robot was moving above her head, which forced her to frequently look up. Another statement found only by male participants assigned to the communication condition, was the generous safety radius in which the robot stopped working when trespassed.

"Robot stopped very early if you got close"(M4C)

"Since the robot was moving above my head, I had to look up from time to time."(F3C)

"Unpleasant noise."(M20NC)

"The noise of the robot was annoying after a while."(M59NC)

VIII. DISCUSSION

Comparing two versions of an AI-based robotic arm collaboration scenario in VR (with and without the robot communicating itself) this study analyzed the qualitative impressions of 80 participants. The usage of robots with appropriate characteristics is essential for a successful collaboration [14]. Yet, no definitive approach for robot properties suitable for HRC has been suggested so far. Therefore, we chose open-ended questions to explore qualitative differences experienced by human participants that encounter either a robot with or without communicative abilities. The data from the qualitative data allowed for a refined evaluation of the robot-arm designed for this collaboration scenario accompanying quantitative results already gathered through an adjacent study [22]. Six different categories, three for each of the two research questions, emerged during analysis. Participants recognized the benefit of collaborating with the robot-arm, as it can assist with tasks that are either monotone or repetitive or assist in jobs that require precision or endurance. Participants noted the potential increase in production efficiency that the abilities of the robot-arm will bring. Also, of interest is the different perception of the relationship to the robot-arm participants had. While participants of the communication condition expressed desire for more human behavior of the robot, the control group wished for a more comprehensible collaboration with the robot, as the guidance and explanation provided by the augmentation was absent. Especially of interest is how participants reflect on their experience after collaborating with the robot-arm, as it grants valuable insights for designing future HRC setups. All participants agree on the robot-arm's speed being too slow. While the virtual robot-arm had the same speed as its real counterpart and aligned with safety regulations of HRC, participants expressed frustrations over the slow speed and reaction time leading to unnecessary waiting, preventing a constant work-flow. A clear distinction can be made between the two conditions regarding the theme of communication. Whereas participants from the control condition stated that they could not identify the intention of the robot, no remarks regarding this were made by participants of the communication condition. Although rated better, criticism regarding the design of the communication were voiced. In consequence, the placement of the text-panels will be reevaluated in future studies.

A. Limitations and Outlook

The majority of participants were students. Although an effort was made to assemble a sample with wide range in prior experience with robots, the composition of the sample is not applicable to a general population. However, an argument can be made, that those students will one day be part of the workforce, which will be exposed to future working arrangements containing AI-driven HRC. Another limitation can be identified in the relative simplicity of the task itself. Conceived with the aim to provide a manageable task, regardless of prior experience, a more elaborate or stress inducing task used for future studies might reveal further insights into the assessment of autonomously acting robots, helping in identifying positive or negative perceived behavior patterns by the robot, therefore optimizing the creation of future HRC setups. Also, the limitations of current VR-technology need to be addressed. Although modern hardware was utilized, the rendition of the collaboration with the virtual robot-arm is merely an approximation in comparison to a real setup. Considering the advantages offered by VR in terms of a safe, dynamic and cost effective method to conduct reproducible studies, enabling HRC research to evaluate robot and work setups before they become reality. In addition, further studies are recommended to conduct experiments with robots unrestricted in speed for comparison purposes. This is possible as the VR-implementation do not contain potential hazards that a real setup would carry.

IX. CONCLUSION

The results of this exploratory qualitative study shows that there is a vast spectrum of aspects that can impair a successful collaboration between humans and industrial robots. However, the study also illustrate that the augmentation with communication channels contribute to the overall comprehension of the collaboration process. Future studies will incorporate the remarks made by the participants in order to approach the ideal design goals for shared-task environments involving autonomous industrial robots. Furthermore, upcoming studies will explore production efficiency and safety related issues which are ongoing concerns regarding HRC.

REFERENCES

[1] H. Hirsch-Kreinsen, P. Ittermann, and J. Falkenberg, Eds., *Digitalisierung industrieller Arbeit: Die Vision Industrie 4.0 und ihre sozialen Herausforderungen*. Baden-Baden: Nomos edition sigma, 2015.

[2] C. Lenz and A. Knoll, "Mechanisms and capabilities for human robot collaboration," in *The 23rd IEEE International Symposium on Robot and Human Interactive Communication*. IEEE, 2014, pp. 666–671.

[3] M. Haag, "Kollaboratives arbeiten mit robotern – vision und realistische perspektive," in *Zukunft der Arbeit in Industrie 4.0*, A. Botthof and E. A. Hartmann, Eds. Berlin, Heidelberg: Springer Berlin Heidelberg, 2015, pp. 59–64.

[4] E. Cha, Y. Kim, T. Fong, and M. J. Mataric, "A survey of nonverbal signaling methods for non-humanoid robots," *Foundations and Trends in Robotics*, vol. 6, no. 4, pp. 211–323, 2015.

[5] I. Iossifidis, C. Theis, C. Grote, C. Faubel, and G. Schoner, "Anthropomorphism as a pervasive design concept for a robotic assistant," in *Proceedings 2003 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS 2003) (Cat. No.03CH37453)*. IEEE, 2003, pp. 3465–3472.

[6] A. L. Guzman, Ed., *Human-machine communication: Rethinking communication, technology and ourselves*, ser. Digital formations. New York and Bern and Berlin: Peter Lang, 2018, vol. vol. 117.

[7] T. Ende, S. Haddadin, S. Parusel, T. Wüsthoff, M. Hassenzahl, and A. Albu-Schäeffer, "A human-centered approach to robot gesture based communication within collaborative working processes," in *2011 IEEE/RSJ International Conference on Intelligent Robots and Systems*, 2011, pp. 3367–3374.

[8] B. Reeves and C. I. Nass, *The media equation: How people treat computers, television, and new media like real people and places*, 1st ed. Stanford, California: CSLI Publ, 1998.

[9] H.-J. Buxbaum, S. Sen, and R. Häusler, "Theses on the future design of human-robot collaboration," in *Human-Computer Interaction. Multimodal and Natural Interaction*, ser. Lecture Notes in Computer Science, M. Kurosu, Ed. Cham: Springer International Publishing, 2020, vol. 12182, pp. 560–579.

[10] A. Arntz and S. C. Eimler, "Experiencing ai in vr: A qualitative study on designing a human-machine collaboration scenario," in *HCI International 2020 - Late Breaking Work*, ser. Communications in Computer and Information Science. Copenhagen: Springer International Publishing, 2020, vol. 1293.

[11] Unity-Technologies. (2018) Machine learning agents. https://github.com/Unity-Technologies/ml-agents. [Online; accessed 13-March-2020].

[12] E. Matsas and G.-C. Vosniakos, "Design of a virtual reality training system for human–robot collaboration in manufacturing tasks," *International Journal on Interactive Design and Manufacturing (IJIDeM)*, vol. 11, no. 2, pp. 139–153, 2017.

[13] E. Tidoni, M. Abu-Alqumsan, D. Leonardis, C. Kapeller, G. Fusco, C. Guger, C. Hintermüller, A. Peer, A. Frisoli, F. Tecchia, M. Bergamasco, and S. M. Aglioti, "Local and remote cooperation with virtual and robotic agents: A p300 bci study in healthy and people living with spinal cord injury," *IEEE transactions on neural systems and rehabilitation engineering : a publication of the IEEE Engineering in Medicine and Biology Society*, vol. 25, no. 9, pp. 1622–1632, 2017.

[14] S. L. Müller, S. Schröder, S. Jeschke, and A. Richert, "Design of a robotic workmate," in *Digital Human Modeling. Applications in Health, Safety, Ergonomics, and Risk Management: Ergonomics and Design*, ser. Lecture Notes in Computer Science, V. G. Duffy, Ed. Cham: Springer International Publishing, 2017, vol. 10286, pp. 447–456.

[15] A. de Giorgio, M. Romero, M. Onori, and L. Wang, "Human-machine collaboration in virtual reality for adaptive production engineering," in *Procedia Manufacturing*, vol. 11, 2017, pp. 1279–1287.

[16] S. Paepcke and L. Takayama, "Judging a bot by its cover: An experiment on expectation setting for personal robots," in *2010 5th ACM/IEEE International Conference on Human-Robot Interaction (HRI)*. IEEE, 2010, pp. 45–52.

[17] B. Hayes and B. Scassellati, "Challenges in shared-environment human-robot collaboration," in *Collaborative Manipulation" Workshop at HRI 2013*, 2013.

[18] S. L. Müller-Abdelrazeq, K. Schönefeld, M. Haberstroh, and F. Hees, "Interacting with collaborative robots—a study on attitudes and acceptance in industrial contexts," in *Social Robots: Technological, Societal and Ethical Aspects of Human-Robot Interaction*, ser. Human–Computer Interaction Series, O. Korn, Ed. Cham: Springer International Publishing, 2019, vol. 4, pp. 101–117.

[19] M. Zinn, O. Khatib, and B. Roth, "A new actuation approach for human friendly robot design," in *IEEE International Conference on Robotics and Automation, 2004. Proceedings. ICRA '04. 2004*. IEEE, 2004, pp. 249–254 Vol.1.

[20] A. Chanseau, K. Dautenhahn, M. Walters, K. Koay, G. Lakatos, and M. Salem, "Does the appearance of a robot influence people's perception of task criticality?" in *2018 27th IEEE International Symposium on Robot and Human Interactive Communication (RO-MAN)*, 08 2018, pp. 1057–1062.

[21] V. Villani, F. Pini, F. Leali, and C. Secchi, "Survey on human–robot collaboration in industrial settings: Safety, intuitive interfaces and applications," *Mechatronics*, vol. 55, pp. 248–266, 2018.

[22] A. Arntz, S. C. Eimler, and H. U. Hoppe, "Augmenting the human-robot communication channel in shared task environments," in *Collaboration Technologies and Social Computing*, ser. Lecture Notes in Computer Science, A. Nolte, C. Alvarez, R. Hishiyama, I.-A. Chounta, M. J. Rodríguez-Triana, and T. Inoue, Eds. Copenhagen: Springer International Publishing, 2020, vol. 12324, pp. 20–34.

[23] S. L. Müller-Abdelrazeq, S. Stiehm, M. Haberstroh, and F. Hees, "Perceived effects of cycle time in human-robot-interaction," in *2018 IEEE Workshop on Advanced Robotics and its Social Impacts (ARSO)*. IEEE, 2018, pp. 25–30.

[24] D. Kirschner, R. Velik, S. Yahyanejad, M. Brandstötter, and M. Hofbaur, "Yumi, come and play with me! a collaborative robot for piecing together a tangram puzzle," in *Interactive Collaborative Robotics*, ser. Lecture Notes in Computer Science, A. Ronzhin, G. Rigoll, and R. Meshcheryakov, Eds. Cham: Springer International Publishing, 2016, vol. 9812, pp. 243–251.

[25] I. Iossifidis and I. Rano, "Modeling human arm motion by means of attractor dynamics approach," in *2013 IEEE International Conference on Robotics and Biomimetics (ROBIO)*, 2013, pp. 2088–2093.

[26] ISO. (2015) Iso 13849-1:2015. https://www.iso.org/standard/69883.html. [Online; accessed 13-March-2020].

[27] ——. (2011) Iso 10218-1:2011. https://www.iso.org/standard/51330.html. [Online; accessed 13-March-2020].

[28] ——. (2016) Iso/ts 15066:2016. https://www.iso.org/standard/62996.html. [Online; accessed 13-March-2020].

[29] A. Juliani, V.-P. Berges, E. Vckay, Y. Gao, H. Henry, M. Mattar, and D. Lange, "Unity: A general platform for intelligent agents." [Online]. Available: http://arxiv.org/pdf/1809.02627v1

5. On the Influence of Autonomy and Transparency on Blame and Credit in Flawed Human-Robot Collaboration

This late-breaking report was accepted and presented in 3/2021 at the 16th Annual Conference for Elementary and Applied Human-Robot Interaction Research (ACM/IEEE HRI 2021). The conference is a highly selective platform to showcase interdisciplinary and multidisciplinary research regarding human-robot interaction from various communities such as robotics, artificial intelligence, and human factors. The late-breaking report format was chosen as this ACM/IEEE HRI track focuses on new and cutting-edge experimental research. Thus, this track is considered the most widely relevant[1] in the HRI community and has received a 90% increase in submissions in recent years[2].

A. Arntz, S. C. Eimler, C. Straßmann, and H. U. Hoppe, "On the Influence of Autonomy and Transparency on Blame and Credit in Flawed Human-Robot Collaboration," in *Companion of the 2021 ACM/IEEE International Conference on Human-Robot Interaction,* C. Bethel, A. Paiva, E. Broadbent, D. Feil-Seifer, and D. Szafir, Eds. New York, NY, USA: ACM, 03082021, pp. 377–381.

Author	**Contribution**	**%**
Alexander Arntz	- Conceptualization of the approach - Implementation of the VR application - Generation of the stimulus material - Conduct of the experimental study	70%
Sabrina C. Eimler	- Supervision - General advice for the study design	10%
Carolin Straßmann	- Contribution to the study design	10%
H. Ulrich Hoppe	- General supervision	10%

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[1] https://humanrobotinteraction.org/2021/guides-to-submission-types/

[2] https://humanrobotinteraction.org/2020/late-breaking-reports/index.html

On the Influence of Autonomy and Transparency on Blame and Credit in Flawed Human-Robot Collaboration

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ABSTRACT

The collaboration between humans and autonomous AI-driven robots in industrial contexts is a promising vision that will have an impact on the sociotechnical system. Taking research from the field of human teamwork as guiding principles as well as results from human robot collaboration studies this study addresses open questions regarding the design and impact of communicative transparency and behavioral autonomy in a human robot collaboration. In an experimental approach, we tested whether an AI-narrative and communication panels of a robot-arm trigger the attribution of more human like traits and expectations going along with a changed attribution of blame and failure in a flawed collaboration.

CCS CONCEPTS

• **Human-centered computing → Empirical studies in collaborative and social computing**.

KEYWORDS

human-robot collaboration; attribution of blame; perception of intelligence; online study

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1 INTRODUCTION

Industrial usage of Human-Robot Collaboration (HRC) is expected to be enhanced by advanced artificial intelligence (AI) technology in the future, enabling robots to operate either partially or fully autonomously in conjunction with the employees [22]. Whereas current implementations of HRC in industrial settings often use non-humanoid robots (e.g. robot-arms) controlled by an operator or following predefined routines, an autonomous AI-driven robot, capable of adapting and reacting in the required task, would embrace the full potential of the HRC concept [2]: Human personnel could be relieved by delegating repetitive or heavy work onto the robot, while contributing through intuition and experienced-based decision-making, thus combining the advantages of both parties [11]. However, besides the technical and safety challenges to be solved, there are reservations against AI and robots in large parts of the general population [29] that need careful investigation. Prior research in the realm of e.g. the Media Equation Theory [27] and CASA [26] has shown that individuals tend to project human characteristics onto robots while interacting with them and that this even holds true for technologies with non-humanoid appearance [9, 28]. Therefore, it can be assumed that principles and results obtained in research on group collaboration might be applicable for HRC as well.

Comparable to collaboration among human personnel, the collaboration with an autonomous robot to achieve a common goal creates an interdependency in the work relation [8]. Errors in such a context can hamper the successful outcome of the procedure. Considering they might lead to costly or hazardous ramifications for the human collaboration partner, it is of interest to investigate if an autonomous robot will be held accountable for an error and which characteristics along with behavior can influence people's attribution of blame. Research that examined the accusation of errors in non-work-related, casual scenarios [24], revealed that more autonomy displayed by a robot-arm results in an increased attribution of errors whereas comprehensibility/transparency of the robot's actions leads to a decrease in blame [17]. However, the attribution of accountability and credit made in HRC-workplace environments involving autonomous robots remains an open question. Also, reservations towards AI need further exploration to design successful and accepted HRC scenarios, especially attributions relevant in collaborative tasks (e.g. manufacturing procedures) are worth being researched.

To explore this, we used the virtual reality sandbox application by [5] that is capable of simulating a variety of industrial HRC scenarios difficult to realize under experimental conditions [20]. The environment contained a robot-arm with autonomous behavior serving as a basis for an online study testing using non-interactive videos, in a collaborative task, the influence of a) the robot-arms

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behavioral autonomy and b) its transparency in communication on the attribution of blame and credit.

2 RELATED WORK

Research addressing the attribution of blame and credit is well established in the field of human group collaboration. The self-serving bias in attribution has been identified as the main contributing factor in people's assessment of outcomes [16]. Two types can be distinguished: the internal attribution, that includes the own characteristics of an individual, and the external attribution, containing outside influences [12]. Internal attribution is often associated with successful outcomes whereas people incline to apply external attribution to poor outcome [23]. Studies involving Human-Robot Interaction showed that this behavior also occurs when people engage with robots [10, 13, 17]. This misattribution can negatively affect trust in the robot's capability to accomplish a task, thus mitigating the collaboration process [15]. While the self-serving bias in attribution provides a strong foundation, contrary to prior studies, Lei and colleagues' participants attributed more credit and less blame to the robot [19]. The studies used divergent representations of robots with different levels of autonomy and communication, which might have contributed to the inconsistent results. Accordingly, the design of the robot has an effect on the described attribution process (compare [17]). To design robots to be the best possible collaboration partners and bypass distrust [15], research is needed to understand which characteristics drive the attribution of blame in the collaboration with robots.

2.1 The Effect of Expected Autonomy

Kim and colleagues [17] demonstrated an influence of the robot's autonomy on the attribution of blame. A robot that presented more autonomy was more likely blamed for an undesirable outcome. This is specifically of interest in industrial collaboration settings, where employees often have misconceptions and negative attitudes towards autonomous systems [29]. Especially the term AI is associated with negative feelings [1], since people are afraid that robots with AI-capabilities will take their jobs. As a consequence of this widespread misconceptions about AI among the general population, people tend to attribute various forms of human-like characteristics and behavior towards such systems [21]. This is also plausible against the background of CASA [26]. It is therefore assumed that the introduction of the term AI along with the autonomous behavior by a robot-arm will invite participants to project more human-like abilities and behavior onto the system [30]. As a result, people will use an external attribution and blame the robot with higher expected autonomy more for errors and negative outcomes of a collaboration process. Accordingly, the following hypotheses are assumed:

H1: Participants attribute more human-like abilities (intelligence, morality) to a robot-arm with AI-capabilities compared to one without.

H2: Participants attribute more blame and less credit to a robot-arm with AI-capabilities compared to one without.

2.2 The Effect of Communication and Transparency

Beside the perceived autonomy and intelligence of the robot, transparency was found to affect the attribution of blame [17]. A robot that explains it's own behavior was found to evoke lower attributions of blame. This might also an explanation for the results of Lei and colleagues, since they tested the attribution of the talking humanoid robot NAO [19]. Communicative behavior that elicits transparency of the robot's behavior, seems to prevent external attribution. In industrial settings robot-arms are often limited in their communicative abilities. As the environment is often loud, verbal outputs would not work. Studies therefore suggest to use text-panels to enrich the communicative output of the robot. Making the robot's behavior transparent to the human collaborator by augmenting the robot with communication capabilities was found to result in various benefits, e.g. perceived stress and general, positive emotions on the side of the human collaborator [4, 5]. Accordingly, we assume that an communication panel affects the perception of the robot as collaboration partner and thereupon leads to fewer external attributions of errors. This leads to the following hypotheses:

H3: Participants perceive a robot-arm equipped with a communication panel as better collaboration partner (more cooperative and better quality of the collaboration) than one one without communication ability.

H4: Participants attribute less blame and more credit to a robot-arm equipped with a communication panel compared to one without.

As described above, studies involving communicative robots often use voice output that distinctly link the statements to the respective robot [17, 19]. However, industrial robots with non-humanoid appearances in extremely loud environments demand different communication channels. A prior study recognized text-panels in natural language as a viable means of communication in industrial HRC settings [3]. Results indicated that proximity and visual relation to the robot-arm are decisive aspects, since the external text statements are not as intuitively assignable to the robot. Only when the communication behavior (text-panel) is assigned to the robot, it is plausible that this affects the attribution process of errors and robot perception. It is therefore of interest if participants associate the text-panels to the robot-arm or whether it is perceived as an other autonomous entity. Thus, the following research question is to be answered:

RQ1: Do participants see the text-panel augmentations as part of the robot-arm or as another autonomous entity?

3 METHOD

For the study, we used a virtual reality simulation of a HRC shared-task setup as described by [3]. Since the pandemic made a VR-lab experiment impossible, an online experiment was set up, in which participants were presented a first-person perspective video of the HRC-setup. In a 2 (augmented communication vs. non-augmented condition) x 2 (AI-narrative vs. non-AI-narrative) between-subjects design participants were asked to imagine themselves in the role of the human worker assigned to the HRC working arrangement. A total of 225 participants took part in the online study. Participants under 18, an outlier aged 99 as well as participants completing the experiment too fast or too slow (i.e. deviating 1.5 standard deviations from mean completion time) were excluded. Altogether 34 were sorted out. The average age of the remaining 191 participants was M = 25.12 (SD = 7.51). 91 were female, 97 male and 3 non-binary people participated.

3.1 Material

Participants were exposed to one of the four conditions. In all conditions participants a virtual representation of a LBR iiwa 7 R800 CR robot-arm was displayed that used multi colored light-signals and action initiating/terminating and standby gestures [5, 18, 25]. In the high-transparency condition (= augmented condition) text-panels in natural language were used to express guidance and explanations. In the low transparency condition (= non-augmented condition), the explanatory and guiding text-panels were omitted, while everything else to be witnessed in the procedure was identical in terms of movement and actions by the robot and the human. The purpose for removing the text-panel, was to withhold the explanation of the robot-arm's behavior provided by the text-panel but retain the other communication methods. This maintained the robot-arm's ability to convey a detected error but obscure the system's interpretation of the error. To manipulate different levels of autonomy, participants were either told that the robot-arm has AI-capabilities or the scene was just depicted as a collaboration between a human worker and a robot-arm. In all conditions, participants witnessed, from a first-person perspective, a simulated shared-task in which they, as the human operator, were tasked to manufacture metal buttons through a press with their robot collaboration partner [5]. During the procedure, both partners deviated from an assembling procedure and made two recognizable errors by either performing the wrong working step or violating the safety distance, causing a delay in the execution of the procedure.

3.2 Measures and Procedure

The online study was set up on the soscisurvey platform. After providing informed consent, participants were exposed to one of the four conditions. A text of their respective condition either told them that the robot in the collaboration scenario was equipped with AI-capabilities or just referred to as a collaboration with a robot-arm. The subsequent video either showed the augmented or non-augmented collaboration scenario. After being exposed to the stimulus, participants rated their attribution of blame to the robot (2 items, α = .820) and to the self for the errors during the assembling task (2 items, α = .820), as well as regarding the attribution of credit to the robot (2 items, α = .616) and the self for task completion (2 items, α = .625) [17]. The Perceived Moral Agency scale by [6] was used to assess morality (6 items, α = .763) and dependency (4 items, α = .683). Embodiment of the robot-arm was assessed through the EmCorp-Scale [14], containing the sub-scales: corporeality (3 items, α = .685), expressiveness (4 items, α = .701), tactile interaction & mobility (6 items, α = .539) and perception & interpretation (7 items, α = .765). To analyze the anthropomorphism (5 items, α = .592), animacy (5 items, α = .661), likeability (5 items, α = .815) and perceived intelligence (5 items, α = .761) of the robot-arm, the questionnaire incorporated the Godspeed-scale by [7]. Moreover, the collaboration success was measured with an ad-scale consisting of 6 items (α = .795). The assessment of the components assigned to the robot was realized through screenshots of the application, where every visible item was highlighted through a bounding box. For each component participants were asked to decide whether or not it belonged to the robot. The questionnaire closed with demographics (e.g. age, gender, job position, educational background).

4 RESULTS

To test the hypotheses, multiple analyses of variance (MANOVA and ANOVA) were run including the relevant independent and dependent variables for testing.

H1: Participants attribute more human-like abilities (intelligence, morality) to a robot-arm with AI-capabilities compared to one without.

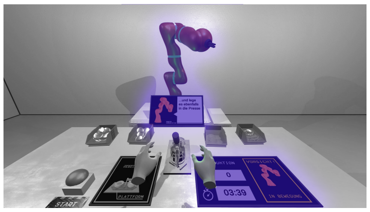
The analysis did not indicate significant differences in the attribution of intelligence and perceived morality between both AI-conditions. Thus, the AI-narrative did not lead to higher perceived intelligence or higher attribution of moral capabilities. The robot-arm was rated significantly better in the ability to perceive and interpret its surroundings (F(1,187) = 5.70, p = 0.018, η_p^2 = 0.03) in the AI-narrative condition (M = 2.37, SD = .66) compared to the non-AI-narrative (M = 2.14 , SD = .73). Moreover, the capacity for cooperation is rated significantly better (F(1,187) = 6.47, p = 0.012, η_p^2 = 0.03) in the AI-narrative condition (M = 3.91, SD = .92) compared the non-AI-narrative (M = 3.55, SD = 1.11). Furthermore, the robot-arm was rated as significantly less dependent on predefined programming (F(1,187) = 5.92, p = 0.016, η_p^2 = 0.03) in the AI-narrative condition (M = 4.22, SD = .74) compared to the non-AI-narrative (M = 4.46, SD = .60). Although the AI-narrative did not lead to more perceived intelligence and morality, these results indicate that participants associate more human-like characteristics to the robot-arm like being independent, cooperative and able to perceive and interpret. Thus, H1 is partly supported.

H2 & H4: Participants attribute more blame and less credit to a robot-arm with AI-capabilities compared to one without and participants attribute less blame and more credit to a robot-arm equipped with a communication panel compared to one without.

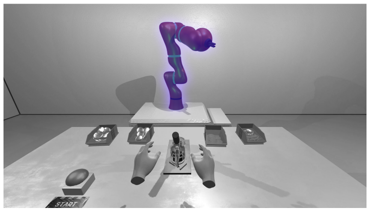
Analyses testing this did not show any differences between the conditions for neither the attribution of blame nor for credit attribution. Therefore, H2 and H4 could not be supported.

H3: Participants perceive a robot-arm equipped with a communication panel as better collaboration partner (more cooperative and better quality of the collaboration) than one one without communication ability.

Results show significant differences (F(1,187) = 5.95, p = 0.016, η_p^2 = 0.003) between the augmented condition (M = 3.57, SD = .62) and the non-augmented condition (M = 3.33, SD = .76) for perceived intelligence. Significant differences occurred for dominance (F(1,187) = 8.67, p = 0.004, η_p^2 = 0.04). The robot-arm in the augmented condition was perceived as more dominant (M = 3.37, SD = .94) than in the non-augmented condition (M = 2.98, SD = .84). A significant difference was found for collaboration success (F(1,186) = 5.34, p = 0.002, η_p^2 = 0.03), augmented condition (M = 2.80, SD = .72) vs. non-augmented (M = 3.05, SD = .77). H3 is supported.



(a) Text-panel condition



(b) Non-text-panel condition

Figure 1: Heat map of the components that participants associated with the robot-arm. The text-panels from the robot-arm were considered part of the robot-arm.

RQ1: Do participants see the text-panel augmentations as part of the robot-arm or as another autonomous entity?

Analyzing the components that were associated with the robot, no significant differences were observed between the AI-narrative condition vs. non-AI-narrative condition. A heat map revealed that participants from all conditions identified the body of the robot-arm (Fig 1). In addition, 93.3% of the participants from the text-panel condition associated the text-panel as part of the collaboration partner. Also, 73.2% of the participants associated the information text-panel featuring warning messages with the robot-arm.

5 DISCUSSION AND LIMITATIONS

This study explored the effect of transparency (i.e. communicative augmentations) and autonomy (i.e. AI-narrative) on the attribution of blame and credit as well as the general perception of the robot and the collaboration in an industrial HRC assembly task setting. Although the introduction of the AI-term and narrative did not lead to a higher attribution of intelligence and morality to the robot it invoked associations with other human-like characteristics (H1): Participants rated the robot-arm as more capable of perceiving and interpreting its surroundings and noted a greater ability for cooperation when they believed it to be equipped with AI. Considering that participants underwent the same procedure and witnessed the same behavior of the robot-arm in all conditions, backed by the research of [30], it can be assumed that participants projected their own mental models and expectations of the AI-term onto the characteristics of the robot-arm. As stated by [30], the wide spectrum of the term AI together with the widespread misconceptions invites people with media biased knowledge to project numerous abilities and expectations onto AI-enhanced systems [29]. Future studies should explore the content of the mental models and expectations and their effects on the collaboration process.

RQ1 investigated which components are attributed to the robot-arm to ensure the statements displayed on the text-panel is associated with the robot-arm. Indeed participants perceived the text-panel as belonging to the robot/ part of the robot-arm. Accordingly, the presence of text-panels as a means for the robot to increase communicative transparency lead to higher attributions of intelligence, dominance and the perception of a more successful collaboration (H3). Although participants perceived the collaboration more successful in the augmented version of the robot-arm, the text-panel did not affect the evaluation of the robot-arm’s perceived cooperativeness. In contrast, the augmented robot-arm was perceived as more dominant. This results could produce conflicts, since the perception of dominance elicits negative feelings in the human collaborator. Especially people with fears and negative attitudes might feel patronized and avoid collaborating with the robot-arm. Thus, designers have to use communication features inducing transparency with caution, since they could trigger a boomerang-effect.

While the perception of the robot-arm was affected by the induced autonomy and transparency (H1, H3), no significant difference regarding blame and credit was found (H2, H4). While other studies showed that the self-serving bias in attribution cannot always be demonstrated in interactions with robots [19], the projected ramification that is expected by the individual [16] must be considered as a limitation of this study.

Due to the restrictions of the COVID-19 pandemic we were unable to conduct an experimental study where participants could actually collaborate with robot-arm in the virtual reality scenario. While the virtual reality sandbox application provided by [5] enabled us to substitute an online study design, no direct interaction with the robot-arm was possible. The immersive effect of the environment might be able to create a sense of more direct involvement with a higher sensitivity for the outcomes of the errors happening. Employees exposed to autonomous robots in industrial HRC settings could face real consequences from errors made during the collaboration e.g. injury or career disadvantages that witnessing a video cannot fully mimic. Future work should address the used scenario using an interaction study to overcome these limitations. Also, future studies should investigate if additional communication augmentations (e.g. voice output) and inputs provided by the text panels affect attributions differently.

6 CONCLUSION

While this study could not replicate established findings from the literature regarding the attribution of blame and credit, results reveal an interesting effect regarding the attribution of human characteristics on the robot-arm caused by an AI-narrative that are worth being further explored. Future studies should look into the dynamics of people’s mental models and preconceptions brought into the collaboration scenario with AI-based robots. Communication behavior should be outbalanced in a way that it does not trigger dominance perception on the one hand, but elicits enough transparency to induce trust in the collaboration partner on the other hand.

REFERENCES

[1] 2017. *Attitudes towards the impact of digitisation and automation on daily life: Report*. Special eurobarometer, Vol. 460. [European Commission], [Brussels].

[2] Arash Ajoudani, Andrea Maria Zanchettin, Serena Ivaldi, Alin Albu-Schäffer, Kazuhiro Kosuge, and Oussama Khatib. 2018. Progress and prospects of the human–robot collaboration. *Autonomous Robots* 42, 5 (2018), 957–975. https://doi.org/10.1007/s10514-017-9677-2

[3] Alexander Arntz and Sabrina C. Eimler. 2020. Experiencing AI in VR: A Qualitative Study on Designing a Human-Machine Collaboration Scenario. In *HCI International 2020 – Late Breaking Posters*, Constantine Stephanidis, Margherita Antona, and Stavroula Ntoa (Eds.). Communications in Computer and Information Science, Vol. 1293. Springer International Publishing, Cham, 299–307. https://doi.org/10.1007/978-3-030-60700-5_38

[4] Alexander Arntz, Sabrina C. Eimler, and H. Ulrich Hoppe. 14.12.2020 - 18.12.2020. “The Robot-Arm Talks Back to Me” - Human Perception of Augmented Human-Robot Collaboration in Virtual Reality. In *2020 IEEE International Conference on Artificial Intelligence and Virtual Reality (AIVR)*. IEEE, 307–312. https://doi.org/10.1109/AIVR50618.2020.00062

[5] Alexander Arntz, Sabrina C. Eimler, and H. Ulrich Hoppe. 2020. Augmenting the Human-Robot Communication Channel in Shared Task Environments. In *Collaboration Technologies and Social Computing*, Alexander Nolte, Claudio Alvarez, Reiko Hishiyama, Irene-Angelica Chounta, María Jesús Rodríguez-Triana, and Tomoo Inoue (Eds.). Lecture Notes in Computer Science, Vol. 12324. Springer International Publishing, Cham, 20–34. https://doi.org/10.1007/978-3-030-58157-2{_}2

[6] Jaime Banks. 2019. A perceived moral agency scale: Development and validation of a metric for humans and social machines. *Computers in Human Behavior* 90 (2019), 363–371. https://doi.org/10.1016/j.chb.2018.08.028

[7] Christoph Bartneck, Dana Kulić, Elizabeth Croft, and Susana Zoghbi. 2009. Measurement Instruments for the Anthropomorphism, Animacy, Likeability, Perceived Intelligence, and Perceived Safety of Robots. *International Journal of Social Robotics* 1, 1 (2009), 71–81. https://doi.org/10.1007/s12369-008-0001-3

[8] César A. Collazos, Luis A. Guerrero, José A. Pino, and Sergio F. Ochoa. 2003. Collaborative Scenarios to Promote Positive Interdependence among Group Members. In *Groupware: Design, Implementation, and Use*, Gerhard Goos, Juris Hartmanis, Jan van Leeuwen, Jesús Favela, and Dominique Decouchant (Eds.). Lecture Notes in Computer Science, Vol. 2806. Springer Berlin Heidelberg, Berlin, Heidelberg, 356–370. https://doi.org/10.1007/978-3-540-39850-9{_}30

[9] Stéphanie Dubal, Aurélie Foucher, Roland Jouvent, and Jacqueline Nadel. 2011. Human brain spots emotion in non humanoid robots. *Social cognitive and affective neuroscience* 6, 1 (2011), 90–97. https://doi.org/10.1093/scan/nsq019

[10] Victoria Groom, Jimmy Chen, Theresa Johnson, F. Arda Kara, and Clifford Nass. 02.03.2010 - 05.03.2010. Critic, compatriot, or chump?: Responses to robot blame attribution. In *2010 5th ACM/IEEE International Conference on Human-Robot Interaction (HRI)*. IEEE, 211–217. https://doi.org/10.1109/HRI.2010.5453192

[11] Buxbaum Hans-Jürgen. 2020. Human-Robot Collaboration. *International Journal of Robotic Engineering* 5, 1 (2020). https://doi.org/10.35840/2631-5106/4121

[12] Fritz. Heider. 2013. *The Psychology of Interpersonal Relations*. Psychology Press. https://doi.org/10.4324/9780203781159

[13] Pamela J. Hinds, Teresa L. Roberts, and Hank Jones. 2004. Whose Job Is It Anyway? A Study of Human-Robot Interaction in a Collaborative Task. *Human–Computer Interaction* 19, 1-2 (2004), 151–181. https://doi.org/10.1080/07370024.2004.9667343

[14] Laura Hoffmann, Nikolai Bock, and Astrid M. v.d. Rosenthal Pütten. 02262018. The Peculiarities of Robot Embodiment (EmCorp-Scale). In *Proceedings of the 2018 ACM/IEEE International Conference on Human-Robot Interaction*, Takayuki Kanda, Selma Ŝabanović, Guy Hoffman, and Adriana Tapus (Eds.). ACM, New York, NY, USA, 370–378. https://doi.org/10.1145/3171221.3171242

[15] Poornima Kaniarasu and Aaron M. Steinfeld. 25.08.2014 - 29.08.2014. Effects of blame on trust in human robot interaction. In *The 23rd IEEE International Symposium on Robot and Human Interactive Communication*. IEEE, 850–855. https://doi.org/10.1109/ROMAN.2014.6926359

[16] Harold. H. Kelley and John. L. Michela. 1980. Attribution theory and research. *Annual review of psychology* 31 (1980), 457–501. https://doi.org/10.1146/annurev.ps.31.020180.002325

[17] Taemie Kim and Pamela Hinds. 06.09.2006 - 08.09.2006. Who Should I Blame? Effects of Autonomy and Transparency on Attributions in Human-Robot Interaction. In *ROMAN 2006 - The 15th IEEE International Symposium on Robot and Human Interactive Communication*. IEEE, 80–85. https://doi.org/10.1109/ROMAN.2006.314398

[18] Ingo Kresse. 2010. licensed under CC-BY-3.0 2010 © by Ingo Kresse, kresse@in.tum.de. https://creativecommons.org/licenses/by/3.0/.

[19] Xin Lei and Pei-Luen Patrick Rau. 2020. Should I Blame the Human or the Robot? Attribution Within a Human–Robot Group. *International Journal of Social Robotics* (2020). https://doi.org/10.1007/s12369-020-00645-w

[20] Séverin Lemaignan, Marc Hanheide, Michael Karg, Harmish Khambhaita, Lars Kunze, Florian Lier, Ingo Lütkebohle, and Grégoire Milliez. 2014. Simulation and HRI Recent Perspectives with the MORSE Simulator. In *Simulation, Modeling, and Programming for Autonomous Robots*, Davide Brugali, Jan F. Broenink, Torsten Kroeger, and Bruce A. MacDonald (Eds.). Lecture Notes in Computer Science, Vol. 8810. Springer International Publishing, Cham, 13–24. https://doi.org/10.1007/978-3-319-11900-7{_}2

[21] Gabriel Lima, Changyeon Kim, Seungho Ryu, Chihyung Jeon, and Meeyoung Cha. 2020. Collecting the Public Perception of AI and Robot Rights. *Proceedings of the ACM on Human-Computer Interaction* 4, CSCW2 (2020), 1–24. https://doi.org/10.1145/3415206

[22] Ruikun Luo, Rafi Hayne, and Dmitry Berenson. 2018. Unsupervised early prediction of human reaching for human–robot collaboration in shared workspaces. *Autonomous Robots* 42, 3 (2018), 631–648. https://doi.org/10.1007/s10514-017-9655-8

[23] Dale T. Miller and Michael Ross. 1975. Self-serving biases in the attribution of causality: Fact or fiction? *Psychological Bulletin* 82, 2 (1975), 213–225. https://doi.org/10.1037/h0076486

[24] Tomohito Miyake, Yuji Kawai, Jihoon Park, Jiro Shimaya, Hideyuki Takahashi, and Minoru Asada. 14.10.2019 - 18.10.2019. Mind perception and causal attribution for failure in a game with a robot. In *2019 28th IEEE International Conference on Robot and Human Interactive Communication (RO-MAN)*. IEEE, 1–6. https://doi.org/10.1109/RO-MAN46459.2019.8956325

[25] MORSE. 2020. KUKA LWR arm actuator. http://www.openrobots.org/morse/doc/0.5/user/actuators/kuka_lwr.html#use-of-the-kuka-lwr

[26] Clifford Nass, Jonathan Steuer, and Ellen R. Tauber. 1994. Computers are social actors. In *Conference companion on Human factors in computing systems - CHI ’94*, Catherine Plaisant (Ed.). ACM Press, New York, New York, USA, 204. https://doi.org/10.1145/259963.260288

[27] Byron Reeves and Clifford Ivar Nass. 1998. *The media equation: How people treat computers, television, and new media like real people and places* (1. paperback ed. ed.). CSLI Publ, Stanford, Calif.

[28] Maike A. J. Roubroeks, Jaap R.C. Ham, and Cees J.H. Midden. 2012. Investigating the media equation hypothesis: do we really see computer agents as human-like? https://fisher.osu.edu/blogs/persuasive2011/ 6th International Conference on Persuasive Technology (PERSUASIVE 2011), PERSUASIVE 2011 ; Conference date: 02-06-2011 Through 05-06-2011.

[29] Astrid Schepman and Paul Rodway. 2020. Initial validation of the general attitudes towards Artificial Intelligence Scale. *Computers in Human Behavior Reports* 1 (2020), 100014. https://doi.org/10.1016/j.chbr.2020.100014

[30] Jakub Złotowski, Diane Proudfoot, Kumar Yogeeswaran, and Christoph Bartneck. 2015. Anthropomorphism: Opportunities and Challenges in Human–Robot Interaction. *International Journal of Social Robotics* 7, 3 (2015), 347–360. https://doi.org/10.1007/s12369-014-0267-6

6. A Virtual Sandbox Approach to Studying the Effect of Augmented Communication on Human-Robot Collaboration

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Author	**Contribution**	**%**
Alexander Arntz	- Conceptualization of the approach - Implementation of the VR application - Conduct of the experimental study	70%
Sabrina C. Eimler	- Supervision - General advice for the study design	15%
H. Ulrich Hoppe	- General supervision	15%

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A Virtual Sandbox Approach to Studying the Effect of Augmented Communication on Human-Robot Collaboration

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Human-Robot Collaboration (HRC) has the potential for a paradigm shift in industrial production by complementing the strengths of industrial robots with human staff. However, exploring these scenarios in physical experimental settings is costly and difficult, e.g., due to safety considerations. We present a virtual reality application that allows the exploration of HRC work arrangements with autonomous robots and their effect on human behavior. Prior experimental studies conducted using this application demonstrated the benefits of augmenting an autonomous robot arm with communication channels on subjective aspects such as perceived stress. Motivated by current safety regulations that hinder HRC to expand its full potential, we explored the effects of the augmented communication on objective measures (collision rate and produced goods) within a virtual sandbox application. Explored through a safe and replicable setup, the goal was to determine whether communication channels that provide guidance and explanation on the robot can help mitigate safety hazards without interfering with the production effectiveness of both parties. This is based on the theoretical foundation that communication channels enable the robot to explain its action, helps the human collaboration partner to comprehend the current state of the shared task better, and react accordingly. Focused on the optimization of production output, reduced collision rate, and increased perception of safety, a between-subjects experimental study with two conditions (augmented communication vs non-augmented) was conducted. The results revealed a statistically significant difference in terms of production quantity output and collisions with the robot, favoring the augmented conditions. Additional statistically significant differences regarding self-reported perceived safety were found. The results of this study provide an entry point for future research regarding the augmentation of industrial robots with communication channels for safety purposes.

Keywords: human-robot collaboration, virtual reality, shared task, augmented communication, production quantity, perceived safety, experimental study, objective measures

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1 INTRODUCTION

State of the art automated production cycles today widely use industrial robots. However, most production processes in heavy industries involve human employees at certain points that either coexist or cooperate with these robots. A shared workspace between humans and robots often demands enormous safety precautions, since robots in these contexts usually possess great physical strength combined with high movement velocities (Meziane et al., 2017). To solve this, strict regulations demand to either fence in these robots or separate them from the workforce. The concept of human-robot collaboration (HRC) requires a paradigm shift for these established safety measures, as this approach envisages industrial robots and employees not only to work together in confined spaces but also to interact directly to accomplish a shared task. HRC creates the potential for new production methods in manufacturing, where tedious, repetitive, and heavy tasks are executed by the robot in collaboration with the adaptive decision-making and individual skill set of the human employee (Ajoudani et al., 2018). Current safety regulations either demand a high expenditure for the collaborative process or diminish the production output (Gerst, 2020). Therefore, jeopardizing the whole concept of HRC, as industries will not invest in complex working arrangements involving collaborative robots that are unprofitable. This requires safety measures, which preserve the individual abilities of both, the human and the robot to contribute to the economic success of the concept through an increase in productivity (Buxbaum et al., 2020). Furthermore, it is anticipated that future iterations of HRC will deploy artificial intelligence, allowing the robot to conduct actions autonomously to some degree. It is assumed that these sophisticated systems will be able to detect their human collaboration partner and act in accordance to prevent hazardous situations (Daugherty and Wilson, 2018). This potential future scenario contains various open questions regarding the design of these working arrangements and people's reactions towards it (Bröhl et al., 2019).

While prior HRC-related studies explored subjective measurements, the assessment of objective results are also important. As mentioned before, creating a benefit for production output is necessary for the adoption of HRC in the industry, which is partly addressed in the research for creating an effective task execution scheduling aim for the robot (Wilcox and Shah, 2012), experimental studies regarding arrangements with augmented collaborative robots and their influence on productivity and safety still leave space for exploration (Buxbaum and Häusler, 2020). This motivates the aim of this paper to complete the subjective data from our prior studies with objective data that analyzes the effect of augmented communication-based HRC regarding the outcome of production volume and collision rate (Arntz et al., 2020a; Arntz et al., 2020b; Arntz and Eimler, 2020).

Robots that are deployed in HRC industrial scenarios come in many shapes and forms, ranging from robot arms to more obscure appearances such as the Stewart parallel robot (Wen et al., 2018), all designed for a specific required task. Covering all these robot representations for HRC studies provides an enormous challenge, since not every robot nor task is suited to be examined in a lab experiment under controlled conditions. Another crucial factor in experimental studies regarding HRC is safety. Considering that exposing participants to robotic systems with hazardous potential violates any ethical guidelines, thus HRC-related experimental studies conducted with real robots will always be restricted in terms of concepts that can be explored (Liu and Wang, 2020).

In addition to the safety restrictions, the realization of an autonomous collaborating robot requires the usage of sophisticated sensor technology that provides the robot with information regarding its environment (Amara et al., 2020). Prior research circumvented this by using the Wizard-of-Oz approach (Weiss et al., 2009), delegating the control of the robot to the experimental supervisor. Therefore, there is little research that combines an autonomous robot that acts under the guidelines for collaboration along with robots with full interaction exposure within a shared task setup (ISO, 2020).

To address these challenges, we used a virtual reality (VR) sandbox that can be used to create a variety of different HRC scenarios, as the VR technology provides a secure and replicable medium to examine human characteristics when exposed to shared task scenarios involving robots (Matsas et al., 2018). Prior research identified immersion as an essential precondition in the collection of behavioral data through VR that can be projected on the real counterpart scenario (Bailenson, 2018). Since robots in their various appearances and features can be simulated with enough fidelity within the VR sandbox application to match their real counterparts, it can be assumed that the reactions from participants exposed to these virtual robots allow for valid predictions for real HRC setups (de Giorgio et al., 2017). This is backed by the works of Bailenson (2018), who describes the usage of VR technology in a diverse array of social studies, i.e., perspective-taking scenarios where participants assume a different role within an unfamiliar context (Bailey and Bailenson, 2017; Roswell et al., 2020). To provide these contexts within the VR sandbox application, we build a library of prefabs containing the necessary functionality to display a variety of different scenarios, in which any virtual robot arm representation can conduct various actions in conjunction with a human partner. Execution of these actions is based on the implementation of machine-learning driven agents that allow in an innovative way to train the virtual robot arm for various experimental setups and tasks. This enables to design and adjust the behavior of the robot based on the established guidelines and reaction of the participant. Ensuring greater comparability between experimental studies compared to the Wizard-of-Oz approach where nuanced procedural deviations by the human operator can affect the outcome (Schlögl et al., 2013).

In the following sections, we introduce the theoretical background that provides the basis for the formulated hypotheses and the research question. Afterward, the experimental study including the stimulus material is described, in which different augmentation conditions are compared to explore their impact on production quantity and collision rate. Additionally, based on the results of a prior study (Arntz et al., 2020b), we investigate whether the communication augmentations lead to higher perceived safety along with a potential difference in collision rate. Afterward, the results are presented and discussed.

2 THEORETICAL BACKGROUND

The current theoretical concept of humans collaborating with robots is derived from the group collaboration between human individuals (Shah et al., 2011). Empirical studies in this research field identified group cognition as essential criteria for successful collaboration among humans (Hart and Staveland, 1988). The term group cognition, proposed by Wegner (Wegner et al., 1991), describes a transactive memory system that contains the shared and organized knowledge of a group of collaborating individuals. This organized knowledge contributes to the collaboration performance within a group through a common mental model which is formed through communication (Peltokorpi and Hood, 2019). Depending on the appropriate information suited for the collaboration context that is exchanged through communication this perceived common model can be beneficial. Individuals within a group become more aware of the organization and roles as well as the specific goals of the shared task. The benefit of a perceived common mental model has also been identified in Human-Robot Interaction research, in which the recognition of the robot's activities combined with a proper reaction to the human commands, can evoke the awareness of group cognition in the human (Shah et al., 2011). This requires a clear understanding of the roles each individual possesses in the process, combined with the prioritization of group needs, which are further aspects for successful collaboration. Applied to the collaboration between humans and robots, the standards are defined as the continuing distribution of sub tasks and immediate coordination of the needed actions to accomplish the common goal (Schmidtler et al., 2014). This requires that the robot must communicate the appropriate proxemics behavior and can follow certain societal norms in terms of gestures and physical contact (Mumm and Mutlu, 2011). However, considering that the majority of robots deployed in industrial environments are built with a non-anthropomorphic appearance (Müller et al., 2017), the formation of such a perception on a cognitive level is much harder to archive than in a robot with a humanoid appearance (Atmaca et al., 2008). Responsible for this are mirror neurons in the brain, which become active while actions are performed by another individual, for the purpose of adapting or improving activities carried out by the respective human (Roesler and Onnasch, 2020). Applied to a collaborative setup, not only the own executed actions, are represented on a cognitive level, but also the anticipation of activities from the partner. A collaboration partner that deviates in its appearance and characteristics, such as an industrial robot can therefore not create the same cognitive stimulus on the human (Sebanz et al., 2005). One approach to induce this stimulus is by eliciting a presence of intention and purposive behavior from the robot through communication (Sebanz and Knoblich, 2009). These characteristics in robots are not only beneficial for the humans' perception of an intended common goal, the capability for communication also lowers the barrier for perceiving it as a social presence, which can contribute to the willingness of humans to collaborate with it (Heerink et al., 2009). Based on this theoretical foundation the first hypothesis is formulated, which assumes that a robot that is augmented with a communication interface that promotes the aforementioned stimulus, contributes to higher production effectiveness and volume within a shared task setup. Although contributions for increasing productivity through HRC are the largest advocates for establishing the concept of collaborating with autonomous robots in the industry, the research focused on these aspects is still in its infancy and should be explored more (Galin and Meshcheryakov, 2020), as comparable studies omit the augmentation aspect of the robot (Heydaryan et al., 2018).

Apart from productivity, another concern for the industry regarding HRC is safety. Currently, potential hazards from the robots are diminished by dividing HRC into three categories: In the first, employees are shielded from the robot either through cages or separated working areas (Haag, 2015). This enables the robot to work faster as no precautions are needed to take for avoiding trespassing human workers. The second category restricts access to the robot. A designated area that separates the robot from its co-workers is omitted, instead, sensors form a light curtain around the robot (Haag, 2015). If the curtain is breached, the robot ceases its current motion. Due to regulations (Rosenstrauch and Kruger, 2017), demanding a generous safety radius around the robot, no direct interactions between the robot and the worker are allowed. The third category uses proximity sensors to calculate the distance of the worker to the robot (Haag, 2015). With these categories designed to meet current technical limitations, the introduction of AI-based robots in shared tasks (Lenz and Knoll, 2014) will likely enable the detection of the motion of intervening employees and to anticipate the movement of people and objects (Zakka et al., 2019). Same with conveying the robot's actions, communicating the detection of potential collisions and their influence in reducing potential accidents are questions of interest regarding HRC (Buxbaum et al., 2020), which will be investigated in the second hypothesis.

The anticipated decrease in collisions enabled by the communication channels is also expected to increase the perception of safety within the collaboration task. This can be attributed to the contribution of communication between entities to the perception of safety within a workspace (Seo, 2005). The safety of a workplace is influenced by a variety of dimensions and can affect the safety performance and perceived safety of an individual (Fernández-Muñiz et al., 2012). One of the frequently discussed dimensions is the awareness of the organizational structure of a task, which in the case of collaborative work is directly linked to the exchange of information regarding the task management (Cigularov et al., 2010). This led to the formation of the third hypothesis, as the communication channels of the robot could raise people's perception of safety in the system compared to a robot without augmented communication capabilities. In addition to the formulated hypotheses, the time participants gazed onto the guidance and explanation provided by the text

FIGURE 1 | The virtual representation of an industry environment served as the background of the workplace arrangement. Equipped with appropriate props and sound cues, this backdrop aimed to provide the context of the setting and facilitate the immersion of the experimental study.

panel channel was of interest, resulting in the research question investigating whether the time affects the productivity of the participants or the collision rate with the robot arm.

2.1 Hypotheses

For the purpose of exploring the effect on production capacity, collision avoidance, and the perceived security of guiding and explanatory augmentation of industrial robots in shared task environments, the following hypotheses were formulated:

- H1: Participants produce more pin-back buttons in the augmented condition compared to the non-augmented condition.
- H2: Participants collide less with the augmented robot arm compared to the non-augmented condition.
- H3: Perception of safety is higher in the augmented condition compared to the non-augmented condition.
- Research question: Does the time participants look at the text panel affect the productivity and collision rate?

3 EXPERIMENTAL STUDY

3.1 Methods

The experimental setup varied the presence vs. absence of augmented communication channels in a between-subjects design where participants were tasked to assemble pin-back button components in collaboration with the autonomously acting robot arm in VR. In the experimental condition, the robot arm was augmented with the three aforementioned communication channels. The non-augmented condition omitted these communication channels.

The sample size was $N = 80$ (40 female), with 40 participants assigned to each of the two conditions. Both conditions contained an equal gender distribution. The average age of the participants was 25 ($M = 25.31$, $SD = 6.10$). The majority of the participants were students with a background in computer science and engineering from the University of Applied Sciences Ruhr West.

3.2 Stimulus Material

To facilitate immersion in the VR sandbox experiments, a virtual environment that emulates an industrial workspace was required. To ensure an authentic depiction, four industry representatives and robot experts were involved in the design process. Qualitative interviews conducted with the experts helped to identify appropriate machinery used in manufacturing plants, the layout of common HRC working arrangements, frequent procedures, and the design of the communication channels. Additional reference material complemented the remarks stated in the interviews (Vysocky and Novak, 2016; Villani et al., 2018), resulting in the final creation of the virtual environment implemented in Unity 3D (Version 2018.4.11f1) (Unity, 2020a) (**Figure 1**).

To ensure stable performance of the virtual environment despite being filled with a variety of props, i.e., pipes, forklifts, and cables. Streaming assets and shader of the objects were optimized for VR usage. This ensured reaching a target rate above ninety frames per second which is crucial for virtual reality, reducing side effects such as motion sickness or eye strain (Jerald, 2016). Non-interactive assets were placed as static objects into the scenery, which allowed for a mixed lighting setup with baked shadow maps for immovable objects and real-time lighting for interactive and dynamic objects. This, in conjunction with the use of pre-calculated reflection cube maps, allowed for a much more elaborated visual fidelity adding to the immersion. The ambient soundscape completed the experience with various industrial background noises composed of public domain audio files mixed with recordings from a steel mill, taken from a preceding project (Zengeler et al., 2020).

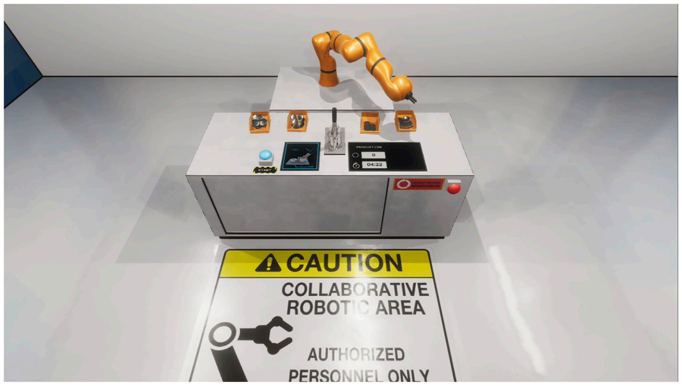

FIGURE 2 | The virtual workplace arrangement at which the participants conducted the shared task in collaboration with the robot arm. Apart from the pin-back button press and the container for the assembly components, the workplace contained a start and emergency shutdown button. Shown is the non-augmented condition where the three communication channels are absent. The virtual workspace where the shared task was executed by the participants in collaboration with the robot arm. The arrangement was designed Note that in the control condition the augmented communication channels are absent.

The locomotion mechanic was implemented through the Oculus API and allowed the users to ambulate either through the controller or by their natural body movement. To discourage the exploration of the environment and keep participants focused on the goal of the HRC workplace, the arrangement was enclosed in a separate room that provided a barrier without breaking the internal consistency of the virtual environment. The workplace arrangement itself consisted of a waist-high desk, where the shared task can be executed in collaboration with the autonomous robot arm (**Figure 2**).

3.2.1 Shared Task

The VR sandbox is designed to address numerous categories of collaboration tasks and procedures. For this purpose, a diverse array of interaction mechanics were implemented that allows manipulating actions such as pushing and pulling virtual objects. The usability of the actions was designed according to established third-party applications like the virtual reality toolkit (VRTK, 2020). For the context of the designed experimental setup, it was necessary to provide a shared task that included the participation of both parties in assigned roles following a coherent representation of a manufacturing process.

Investigating several manufacturing processes involving the usage of collaborative robots in real industries, resulted in cumbersome procedures that were deemed too taxing for inexperienced participants. For this purpose, a comprehensible alternative was conceived in the usage of the Badgematic Flexi Type 900 (59 mm) press as a shared task to produce pin-back buttons (Badgematic, 2020). The use of stand-ins for real manufacturing tasks can be found in several research setups involving HRC (Sen et al., 2020; Williams et al., 2020).

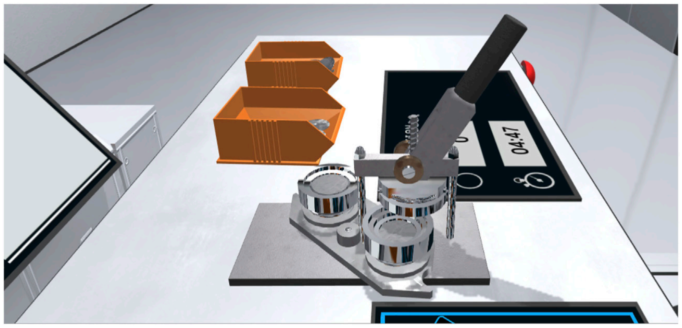

FIGURE 3 | The Participants operated the virtual pin-back button press in collaboration with the robot arm. The implemented interaction mechanics emulated the physical button press and enabled participants to use the lever and the rotation tray. Authentic sound and haptic feedback completed the representation.

The virtual representation of the button press was authentically modeled after the real one, using Autodesk Maya 2018 (**Figure 3**) (Autodesk, 2020). The pin-back button press consisted of three components. While the frame of the press itself was static, the stamp platform of the press and the associated lever were intractable by the participants through the usage of the Oculus Rift touch controller. To mimic the real characteristics of the button press, both interactive components were equipped with a hinge point and a rotator that interacted with the handgrip mechanic of the Oculus integration (Oculus, 2020b). Simulated friction was implemented to create the illusion of a resistance that is required when using the lever or turning the stamp platform. Audio sources were added to the components of the pin-back button press, which emitted sounds recorded from its real counterpart, varying in intensity based on the force of which the lever is pulled, the stamp platform is turned or a segment of the pin-back buttons is either inserted or extracted.

The shared task itself involved a total of nine individual working steps which were executed alternately between the human participant and the autonomous robot arm (Arntz et al., 2020a) (**Figure 4**). The procedure was initiated by the participant pressing the start button. The robot arm then moved to the respective storage container to pick up the first component of the pin-back button. After the robot arm grabbed the first component, it was inserted by the robot arm into the first tray of the pin-back button press. The robot arm retracted then to make way for the participant, who was required to rotate the press tray and operate the lever of the pin-back button press. The next step was for the robot arm to transfer the second and third pin-back button component successively into the empty remaining tray. Subsequently, the press tray was again rotated by the participant followed by pulling the lever and another press rotation. The robot arm was then tasked to extract the finished pin-back button from the press and move it to the respective storage container. Once a full production cycle was complete, the process for the production of the next pin-back button began immediately. The number of the produced pin-back buttons in conjunction with the remaining time was displayed to the user via a virtual monitor placed on the work desk in front of the participant. An emergency shutdown button that terminated all operations from the robot arm gave participants additional security measures and was designed and implemented following common industry safety protocols (Heydaryan et al., 2018).

3.2.2 The Collaborative Robot Arm

Although the VR sandbox was created to allow any form of robot collaboration partner to be evaluated, this scenario used a representation of the KUKA LBR iiwa 7 R800 CR series (KUKA, 2020), which is widely used in various industries and application scenarios. To ensure an authentic portrayal of the virtual robot arm, reference manuals and schematics from the manufacturer were consulted in combination with intensive examination of the real pendant (Kresse, 2010; Lemaignan et al., 2014; KUKA, 2016; MORSE, 2020). Also of importance was the sound for auditory location in collaboration setups involving robots (Cha et al., 2018). Multiple sound recordings from the real robot arm were combined to recreate the distinctive soundscape of the LBR iiwa series through the audio tools of the Unity 3D engine. This resulted in an accurate representation of the visuals and characteristics of the robot arm.

The collaboration aspect of the experimental setups within the VR sandbox demanded the robot arm to react adequately towards the actions of the participants. Therefore, the usage of an animation controller that contains a pre-defined set of animated movements was rejected in favor of an inverse kinematic system. This allowed calculation of the required joint angles for the robot arm to reach any target position as well as dynamic movement. Following the structure of the real LBR iiwa series, the virtual model comprised seven degrees-of-freedom (DoF) in a spherical-rotation-spherical kinematic structure using the same parameter as the real robot arm (Faria et al., 2018; Doliwa, 2020a). The inverse kinematic implementation for the VR sandbox was based on a closed-form solution, which provided better performance compared to a numeric solution (Artemiadis, 2013). The inverse kinematic system made use of the Denavit-Hartenberg parameter, as the basis for the calculation in 7-DoF (Faria et al., 2018). In addition to the movement characteristics, the range of angles, the joints can cover derived from the real LBR iiwa series had to be implemented to prevent that the robot arm moves through itself (Doliwa, 2020b). For further interactions with the environment and the participant, each segment of the robot arm was outfitted with collision properties using the Unity 3D built-in tools enabling it to register contact with other objects. This also allowed to monitor and record the robot arms collision rate for the objective data acquisition.

3.2.3 Capabilities of the Robot Arm

To present a wide range of collaboration setups with autonomous robots via the VR sandbox, it was necessary to implement the ability of the robotic arm to perform the collaborative task independently of an external controller such as the Wizard-of-Oz approach. Although the working steps for the robot arm to execute within most collaboration tasks are determined, the actions of the human collaboration partner introduce an unpredictable element, to which the robot arm must react adequately in a functional, predictable or legible way (Dragan et al., 2013). For the VR sandbox, the capabilities of the robot arm were implemented based on the following goals:

- Identification: the robot arm is required to detect the movement of the participant represented by the hands and the head of the VR avatar and takes countermeasures to avoid dangerous collisions.
- Adaption: The robot arm should adapt to the work pace of the participant and either increase or decrease its movement speed in accordance with the ISO TS 15066 regulations.
- Execution: The robot arm can complete its working part of the shared task.
- Verification: the robot arm is capable of recognizing that the action of the participant follows the working procedure
- Notification: the robot arm is capable to communicate its actions and possible detected deviations from the procedure.

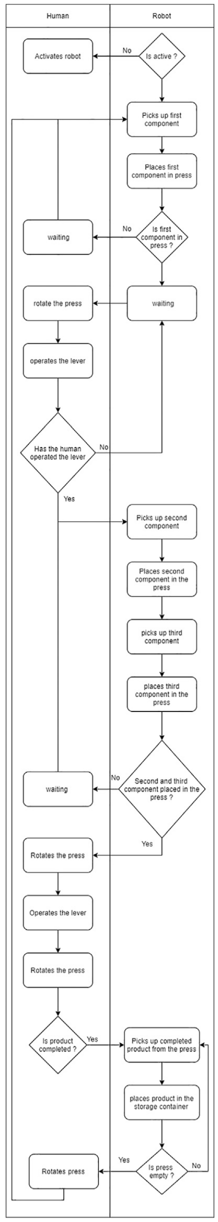

FIGURE 4 | The diagram illustrates the individual procedures required by the human participant and the virtual robot arm to execute the shared task.

Incorporating the Unity 3D Machine Learning Agents (ML-Agents) in conjunction with the inverse kinematics system enabled the robot arm to conduct these defined characteristics. The ML-Agents open-source plugin provides a framework for the application of various machine learning methods, i.e., reinforcement learning to virtual objects through a Python API and the TensorFlow interface. The ML-Agents SDK itself contains three major components: The first is the agent, which gathers information about the current state of the scene and can execute actions. These actions are determined within the second component, the Brain, which contains the various rules and conditions for the decision-making of each of the corresponding agents. The third component is the Academy, responsible for the global coordination of the simulated environment (Juliani et al., 2018) (**Figure 5**).

For the ML-Agents framework to assume control over the inverse kinematic system of the robot arm, a Unity GameObject serving as the target for the inverse kinematics-solver was equipped with the provided agent component from the SDK. This agent determined the movement and the speed at which the robot arm heading for its target. The procedure of the shared task with its designated roles was then modeled by adopting the Relational Action Processes (RAP) established by Toussaint et al. (2016). Through the usage of the relational Markov Decision Process, which is commonly implemented for decision processes of agents performing within an environment, the model enabled the simultaneous operation of several actions, either sequential or asynchronously, depending on the current requirement (Munzer et al., 2018). Additional information from two agents monitoring the states of the pin-back button press tracked the current progress of the task and the speed at which the participant conducted it, were used to enable the robot arm to adapt its movement speed to the working pace of the human partner. This increase in speed was limited by the ISO TS 15,066 regulations (ISO, 2020). Further information regarding the movement of the robot arm was relayed from three agents attached to both hands and the head of the VR avatar, for the robot arm to avoid collisions with the participant. Depending on the current speed the robot arm either attempted to evade the participant while slowing down incrementally or ceasing all motions instantly. This was implemented mimicking the real characteristics of the real robot arm model, as the robot arm has to intercept its momentum, therefore a certain breaking distance is required.

Also, the possibility that the robot arm could be stuck either by the surrounding objects or by a loop had to be considered and counteracted. For this purpose, Unity's built-in collision system was complemented by a raycast system that sends out radial rays to detect surface meshes of the 3D objects in the vicinity, as the existing Unity collision system only detects entering and exiting collision states. Conducting the learning process of the robot arm without the raycast system would distort the outcome as the ML-Agent framework would not notice states of continuous collision from the robot arm with adjacent objects. A reward system for following the current required target while considering the state of the other agents monitoring the various other items within the virtual environment and punishment for moving away was implemented. Based on the different states of the items necessary for the shared task, these rewards and punishments were adjusted or inverted, enabling the robot arm to follow the

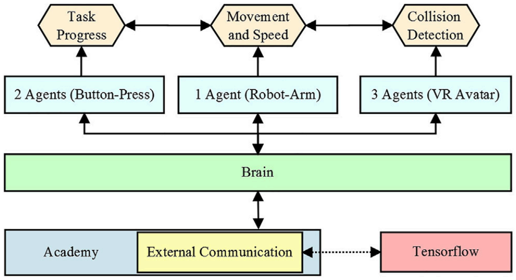

FIGURE 5 | The schematics of the ML-Agents framework consisted of three components, the agents, the brain, and the academy (Juliani et al., 2018). The agents monitored the states of the environment and assumed control over the robot arm. Determined by the brain, the robot arm acted based on learned behavior stored in the academy.

procedure for producing a pin-back button in collaboration with human input in this experimental setup (Arntz et al., 2020a). This allowed the robot arm to react and adjust to user input and follow the necessary working procedure while adapting its operating speed over time to keep pace with the participant.

The agents were trained by using recorded data from the collaboration process within the application from nine sessions conducted with three individuals each. A single training segment was defined as the necessary actions for the agents to accomplish the individual working steps of the procedure. The segment was considered to have failed, if the agents reached a collision score of fifty in conjunction with more than eight hundred attempts to reach the respective target, i.e., removing the pin-back component from the press.

An expected disadvantage of an agent-controlled kinematic system compared to predefined animations is the potential tremble in the movement due to noise in the training sample. To mitigate this, a per degree movement penalty was implemented to smooth out the motion of each joint of the robot arm as much as possible, ensuring a close depiction of the virtual robot arm's movement to its real counterpart.

An interface component managed the transfer of variables between the agents and the scripts attached to the various non-interactable objects within the environments, such as the display that presented the production quantity to the respective participant. The same approach was used for the three distinct augmentation channels for the communication methods.

3.2.4 Augmenting Channels for Guidance and Explanation

To evoke the impression of an intended behavior, three distinct unidirectional communication channels were conceptualized. Based on a pre-study (Arntz and Eimler, 2020), the following augmentations were implemented for the VR sandbox: 1) Text communication in natural language, 2) Multi-colored light signals, 3) Action initiating/terminating and standby gestures. The essential purpose of these augmentation channels was to notify about the progress within the task procedure, explain the current action that the robot arm conducted, alert any potentially hazardous situations, and provide feedback to the activities of the human collaboration partner. The first goal was realized through the text communication panel, which was represented through a virtual display containing written statements that explained the ongoing action of the robot arm. To enhance the associations of these statements to the robot arm, the virtual display was placed directly in front of the robot (**Figure 6**). A pre-study revealed that the adjacent positioning of the virtual display strengthened the impression that these statements originated from the robot arm (Arntz and Eimler, 2020). This was complemented through a stylized graphic of the robot arm that was placed right next to the text, which was embedded in a speech bubble. The text itself was formulated in the first-person form to give a further impression of an intended behavior, a design choice taken from voice assistants, such as Amazon Alexa and Apple Siri (Hoy, 2018). Although the phrasing of the statements from the text panel emulated a personality akin to the aforementioned voice assistants, the usage of speech by the robot arm was dismissed for this experimental study. Several qualitative statements from the prior study indicated that the presence of voice output encouraged the user's expectation of voice input (Arntz and Eimler, 2020). Since many available conversational AI and natural language processing tools are designed to recognize speech patterns in soundscapes polluted through the presence of other media devices (Papayiannis et al., 2018), no robust solution for industrial ambient noise was available. Although the text panel denies the capability for two-way communication exchange, it was suitable for the intended goal of this study to provide explanation and guidance. In total, the robot arm was able to express forty-two pre-defined statements, counting three variations for fourteen distinct statements to avoid sequential repetitions of the phrasing. To implement the text communication channel, a Unity UI (user interface) Canvas was placed in the world view of the scene which contained a label element. The text was then displayed through Unity's build-in text rendering technology TextMeshPro with no additional performance cost (Unity, 2020b).

The second augmentation consisted of multi-colored light signals, which were directly attached to the actuators of the robot arm. The concept of these light signals was to alert for potentially dangerous situations with a visual stimulus that is directly in the field of view of the participant and comprehensible at a glance. Derived from suggestions made from qualitative statements from a preceding study (Arntz and Eimler, 2020), a green light was used for signaling the normal operation of the shared task, while a red light indicated erroneous deviance from the procedure or a detected collision. The light signals were implemented by using a light-emitting shader on the actuator rings of the robot arm model. Based on the received input, the shader changed its color properties and was able to switch from red to green and vice versa or black in the case the robot arm was shut down. To provide further illumination of the surroundings, points lights were attached to the light signals to enhance the visual fidelity. To add a further explanation, the light signals were accompanied by notification labels that were shown on a virtual

FIGURE 6 | The text panel provided guidance for the current task and an explanation of the robot arms' behavior. The text was displayed within a speech bubble next to a stylized representation of the robot arm to strengthen the affiliation of the statements to the robot arm. The communication was formulated in the first-person form to evoke the perception of the robot arm as a collaboration partner instead of a tool ("*I'm waiting for you to turn the platform*").

display (**Figure 7**). A green light signal was shown in conjunction with a general caution warning, that reminded the participant that the robot arm was in motion. If the red light signal was triggered based on an imminent collision, a warning label alerted the participant that he/she was too close to the robot arm.

The third augmentation was the capability of the robot arm to conduct three gestures (action initiating, action terminating, and standby). Apart from the general approach of providing guidance and explanation, the capability of using gestures was implemented to strengthen the perception of an intended behavior from the robot arm and contribute to the safety attribution of the system. The purpose of the action initiating gesture was to signal the human to proceed with the objective in case no action by the participant was detected. If the collaboration process was stalled through the participant's inactivity, the robot arm pointed towards the object that was necessary for the subsequent working step (Arntz et al., 2020a). The concept behind this gesture was to reinforce the impression of agency by the robot arm to pursue the objective of the shared task. The counterpart was the action terminating gesture, that was triggered if deviance from the procedure was detected. The robot arm erected its front and rotated the front section with the attached clamps similar to a dismissive hand wave (Arntz et al., 2020a). The goal was not only to notify the human collaboration partner of an incorrect action but also to evoke the impression that the robot arm has a sense of awareness. The same applied to the standby gesture, where the robot arm retracted itself from the button press after completing its working step (Arntz et al., 2020a). This was implemented to enable the robot arm to make room for the human collaboration partner to conduct their activities and meet the expectation of the appropriate proxemics (Mumm and Mutlu, 2011). The design of these gestures was inspired by Ende et al. (2011), who evaluated several approaches for gestures in collaborative working processes. To further enhance the perception of safety the works of Koay were consulted, regarding the movement of the robot arm (Koay et al., 2017). The behavior of the robot arm was adapted to consider social norms for personal space and avoiding sudden motions that could be interpreted as threatening by some people.

3.3 Measures

To measure the number of produced pin-back buttons and the collision rate, objective data tracked by the VR application were used. The designated data-set for productivity measured the quantity of pin-back buttons the participant produced in collaboration with the robot arm (H1). The second objective data set detected the number of collisions the participant had with the robot arm (H2). A third objective measure tracked the duration in seconds the participants watched the text panel with the guidance and explanation provided by the augmented robot arm. This measure was only present in the experimental condition, due to the absence of the text panel augmentation in the non-augmented condition.

In addition to the objective measurements, self-reported data were surveyed. The used questionnaire was formulated in German. Items either taken or altered from sources in the English language were translated to German by one researcher and then translated back independently by another researcher to ensure correctness. Measuring the influence of the robot arm's augmentation on the perceived safety of the participants was done by utilizing self-reported questionnaire data. To measure the perception of safety provided by the augmentation channels of the robot arm (H3), four scales were used. The first contained five items regarding safety aspects of the workplace ($\alpha = 0.69$; **Table 1**) measured on a 5-point Likert scale (1 = very dissatisfied; 5 = very satisfied) which were modified by adding the word virtual to fit the context of the experimental setup from the Construct validity of a physical work environment satisfaction questionnaire (Carlopio, 1996). The second scale covered the perceived safety of the robot arm with three items ($\alpha = 0.66$; **Table 2**), measured on a 5-point Likert scale (1 = strongly disagree; 5 = strongly agree) based on the survey methods for Human-Robot Interaction established by Lasota et al. (2017). The survey contained four items of the perceived safety scale. One of which was excluded because it negatively affected the reliability. The fact that Cronbach's alpha value is below 0.7 can be explained by the small item size of the used scale (Bujang et al., 2018). While a low alpha is generally considered unfavorable, according to George and Mallery and supported by Hinton et al., an alpha value between 0.6 and 0.7 is still valid for statistical operations (Darren and Mallery, 2003; Hinton et al., 2014). The third scale rated the augmentation channels of the robot arm in terms of comprehensibility and effectiveness (4 items, $\alpha = 0.85$; **Table 3**) measured on a 5-point Likert scale (1 = very bad; 5 = very good). General satisfaction regarding the collaboration with the robot arm was assessed by using four items rated on a 5-point Likert scale (1 = very satisfied; 5 = very unsatisfied) ($\alpha = 0.72$; **Table 4**). Furthermore, the pre and post-questionnaires contained various items. i.e., regarding the assessment of the robot arm in terms of prior experience with industrial robots and the second edition of the Technology Acceptance Model (TAM2) which were used as control variables (Arntz et al., 2020a).

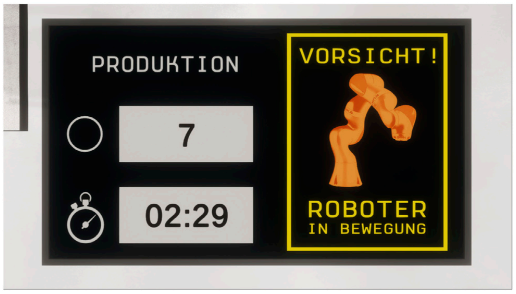

FIGURE 7 | Additional notifications complemented the communication channels, informing the participant about the current activity status of the robot arm ("*Caution! Robot in motion*"). The left side of the display contained information about the shared task by showing the remaining time and the production quantity to the participant.

3.4 Experimental Procedure

At the beginning of the experimental study, participants were asked to sign a declaration of consent. This was followed by a short briefing, informing the participant about the aim of the study. Subsequently, the participants were asked by the study supervisor to complete the pre-questionnaire, provided through a desktop computer present in the lab. A small wall gave the participants the privacy to answer the pre-questionnaire without time constraints.

The next stage was the use of the VR application. The supervisor instructed the participants about the Oculus Rift S VR hardware (Oculus, 2020a), its usage, and controls. With no questions remaining, the participants were provided with a special disposable mask, to enhance hygiene and reduce wear on the device. The VR headset was properly mounted, a tutorial scene was loaded. This scene contained the full industrial environment, without the robot arm. The purpose of this was to allow participants to get used to the VR experience and the interaction mechanics of the virtual environment. With about fifteen square meters of free-range, participants were provided with enough space to move within the restrictions of the connection cable of the device. Once the participant has signaled to be ready, the actual stimulus material was loaded, containing the shared task environment with the autonomous robot arm. After the collaboration process started, the participant was given 10 min to produce as many pin-back buttons as possible, following the procedure described in **Section 3.2.1**. After the remaining time had been up, the application informed the participant that the procedure has ended.

The supervisor aided the participant to remove the VR headset and gave the instruction to complete the post-questionnaire. The procedure was concluded with a debriefing containing about the study. Participants were thanked and dismissed from the lab. The whole experimental procedure took about 30 min.

4 EXPERIMENTAL RESULTS

In this section, the results of the experimental study are presented using the hypotheses as a structuring element. For the data processing and analysis, the software Statistical Product and Service Solutions (SPSS) in version 22 from IBM was used.

4.1 H1: Participants Produce More Pin-Back Buttons in the Augmented Condition Compared to the Non-Augmented Condition

To test H1, an ANCOVA was calculated using the experimental condition as an independent and the production output as a dependent variable and the rating of the augmentation channels, prior experience with industrial robots, and technology affinity (TAM2) as the covariates. Supporting H1 results show a statistically significant difference between conditions ($F(1,75) = 12.63$, $p < 0.01$, $\eta_p^2 = .40$). In the augmented condition the average production quantity was higher ($M = 8.2$, $SD = 1.40$) than in the non-augmented condition ($M = 6.15$, $SD = 1.53$) (**Figure 8**). The production output and the assessment of the augmentation channels were found to be moderate correlated ($r(80) = 0.39$, $p < 0.01$).

4.2 H2: Participants Collide Less With the Augmented Robot Arm Compared to the Non-augmented Condition

H2 was tested by using an ANCOVA with the experimental condition as the independent and the detected collisions as a dependent variable and the assessment of the augmentation channels, prior experience with industrial robots and technology affinity (TAM2) as the covariates. The results revealed a statistically significant difference separating both conditions ($F(1,75) = 5.93$, $p < 0.01$, $\eta_p^2 = .24$). The augmented condition on average showed less detected collisions between the participants and the robot arm ($M = 53.57$, $SD = 47.40$) compared to the non-augmented condition ($M = 118.82$, $SD = 81.49$) (**Figure 9**). Collision rate and assessment of the augmentation channels were found to be correlated ($r(80) = 0.24$, $p = 0.03$) supporting H2.

4.3 H3: Perception of Safety is Higher in the Augmented Condition Compared to the Non-Augmented Condition

The third hypothesis was examined by calculating an ANCOVA that contained the experimental condition as the independent variable and the perceived safety rating of the robot arm as the dependent variable with the safety aspects of the workplace as the covariate. The results indicated a statistically significant difference between the two conditions ($F(1,77) = 5.47$, $p < 0.01$, $\eta_p^2 = .12$), with the perceived safety rated slightly higher on average in the augmented condition ($M = 3.33$, $SD = 0.59$) compared to the control non-augmented condition ($M = 3.17$, $SD = 0.58$). The results support H3.

TABLE 1 | Workplace safety is measured by the items derived from the physical work environment satisfaction questionnaire by Carlopio (1996).

For each statement, please consider to what extent you think it is true	
No.	**1 = very dissatisfied; 5 = very satisfied**
1	How satisfied were you with the security measures in your virtual workspace?
2	How satisfied were you with the overall design of your virtual workspace?
3	How satisfied were you with the amount of time the robot gave you to do your work?
4	How satisfied were you with the amount of work you needed to complete the task?
5	How satisfied were you with the amount of work the robot required to complete its task?

TABLE 2 | The items for the perceived safety scale are based on the scale by Lasota et al. (2017).

For each statement, please consider to what extent you think it is true	
No.	**1 = strongly disagree; 5 = strongly agree**
1	I am of the opinion that an accident with the robot (e.g. a collision) can happen or can happen again
2	I felt safe in the presence of the robot
3	I believe that other people feel safe in the presence of the robot

TABLE 3 | The items used for the rating of the communication channels.

For each statement, please consider to what extent you think it is true	
No.	**1 = very bad; 5 = very good**
1	In general, the robot's communication was…
2	The robot's light signals were…
3	The robot's text panel cues were…
4	The robot's gestures were…

TABLE 4 | The items measuring the satisfaction regarding the collaboration with the robot arm.

For each statement, please consider to what extent you think it is true	
No.	**1 = very dissatisfied; 5 = very satisfied**
1	How satisfied were you with the efficiency of the robot?
2	How satisfied were you with the robot's effectiveness?
3	How satisfied were you with the flexible working speed of the robot?
4	How satisfied were you with the danger warnings you received from the robot?
5	How satisfied were you with the way the robot tries to avoid accidents?

4.4 Research Question: Does the Time Participants Look at the Text Panel Affect the Productivity and Collision Rate?

Results of the Pearson correlation indicated that there was no statistically significant effect between the time participants looked at the display and the collision rate nor the production output with an average display gaze of 253.02 s (*SD* = 99.61).

5 DISCUSSION

With the aim to provide an adaptive and accessible application suitable for HRC experimental studies, we developed a VR sandbox as a modular platform, as described in chapter 3.2. Based on best practices from prior work (Straßmann et al., 2019; Kessler et al., 2020), every mechanic was designed and implemented as a modular component, that can be adjusted, extended, or omitted to fit the current experimental study's requirements. Apart from a library of assets that can be used to create the virtual environments to emulate industrial workplaces, the VR sandbox provides the tools to enable interactions with a robot as well as with other machinery, inverse kinematics, or the usage of machine learning independent of the robot model to be explored for HRC. This allows the VR sandbox to adapt and replicate a variety of workplace setups involving shared tasks with industrial robots within an authentic and safe environment for HRC research. The usage of simulated industrial environments through augmented and virtual reality is established itself throughout various fields of research (Daling et al., 2020; Dyck et al., 2020; Shahid et al., 2020). However, compared to our VR sandbox, these applications for simulating industrial settings are designed with one specific use case in mind, precluding the usage for an iterative and flexible experimental process (Shu et al., 2018). The usage of a virtual environment comes with certain restrictions, as it is always merely an approximation of the real counterpart. However, real lab-controlled experimental studies similar in scope and objective are also often met with compromise in depicting believable industrial settings (Arntz et al., 2020c). The

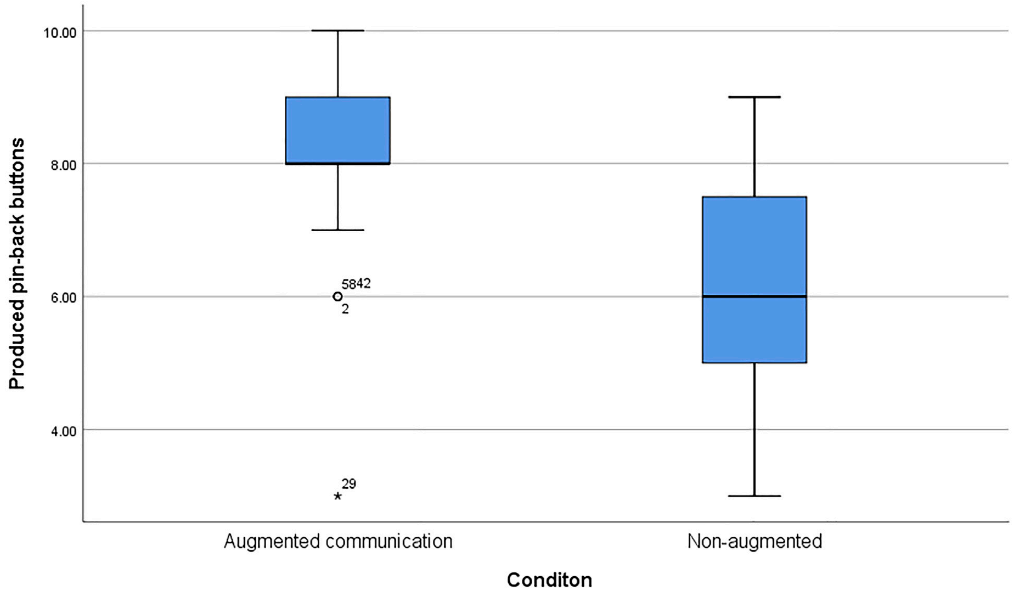

FIGURE 8 | The chart presents the average number of pin-back buttons produced by the participants in collaboration with the robot arm. The augmented condition (*M* = 8.20, *SD* = 1.40) resulted in a higher production output than the non-augmented condition (*M* = 6.15, *SD* = 1.53).

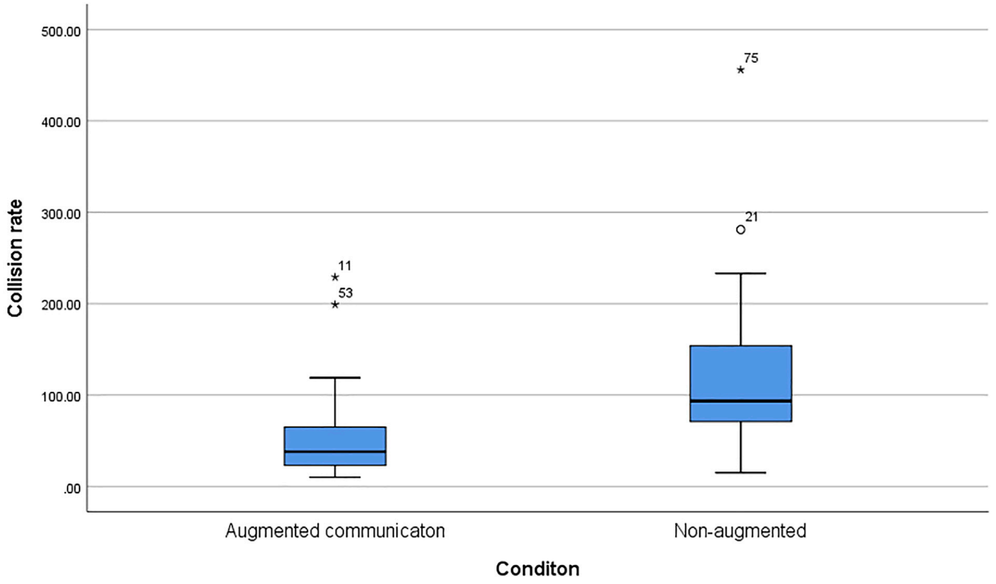

FIGURE 9 | The box plot shows the average collision rate between the robot arm and the participants for the augmented condition (*M* = 53.57, *SD* = 47.40) in comparison to the non-augmented condition (*M* = 118.82, *SD* = 81.49).

benefit of the VR sandbox lies in the reduced effort to conduct experimental studies as the functionality can be iterated across different robot representations without starting all over again, compared to experiments conducted within real lab conditions. Another advantage is the simple collection of objective measures that can complement subjective or self-reported qualitative and quantitative measures to explore various research questions regarding HRC.

The goal of this experimental study was to examine the effect of augmented communication on productivity and safety in shared task setups involving the collaboration between humans and autonomous industrial robots. Prior studies conducted within the VR sandbox focusing on subjective measures revealed various benefits of equipping a robot arm with communication channels in HRC setups (Arntz et al., 2020a; Arntz et al., 2020b). Yet one of the key aspects determining the success of HRC remains largely open: the economic point of view, which mainly addresses productivity and safety concerns (Buxbaum et al., 2020). Motivated by this, it is necessary to investigate if the usage of augmented communication can also result in advantages regarding objective measurements such as productivity and safety.

In accordance with the first hypothesis that addresses the number of produced pin-back buttons, participants of the augmented condition generated a higher production quantity compared to the control group. Considering that the assessment of the communicative augmentation strongly correlated with the quantity of produced assets, it can be assumed, that the explanation and guidance provided by the robot arm contributed to participants performing better in terms of productivity. According to human group collaboration research (Shah et al., 2011), the communication channels might contribute to forming distinguished roles within the collaboration process. Participants assigned to the control condition did not receive any guidance and explanation from the robot arm, which required that they fathomed the procedure based on their own mental model (Peltokorpi and Hood, 2019). This probably affected the quantity of produced pin-back buttons, as participants of the control condition, required more time to acclimate to the procedure. Although the task used in this experimental study was fairly simple in execution compared to common industry procedures, the combined objective and subjective results indicate that the augmentation channels can help to support the collaboration process between humans and autonomous robots in terms of production efficiency. While it can be assumed, that industrial employees were familiar with the necessary working steps of their assigned task compared to the inexperienced participants, it can be argued that due to more dynamic production cycles in the future, employees will be exposed to regularly shifting procedures. Communication channels that provide guidance and explanation from the robot, might help to mitigate necessary training time and reduce fear of wrong-doing, therefore contribute to maintaining a high production capacity, consequently support the economic success of the HRC concept. However, since the VR sandbox is capable of recreating a variety of distinct scenarios, it is recommended that future studies extend the complexity of the collaborative task to further investigate the impact of each augmentation channel on people's productivity.

The second hypothesis stated a reduction in collisions between the robot arm and the participants in the augmented condition. The results support the hypothesis that participants of the augmented condition collided less frequently and that this occurrence correlated with the assessment of the communication channels. Considering that the robot arm's augmentations enabled it to convey potential hazardous situations through multiple channels, it can be assumed that participants were better suited to recognize these collisions and adapt their behavior to prevent them (Zakka et al., 2019). Although the results show a significant gap between both conditions regarding the collision rate, it can be argued that in a real HRC procedure, the difference would be less significant. The reason for this can be seen in the limitations of the VR technology which currently omits tactile feedback. Although the vibration motors of the Oculus Touch Controller were used to signal a collision, it cannot be ruled out that this stimulus was not correctly interpreted by all participants, thus minor collisions were possibly not noticed by the participants.

The third hypothesis complemented the gathered objective measures of the collision rate with the subjective survey to examine if the potential benefit from the augmentations in safety affected the participants' perception. The results of the experimental study indicate a contribution of the augmentations of the robot arm towards a stronger perception of safety by the participants. With both the perceived safety of the system and the workplace scored better in the augmented condition, a statistically significant difference could be detected. It can be argued that the information provided by the augmentation channels reduced the uncertainty and therefore contributed towards the impression of a safe system (Seo, 2005; Arntz et al., 2020a). A possibility to strengthen this impression is the inclusion of a backchannel in the communication of the robot arm. Since the perception of safety is influenced by the awareness of an organizational structure within a task, which is formed by exchanging information between those involved in the collaboration (Cigularov et al., 2010). The lack of the ability to respond to the robot i.e., asking to clarify a statement or situation may diminish the impression of group cognition as the criteria for communication exchange is not met (Hart and Staveland, 1988). The presence of the impression of mutual understanding about the current situation within a collaboration setup contributes to the perception of safety. While implementation of the three communication channels that were exclusively one-sided could deliver this understanding for the short and simple task deployed in this setup. A real shared task involving more complex setups might demand a stronger communication exchange (Cigularov et al., 2010). The research question examined the affect of display gaze time on the production output and collision rate. No statistically significant correlation was found. Considering that no dedicated eye-tracking device was used for this measurement, the results might be insufficient regarding the precision of the implementation. It can be argued that the usage of a distinct focal point in the center of each eye respectively detecting an overlap with the virtual display, may not cover any peripheral vision of a VR user. While it can be stated that due to the lenses of the VR headset, which contain only a small focal point in the center for displaying a sharp image to the person wearing the device, usually, the center point is where the user focuses their attention. Therefore vindicating the approach of the implementation. However, it is advised to use proper eye-tracking hardware in future iterations of HRC-related studies involving communication channels to ensure precise data.

5.1 Limitations

Limitations include the respective constraints of the VR technology, the study design, and the composition of the sample that is discussed in the following.

While the study used a sophisticated VR headset, the image resolution of the device still diminishes the visual fidelity of the experience. In conjunction with the limited interaction capabilities of the motion-based controller, the usage of VR can only approximate the realism of a shared task study involving a real robot. Influences that are present in real HRC setups, like touching the robot or the components that are part of the collaboration are omitted in VR, resulting in the absence of a sensory channel that might contribute to the assessment of the situation. However, findings from preceding studies suggest that the participants immersed themselves into the experience and even recognized sudden or unexpected movement by the robot arm as threatening (Arntz et al., 2020a; Arntz et al., 2020b), although the VR application posed no real danger. This indicates that the technology is suitable for exploring HRC concepts before they become reality and therefore helps to optimize these workplace setups.

A noteworthy limitation regarding the study design is the usage of the pin-back button press as a shared task. While the usage of a collaborative robot for such a simple task is exaggerated and not appropriate for an industrial context, the relative straightforwardness of the pin-back button machine allowed to establish a comprehensible shared task scenario. Participants independent of prior experience were, therefore, able to execute the procedure and develop a work pace based on the guidance and explanations of the robot arm. Albeit not applicable to complex procedures that are found in industrial manufacturing, the used task allowed to gather insights into the participants' behavior when exposed to such a scenario. Another limitation in the study design is the short exposure time of the participants with the stimulus material. Considering that industrial employees tasked to collaborate with robots are expected to work with them during prolonged shifts, the dynamic of that relationship that might emerge in this time frame cannot be emulated by the 10 min that were applied in this study. While similar HRC studies are conducted with comparable exposure times for the participants, it is advised to investigate possible deviations from the hereby gathered results in long term studies.

Further worthy of mentioning is the composition of the participants. The sample consisted predominantly of students associated with the field of computer science and engineering. Thus, the gathered results do not apply to the general population and in particular to experienced industrial workers. However, because the presented scenario involving AI-enhanced autonomous robots deployed for collaboration can be anticipated for the future, the usage of students that provide the forthcoming workforce can be argued as appropriate.

An additional limitation in this experimental study is the moderate reliability of the perceived safety scale used for H3 (described in **Section 3.3**). Although a Cronbach's alpha value below 0.7 can emerge due to the small number of items used in the scale (Cortina, 1993), further revisions and validations of this scale are required for expanded HRC experimental studies.

6 CONCLUSION

The concept of complementing the individual skills of human employees with the advantages of robots will become ever so important in industries with increasing competitiveness and dynamic production cycles. However, current implementations of shared workspaces between humans and robots are restricted by necessary safety precautions that limit the areas of application where the combined work of robots and humans can create an economic benefit. Augmenting autonomous robots in shared task environments with communication channels shows promise in enhancing production quantity, reducing collision risk, and perceived safety. These factors play a significant role in establishing HRC in the industry, as only an economical and safe implementation of the concept convinces industry decision-makers to adopt this approach. The results of this study indicate that these augmentations that contribute to actual safety by reducing collisions between the robot and the human collaboration partner, also increase the perceived safety of the system. Nonetheless, the tendency for augmentation for autonomous acting robots to award several advantages to the collaboration process, implicates that HRC-related research and the industry should examine different approaches on how to integrate communication-based augmentation into these work scenarios for upcoming production processes. To cover this subject, the presented virtual reality sandbox application provides the first step for a flexible tool to investigate potential solutions for these essential questions for HRC.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusion of this article will be made available by the authors, without undue reservation.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by the Ethics committee of the division of Computer Science and Applied Cognitive Sciences at the Faculty of Engineering from the University of Duisburg-Essen. The participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

This work is the result of a virtual reality application in conjunction with an experimental study that was designed, implemented and analyzed by AA and supervised by SE and HH. AA, as the first author, took the lead in writing the first draft of the articles, with edits made by SE and HH. All authors have read and approved the final articles.

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REFERENCES

Ajoudani, A., Zanchettin, A. M., Ivaldi, S., Albu-Schäffer, A., Kosuge, K., and Khatib, O. (2018). Progress and Prospects of the Human-Robot Collaboration. *Auton. Robot* 42, 957–975. doi:10.1007/s10514-017-9677-2

Amara, V. D., Malzahn, J., Ren, Z., Roozing, W., and Tsagarakis, N. (2020). “On the Efficient Control of Series-Parallel Compliant Articulated Robots,” in 2020 IEEE International Conference on Robotics and Automation (ICRA) (IEEE), 385–391. doi:10.1109/ICRA40945.2020.9196786

Arntz, A., and Eimler, S. C. (2020). “Experiencing Ai in Vr: A Qualitative Study on Designing a Human-Machine Collaboration Scenario,” in *HCI International 2020 – Late Breaking Posters of Communications in Computer and Information Science*. Editors C. Stephanidis, M. Antona, and S. Ntoa (Cham: Springer International Publishing), 1293, 299–307. doi:10.1007/978-3-030-60700-5_38

Arntz, A., Eimler, S. C., and Hoppe, H. U. (2020b). “"The Robot-Arm Talks Back to Me" - Human Perception of Augmented Human-Robot Collaboration in Virtual Reality,” in 2020 IEEE International Conference on Artificial Intelligence and Virtual Reality (AIVR) (IEEE), 307–312. doi:10.1109/AIVR50618.2020.00062

Arntz, A., Eimler, S. C., and Hoppe, H. U. (2020a). “Augmenting the Human-Robot Communication Channel in Shared Task Environments,” in *Collaboration Technologies and Social Computing of Lecture Notes in Computer Science*. Editors A. Nolte, C. Alvarez, R. Hishiyama, I.-A. Chounta, M. J. Rodríguez-Triana, and T. Inoue (Cham: Springer International Publishing), 12324, 20–34. doi:10.1007/978-3-030-58157-2_2

Arntz, A., Keßler, D., Borgert, N., Zengeler, N., Jansen, M., Handmann, U., et al. (2020c). “Navigating a Heavy Industry Environment Using Augmented Reality - a Comparison of Two Indoor Navigation Designs,” in *Virtual, Augmented and Mixed Reality. Industrial and Everyday Life Applications of Lecture Notes in Computer Science*. Editors J. Y. C. Chen and G. Fragomeni (Cham: Springer International Publishing), 12191, 3–18. doi:10.1007/978-3-030-49698-2_1

Artemiadis, P. (2013). Closed-form Inverse Kinematic Solution for Anthropomorphic Motion in Redundant Robot Arms. *Adv. Robotics Automation* 02, 1–7. doi:10.4172/2168-9695.1000110

Atmaca, S., Sebanz, N., Prinz, W., and Knoblich, G. (2008). Action Co-representation: the Joint Snarc Effect. *Soc. Neurosci.* 3, 410–420. Dataset. doi:10.1080/17470910801900908

Autodesk, M. (2020). Available at: https://www.autodesk.com/products/maya/overview?plc=MAYA&term=1-YEAR&support=ADVANCED&quantity=1

Badgematic (2020). Badge Maker 900 Flexi 59 Mm. Available at: https://www.badgematic.de/en/badge-maker-900-flexi-59-mm.

Bailenson, J. (2018). *Experience on Demand: What Virtual Reality Is, How it Works, and what it Can Do*. first edition edn. New York, NY and London: W.W. Norton & Company.

Bailey, J. O., and Bailenson, J. N. (2017). “Immersive Virtual Reality and the Developing Child,” in *Cognitive Development in Digital Contexts* (Elsevier), 181–200. doi:10.1016/B978-0-12-809481-5.00009-2

Bröhl, C., Nelles, J., Brandl, C., Mertens, A., and Nitsch, V. (2019). Human-Robot Collaboration Acceptance Model: Development and Comparison for Germany, Japan, China and the USA. *Int. J. Soc. Robotics* 11, 709–726. doi:10.1007/s12369-019-00593-0

Bujang, M. A., Omar, E. D., Omar, E. D., and Baharum, N. A. (2018). A Review on Sample Size Determination for Cronbach’s Alpha Test: A Simple Guide for Researchers. *Mjms* 25, 85–99. doi:10.21315/mjms2018.25.6.9

Buxbaum, H.-J., and Häusler, R. (2020). “Ladenburger Thesen zur zukünftigen Gestaltung der Mensch-Roboter-Kollaboration,” in *Mensch-Roboter-Kollaboration*. Editor H.-J. Buxbaum (Wiesbaden: Springer Fachmedien Wiesbaden), 293–317. doi:10.1007/978-3-658-28307-0_19

Buxbaum, H.-J., Sen, S., and Häusler, R. (2020). “Theses on the Future Design of Human-Robot Collaboration,” in *Human-Computer Interaction. Multimodal and Natural Interaction of Lecture Notes in Computer Science*. Editor M. Kurosu (Cham: Springer International Publishing), 12182, 560–579. doi:10.1007/978-3-030-49062-1_38

Carlopio, J. R. (1996). Construct Validity of a Physical Work Environment Satisfaction Questionnaire. *J. Occup. Health Psychol.* 1, 330–344. doi:10.1037/1076-8998.1.3.330

Cha, E., Fitter, N. T., Kim, Y., Fong, T., and Matarić, M. J. (2018). “Effects of Robot Sound on Auditory Localization in Human-Robot Collaboration,” in Proceedings of the 2018 ACM/IEEE International Conference on Human-Robot Interaction. Editors T. Kanda, S. Ŝabanović, G. Hoffman, and A. Tapus (New York, NY, USA: ACM), 434–442. doi:10.1145/3171221.3171285

Cigularov, K. P., Chen, P. Y., and Rosecrance, J. (2010). The Effects of Error Management Climate and Safety Communication on Safety: a Multi-Level Study. *Accid. Anal. Prev.* 42, 1498–1506. doi:10.1016/j.aap.2010.01.003

Cortina, J. M. (1993). What Is Coefficient Alpha? an Examination of Theory and Applications. *J. Appl. Psychol.* 78, 98–104. doi:10.1037/0021-9010.78.1.98

Daling, L. M., Abdelrazeq, A., and Isenhardt, I. (2020). “A Comparison of Augmented and Virtual Reality Features in Industrial Trainings,” in *Virtual, Augmented and Mixed Reality. Industrial and Everyday Life Applications of Lecture Notes in Computer Science*. Editors J. Y. C. Chen and G. Fragomeni (Cham: Springer International Publishing), 12191, 47–65. doi:10.1007/978-3-030-49698-2_4

Darren, G., and Mallery, P. (2003). *SPSS for Windows Step by Step: A Simple Guide and Reference, 11.0 Update*. Allyn & Bacon.

Daugherty, P. R., and Wilson, H. J. (2018). *Human + Machine: Reimagining Work In the Age Of AI*. La Vergne: Harvard Business Review Press.

de Giorgio, A., Romero, M., Onori, M., and Wang, L. (2017). Human-machine Collaboration in Virtual Reality for Adaptive Production Engineering. *Proced. Manufacturing* 11, 1279–1287. doi:10.1016/j.promfg.2017.07.255

Doliwa, S. (2020a). *Entwicklung eines kalman-filters zum tracking bewegter objekte für zeitlich koordinierte schlagbewegungen eines antropomorphen roboterarms*. Unpublished.

Doliwa, S. (2020b). Inverse Kinematics of the KUKA LBR Iiwa R800 (7 DOF). *Tech. Rep.* 1, 1–7. doi:10.5281/zenodo.4063575

Dragan, A. D., Lee, K. C. T., and Srinivasa, S. S. (2013). “Legibility and Predictability of Robot Motion,” in 2013 8th ACM/IEEE International Conference on Human-Robot Interaction (HRI) (IEEE), 301–308. doi:10.1109/HRI.2013.6483603

Dyck, F., Stöcklein, J., Eckertz, D., and Dumitrescu, R. (2020). “Mixed Mock-Up - Development of an Interactive Augmented Reality System for Assembly Planning,” in *Virtual, Augmented and Mixed Reality. Design and Interaction of Lecture Notes in Computer Science*. Editors J. Y. C. Chen and G. Fragomeni (Cham: Springer International Publishing), 12190, 37–49. doi:10.1007/978-3-030-49695-1_3

Ende, T., Haddadin, S., Parusel, S., Wusthoff, T., Hassenzahl, M., and Albu-Schaffer, A. (2011). “A Human-Centered Approach to Robot Gesture Based Communication within Collaborative Working Processes,” in 2011 IEEE/RSJ International Conference on Intelligent Robots and Systems. IEEE, 3367–3374. doi:10.1109/IROS.2011.6094592

Faria, C., Ferreira, F., Erlhagen, W., Monteiro, S., and Bicho, E. (2018). Position-based Kinematics for 7-dof Serial Manipulators with Global Configuration Control, Joint Limit and Singularity Avoidance. *Mechanism Machine Theor.* 121, 317–334. doi:10.1016/j.mechmachtheory.2017.10.025

Fernández-Muñiz, B., Montes-Peón, J. M., and Vázquez-Ordás, C. J. (2012). Safety Climate in Ohsas 18001-certified Organisations: Antecedents and Consequences of Safety Behaviour. *Accid. Anal. Prev.* 45, 745–758. doi:10.1016/j.aap.2011.10.002

Galin, R. R., and Meshcheryakov, R. V. (2020). “Human-robot Interaction Efficiency and Human-Robot Collaboration,” in *Robotics: Industry 4.0 Issues & New Intelligent Control Paradigms of Studies in Systems, Decision and Control*. Editor A. G. Kravets (Cham: Springer International Publishing), 272, 55–63. doi:10.1007/978-3-030-37841-7_5

Gerst, D. (2020). “Mensch-Roboter-Kollaboration - Anforderungen an eine humane Arbeitsgestaltung,” in *Mensch-Roboter-Kollaboration*. Editor H.-J. Buxbaum (Wiesbaden: Springer Fachmedien Wiesbaden), 145–162. doi:10.1007/978-3-658-28307-0_10

Haag, M. (2015). “Kollaboratives Arbeiten mit Robotern - Vision und realistische Perspektive,” in *Zukunft der Arbeit in Industrie 4.0*. Editors A. Botthof and E. A. Hartmann (Berlin, Heidelberg: Springer Berlin Heidelberg), 59–64. doi:10.1007/978-3-662-45915-7_6

Hart, S. G., and Staveland, L. E. (1988). “Development of Nasa-Tlx (Task Load index): Results of Empirical and Theoretical Research,” in *Human Mental Workload of Advances in Psychology* (Elsevier), 52, 139–183. doi:10.1016/S0166-4115(08)62386-9

Heerink, M., Kröse, B., Evers, V., and Wielinga, B. (2009). Influence of Social Presence on Acceptance of an Assistive Social Robot and Screen Agent by Elderly Users. *Adv. Robotics* 23, 1909–1923. doi:10.1163/016918609X12518783330289

Heydaryan, S., Suaza Bedolla, J., and Belingardi, G. (2018). Safety Design and Development of a Human-Robot Collaboration Assembly Process in the Automotive Industry. *Appl. Sci.* 8, 344. doi:10.3390/app8030344

Hinton, P. R., McMurray, I., and Brownlow, C. (2014). *SPSS Explained*. second edition edn. London and New York: Routledge.

Hoy, M. B. (2018). Alexa, Siri, Cortana, and More: An Introduction to Voice Assistants. *Med. reference Serv. Q.* 37, 81–88. doi:10.1080/02763869.2018.1404391

ISO (2020). Iso/ts 15066:2016. Available at: https://www.iso.org/standard/62996.html [Dataset]

Jerald, J. (2016). *The VR Book: Human-Centered Design for Virtual Reality of and San Rafael: Association for Computing Machinery and Morgan & Claypool Publishers*. first edition edn, 8. New York, NY: ACM Books. doi:10.1145/2792790

Juliani, A., Berges, V.-P., Teng, E., Cohen, A., Harper, J., Elion, C., et al. (2018). Unity: A General Platform for Intelligent Agents. Available at: http://arxiv.org/pdf/1809.02627v2 [Dataset]

Kesler, D., Arntz, A., Friedhoff, J., and Eimler, S. C. (2020). “Mill Instructor: Teaching Industrial Cnc Procedures Using Virtual Reality,” in 2020 IEEE International Conference on Artificial Intelligence and Virtual Reality (AIVR) (IEEE), 231–234. doi:10.1109/AIVR50618.2020.00048

Koay, K. L., Syrdal, D., Bormann, R., Saunders, J., Walters, M. L., and Dautenhahn, K. (2017). “Initial Design, Implementation and Technical Evaluation of a Context-Aware Proxemics Planner for a Social Robot,” in *Social Robotics of Lecture Notes in Computer Science*. Editors A. Kheddar, E. Yoshida, S. S. Ge, K. Suzuki, J.-J. Cabibihan, F. Eyssel, et al. (Cham: Springer International Publishing), 10652, 12–22. doi:10.1007/978-3-319-70022-9_2

Kresse, I. (2010). licensed under cc-by-3.0 2010 © by ingo kresse, kresse@in.tum.de. Available at: https://creativecommons.org/licenses/by/3.0/. [Dataset]

KUKA (2020). Lbr Iiwa. Available at: https://www.kuka.com/en-gb/products/robotics-systems/industrial-robots/lbr-iiwa [Dataset]

KUKA (2016). Sensitive Robotics Lbr Iiwa. Available at: https://www.kuka.com/-/media/kuka-downloads/imported/9cb8e311bfd744b4b0eab25ca883f6d3/kuka_sensitiverobotics_lbriiwa_insert_en.pdf?rev=82b2ad0795854609a53c500cb896eb3a&hash=742380F2B4D6B32C4A037EF5EBEE5C78 [Dataset]

Lasota, P. A., Fong, T., and Shah, J. A. (2017). A Survey of Methods for Safe Human-Robot Interaction. *FNT in Robotics* 5, 261–349. doi:10.1561/2300000052

Lemaignan, S., Hanheide, M., Karg, M., Khambhaita, H., Kunze, L., Lier, F., et al. (2014). “Simulation and Hri Recent Perspectives with the morse Simulator,” in *Simulation, Modeling, and Programming for Autonomous Robots*. Editors D. Brugali, J. F. Broenink, T. Kroeger, and B. A. MacDonald (Cham: Springer International Publishingof Lecture Notes in Computer Science), 8810. 13–24. doi:10.1007/978-3-319-11900-7_2

Lenz, C., and Knoll, A. (2014). “Mechanisms and Capabilities for Human Robot Collaboration,” in The 23rd IEEE International Symposium on Robot and Human Interactive Communication (IEEE), 666–671. doi:10.1109/ROMAN.2014.6926329

Liu, H., and Wang, L. (2020). Remote Human-Robot Collaboration: A Cyber-Physical System Application for hazard Manufacturing Environment. *J. Manufacturing Syst.* 54, 24–34. doi:10.1016/j.jmsy.2019.11.001

Matsas, E., Vosniakos, G.-C., and Batras, D. (2018). Prototyping Proactive and Adaptive Techniques for Human-Robot Collaboration in Manufacturing Using Virtual Reality. *Robotics and Computer-Integrated Manufacturing* 50, 168–180. doi:10.1016/j.rcim.2017.09.005

Meziane, R., Otis, M. J.-D., and Ezzaidi, H. (2017). Human-robot Collaboration while Sharing Production Activities in Dynamic Environment: Spader System. *Robotics and Computer-Integrated Manufacturing* 48, 243–253. doi:10.1016/j.rcim.2017.04.010

MORSE (2020). Kuka Lwr Arm Actuator. Available at: http://www.openrobots.org/morse/doc/0.5/user/actuators/kuka_lwr.html#use-of-the-kuka-lwr [Dataset]

Müller, S. L., Schröder, S., Jeschke, S., and Richert, A. (2017). “Design of a Robotic Workmate,” in *Digital Human Modeling. Applications in Health, Safety, Ergonomics, and Risk Management: Ergonomics and Design*. Editor V. G. Duffy (Cham: Springer International Publishing of Lecture Notes in Computer Science), 10286, 447–456. doi:10.1007/978-3-319-58463-8_37

Mumm, J., and Mutlu, B. (2011). “Human-robot Proxemics,” in Proceedings of the 6th international conference on Human-robot interaction - HRI ’11. Editors A. Billard, P. Kahn, J. A. Adams, and G. Trafton (New York, New York, USA: ACM Press), 331. doi:10.1145/1957656.1957786

Munzer, T., Toussaint, M., and Lopes, M. (2018). Efficient Behavior Learning in Human-Robot Collaboration. *Auton. Robot* 42, 1103–1115. doi:10.1007/s10514-017-9674-5

Oculus (2020a). Rift S: Vr-Headset. Available at: https://www.oculus.com/rift-s/ [Dataset].

Oculus (2020b). Unity Integration. Available at: https://developer.oculus.com/downloads/unity/ [Dataset].

Papayiannis, C., Amoh, J., Rozgic, V., Sundaram, S., and Wang, C. (2018). “Detecting media Sound Presence in Acoustic Scenes,” in *Interspeech 2018* (Lous Tourils, France: ISCA), 1363–1367. doi:10.21437/Interspeech.2018-2559

Peltokorpi, V., and Hood, A. C. (2019). Communication in Theory and Research on Transactive Memory Systems: A Literature Review. *Top. Cogn. Sci.* 11, 644–667. doi:10.1111/tops.12359

Roesler, E., and Onnasch, L. (2020). “Teammitglied oder Werkzeug - Der Einfluss anthropomorpher Gestaltung in der Mensch-Roboter-Interaktion,” in *Mensch-Roboter-Kollaboration*. Editor H.-J. Buxbaum (Wiesbaden: Springer Fachmedien Wiesbaden), 163–175. doi:10.1007/978-3-658-28307-0_11

Rosenstrauch, M. J., and Kruger, J. (2017). "Safe Human-Robot-Collaboration-Introduction and experiment Using Iso/ts 15066," in 2017 3rd International Conference on Control, Automation and Robotics ICCAR (IEEE), 740–744. doi:10.1109/ICCAR.2017.7942795

Roswell, R. O., Cogburn, C. D., Tocco, J., Martinez, J., Bangeranye, C., Bailenson, J. N., et al. (2020). Cultivating Empathy through Virtual Reality: Advancing Conversations about Racism, Inequity, and Climate in Medicine. *Acad. Med. : J. Assoc. Am. Med. Colleges* 95, 1882–1886. doi:10.1097/ACM.0000000000003615

Schlögl, S., Doherty, G., and Luz, S. (2013). "Managing Consistency in Wizard of Oz Studies: A Challenge of Prototyping Natural Language Interactions," in *MobileHCI Workshop on Prototyping to Support the Interaction Designing in Mobile Application Development* (Munich, Germany: PID-MAD 2013).

Schmidtler, J., Hölzel, C., Knott, V., and Bengler, K. (2014). "Human Centered Assistance Applications for Production," in Conference: 5th International Conference on Applied Human Factors and Ergonomics. doi:10.13140/RG.2.1.1608.7203

Sebanz, N., and Knoblich, G. (2009). Prediction in Joint Action: what, when, and where. *Top. Cogn. Sci.* 1, 353–367. doi:10.1111/j.1756-8765.2009.01024.x

Sebanz, N., Knoblich, G., and Prinz, W. (2005). How Two Share a Task: Corepresenting Stimulus-Response Mappings. *J. Exp. Psychol. Hum. Perception PerformanceHuman perception Perform.* 31, 1234–1246. doi:10.1037/0096-1523.31.6.1234

Sen, S., Buxbaum, H.-J., and Kremer, L. (2020). "The Effects of Different Robot Trajectories on Situational Awareness in Human-Robot Collaboration," in *Human-Computer Interaction. Multimodal and Natural Interaction*. Editor M. Kurosu (Cham: Springer International Publishingof Lecture Notes in Computer Science), 12182, 719–729. doi:10.1007/978-3-030-49062-1_50

Seo, D.-C. (2005). An Explicative Model of Unsafe Work Behavior. *Saf. Sci.* 43, 187–211. doi:10.1016/j.ssci.2005.05.001

Shah, J., Wiken, J., Williams, B., and Breazeal, C. (2011). "Improved Human-Robot Team Performance Using Chaski, a Human-Inspired Plan Execution System," in Proceedings of the 6th international conference on Human-robot interaction - HRI '11. Editors A. Billard, P. Kahn, J. A. Adams, and G. Trafton (New York, New York, USA: ACM Press). doi:10.1145/1957656.195766829

Shahid, M. A., Jesche, B.-P., Olbrich, M., Graf, H., Franek, A., Kuijper, A., et al. (2020). "Measurement Based Ar for Geometric Validation within Automotive Engineering and Construction Processes," in *Virtual, Augmented and Mixed Reality. Industrial and Everyday Life Applications*. Editors J. Y. C. Chen and G. Fragomeni (Cham: Springer International Publishingof Lecture Notes in Computer Science), 12191, 154–165. doi:10.1007/978-3-030-49698-2_11

Shu, B., Sziebig, G., and Pieska, S. (2018). "Human-robot Collaboration: Task Sharing through Virtual Reality," in IECON 2018 - 44th Annual Conference of the (IEEE Industrial Electronics Society IEEE), 6040–6044. doi:10.1109/IECON.2018.8591102

Straßmann, C., Eimler, S. C., Arntz, A., Keßler, D., Zielinski, S., Brandenberg, G., Dümpel, V., and Handmann, U. (2019). "Relax Yourself - Using Virtual Reality to Enhance Employees' Mental Health and Work Performance," in Extended Abstracts of the 2019 CHI Conference on Human Factors in Computing Systems - CHI EA '19. Editors S. Brewster, G. Fitzpatrick, A. Cox, and V. Kostakos (New York, New York, USA: ACM Press), 1–6. doi:10.1145/3290607.3312946

Toussaint, M., Munzer, T., Mollard, Y., Li Yang Wu, L. Y., Ngo Anh Vien, N. A., and Lopes, M. (2016). "Relational Activity Processes for Modeling Concurrent Cooperation," in 2016 IEEE International Conference on Robotics and Automation (ICRA) (IEEE), 5505–5511. doi:10.1109/ICRA.2016.7487765

Unity (2020a). Badge Maker 900 Flexi 59 Mm. Available at: https://unity3d.com/de/unity/qa/lts-releases [Dataset]

Unity (2020b). Textmeshpro. Available at: https://docs.unity3d.com/Manual/com.unity.textmeshpro.html [Dataset]

Villani, V., Pini, F., Leali, F., and Secchi, C. (2018). Survey on Human-Robot Collaboration in Industrial Settings: Safety, Intuitive Interfaces and Applications. *Mechatronics* 55, 248–266. doi:10.1016/j.mechatronics.2018.02.009

VRTK (2020). Virtual Reality Toolkit. Available at: https://vrtoolkit.readme.io/ [Dataset]

Vysocky, A., and Novak, P. (2016). Human - Robot Collaboration in Industry. *Mm Sj* 2016, 903–906. doi:10.17973/mmsj.2016_06_201611

Wegner, D. M., Erber, R., and Raymond, P. (1991). Transactive Memory in Close Relationships. *J. Personal. Soc. Psychol.* 61, 923–929. doi:10.1037/0022-3514.61.6.923

Weiss, A., Bernhaupt, R., Schwaiger, D., Altmaninger, M., Buchner, R., and Tscheligi, M. (2009). "User experience evaluation with a wizard of oz approach: Technical and methodological considerations," in 2009 9th IEEE-RAS International Conference on Humanoid Robots (IEEE), 303–308. doi:10.1109/ICHR.2009.5379559

Wen, K., Du, F., Zhang, J., and Yang, J. (2018). An Alignment Method of Human-Robot Collaboration Based on the Six-Dimensional Force/torque Dynamic Measurement for Large-Scale Components. *J. Robotics* 2018, 1–7. doi:10.1155/2018/2914871

Wilcox, R., and Shah, J. (2012). "Optimization of Multi-Agent Workflow for Human-Robot Collaboration in Assembly Manufacturing," in *Infotech@ Aerospace 2012* (Reston, Virigina: American Institute of Aeronautics and Astronautics), 210–220. doi:10.2514/6.2012-2535

Williams, T., Hirshfield, L., Tran, N., Grant, T., and Woodward, N. (2020). "Using Augmented Reality to Better Study Human-Robot Interaction," in *Virtual, Augmented and Mixed Reality. Design and Interaction*. Editors J. Y. C. Chen and G. Fragomeni (Cham: Springer International Publishingof Lecture Notes in Computer Science), 12190, 643–654. doi:10.1007/978-3-030-49695-1_43

Zakka, K., Zeng, A., Lee, J., and Song, S. (2019). *Form2fit: Learning Shape Priors for Generalizable Assembly from Disassembly*[Dataset].

Zengeler, N., Arntz, A., Keßler, D., Grimm, M., Qasem, Z., Jansen, M., et al. (2020). "Person Tracking in Heavy Industry Environments with Camera Images," in *Science and Technologies for Smart Cities*. *g*. Editors H. Santos, G. V. Pereira, M. Budde, S. F. Lopes, and P. Nikolic (Cham: Springer International Publishingof Lecture Notes of the Institute for Computer Sciences, Social Informatics and Telecommunications Engineerin), 323, 324–336. doi:10.1007/978-3-030-51005-3_27

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7. Summary and Future Research

This chapter concludes the presented work with a brief summary followed by a discussion of the specific contributions accompanied by the specifications of the limitations. In addition, this section contains descriptions of upcoming projects that will use the HRC VR application, followed by further suggestions for future research and a conclusion.

7.1. Summary

This dissertation presented a versatile research tool for HRC concepts in the form of a VR application and five studies informing the design and testing of the previously established research questions (cf. Section 1.2). These research questions, tested in experiments with participants either using VR application directly or adapted as a video stimulus addressed the challenges of HRC (cf. Section 1.1.2) through quantitative, qualitative, and objective measurements. Considering that these challenges hamper current HRC implementations and the restrictions to confront these challenges in safe and replicable empirical studies, the VR application resulting from the work was conceptualized and developed as an alternative to exploring current ongoing and upcoming HRC scenarios. Although the usage of mixed reality technologies is already applied in the field of HRC (cf. Section 1.3.1), as of yet no dedicated VR platform for conducting experimental studies has been established. As ascertained in the research of behavioral psychology (cf. Section 1.3.2), it can be assumed that this presented VR application provides a useful tool to the HRC research community in validating current and exploring new concepts to design safe, effective and autonomous HRC arrangements that are conforming to user expectations.

The preliminary study of Chapter 2 explored the expectations of participants towards the presented collaborative robot in a qualitative approach. Apart from the answers that emphasized the importance of competence, reliability, trust, and independence, Chapter 2 helped to shape subsequent studies of the HRC VR application by tweaking the representation of the communication methods and adding the multi-colored light signal as a dedicated channel to the virtual robot. Also, the preliminary study helped to identify the characteristics that the participants associated with an intelligent system, an aspect that was important for the design of the robot's behavior in subsequent studies (cf. Chapter 5).

As previously established in Section 1.1.2, communication cues are important for the collaboration relationship. To explore this, Chapter 3 focused on the augmented communication channels of the robot and explored their influence on the participant's perceived stress, associated emotions, and the social presence of the robot. Compared in a between-subjects-design, 80 participants were confronted in an experimental setup either with an autonomous robot augmented with communication channels or collaborated with a robot without the capabilities to express itself. This experimental setup was shared with all experimental studies for comparison purposes, with the exception of Chapter 2, serving as the preliminary study, and Chapter 5. Results showed that the used communication channels contributed to less perceived stress, more positive emotions, and the impression of an increased social presence. All three attributes are important aspects of the collaboration relationship as they can affect an individual's willingness to work with the system. Considering that a robot that evokes stress and negative emotions due to uncertainty, while displaying autonomous skills without the impression of a social presence might induce aversion. Viewed from the perspective of human factors, these aspects can jeopardize an effective collaboration relationship, if not designed adequately. The results of this study contribute to the HRC research by showing that this communication arrangement can improve the human factors aspects during a collaboration scenario.

Chapter 4 examined the individual positive and negative aspects of the collaboration robot in a qualitative approach. Results revealed themes regarding the positive perceived aspects such as the experienced assistance provided by the autonomous robot, the efficiency of the robot, and the resulting collaboration relationship. Attributes that were criticized across both conditions (communication vs. non-communication) were the slow working pace of the robot and the unpleasant noise of the actuators. Participants from the non-communication conditions lamented the lack of communication by the robot, resulting in the perception of uncertainty during the collaboration. While the study investigated the characteristics of the presented robot from the LBR iiwa series [119], aspects such as the slow working speed dictated by safety guidelines along with the unpleasant sound can be applied to a variety of different collaboration robots. Therefore, the qualitative answers from this study supply designers of collaboration setups with valuable suggestions for upcoming HRC setups.

Chapter 5 shifted its focus on the attribution of blame and credit during the collaboration with an autonomous robot. Due to widespread reservations against automated systems among the population, the study setup was distinguished in a 2 (augmented communication vs. non-augmented condition) x 2 (AI-narrative vs. non-AI-narrative) setup. In the augmented communication condition an artificial intelligence narrative emphasized the competence of the robot. While participants did not show any statistically significant difference in the attribution of blame and credit between the conditions, the ability to communicate led to the perception of the robot as a better collaboration partner. Results of this study provide valuable insights into the attribution of the robot with human characteristics due to the mere presence of an AI narrative and the confirmation of the importance of communication channels in a collaboration between humans and robots.

The collection of objective measurements in general is uncommon in HRC empirical research involving participants and prohibited regarding the measurements of the collision rate, due to the aforementioned safety concerns (cf. Section 1.1.2). For this reason, the study described in Chapter 6 compared the production rate and the collision frequency between the conditions (communication vs. non-communication). The results indicated that communication channels can help to improve production rates and reduce collisions with the robot, as participants from the communication condition outperformed their peers from the non-communication condition. These results provide a contribution to the overall goal of HRC research to improve safety conditions in collaboration settings. Another aspect is that the communication not only resulted in actually increased safety but also in perceived safety.

7.2. Specific Contributions

The collaboration between two humans involves complex layers of social interactions that influence the relationship between the collaborating parties and the effectiveness of the collaborative activity [59], [71]. Human-Robot Collaboration, especially with the anticipation of intelligent and autonomous robots in the near future [12], [14], contains no less complexity in the exchange between the two collaboration partners.

To develop guidelines that address the challenges of the effective implementation of the HRC concept, extensive research is required to fathom the intricate characteristics of the collaboration between the two parties [37]. Since the examination of HRC in controlled studies requires extensive precautions and elaborate setups, the main contribution of this thesis is to provide a VR-based research platform that enables the research of HRC workplace arrangements as well as results on its design and the exploration of challenges concerning safety, expectation conformity, task allocation, and autonomous behavior (cf. Section 1.1.2). To illustrate the contribution, it is important to put the developed VR application in context with previous implementations of VR in the domain of HRC (cf. Section 1.3.1). Existing applications aim to either integrate the virtual content into the real HRC setup [89], simulating the robot to analyze pre-calculated trajectory paths for optimizing the movement [90], or act as a training tool to prepare personnel with the operation procedures of the robot [93]. The concept of using VR as a means to gain insights into user reactions and behavior for experimental studies is not covered by these applications. Furthermore, the usage of ML to achieve a level of autonomy from the robot while being tasked with the objective to accomplish a shared task in collaboration with a human partner is another unique aspect that is found in the hereby presented VR application dedicated to empirical studies. Completed with the interaction mechanics, communication interfaces, and the capability to collect objective measurements during the collaboration procedure, the VR application is intended to support the HRC research community in exploring the complex dynamics of humans collaborating with industrial robots in experimental studies without the effort of real organized lab setups. Researchers are empowered through this VR application to investigate new concepts and existing scenarios without exposing their participants to potential dangerous implementations while being able to accurately repeat the respective test conditions for each participant. Even without the usage of VR Hardware, the virtual environment can be used to create additional stimulus material in various forms of media such as images and videos (c.f. Chapter 5). Apart from the aforementioned benefits, the accessibility of different settings through the VR application might help to mitigate the current threshold of research in the domain of HRC which is associated with high acquisition costs of the individual robots, and propel the concept out of the Human-Robot Interaction niche. Concepts and/or constructs that are robust (strong, not fragile when used in studies) and have received considerable backing by research could therefore attract more industries to invest in the HRC approach and support their staff with collaborative robots. This is especially relevant due to an aging population that stays longer in the workforce, which is recognized in the silver society megatrend [149]. Adjacent to this is the megatrend of emerging health awareness [150], as physically demanding tasks can be delegated onto the robot, relieving personnel, which contributes to maintaining their health and might reduce their sick leave.

In addition to the VR application as a technical achievement, this thesis makes a specific contribution to the empirical research in the field of HRC, both in terms of providing a research tool as well as through the identification of aspects of empirical concern and ensuing hypotheses. By orchestrating multiple methods such as qualitative, quantitative, and objective measurements for the collection of relevant data, the results of this dissertation provide valuable implications regarding the challenges of HRC. As described in Section 1.1.2, previous HRC research involving autonomous robots often favors the technical implementation and neglects the human requirements for the system [60]. The qualitative answers described in the studies from Chapter 2 and Chapter 4 provide relevant statements for the general expectations and impressions of an autonomous collaboration robot in an industrial setting. Although the sample size for the study in Chapter 2 was small (further described in Section 4 of Chapter 2), previous studies neglected the exploration of users' expectations towards industrial collaboration robots through qualitative answers [151], making the gathered statements nevertheless valuable for the HRC research community.

In accordance with the theoretical foundation of the collaboration process among humans which is further detailed in Chapter 3 (Section 2) and Chapter 6 (Section 2), the empirical studies from Chapters 3, 4, 5, and 6 confirmed the various benefits of equipping an autonomous robot in a shared task environment with multi-modal communication channels and validated the combination of the used communication interfaces. Since the time participants were exposed to the collaboration was short due to its execution as an experimental study in a lab setting, no long-term effects can be presented. However, the trend across the presented studies indicates the advantages of the communication channels in the domain of perceived stress, positive emotions, social presence, the general impression of the robot as a collaboration partner, increased production quantity, reduced collisions, and safety perception. Real collaboration setup involving robots can benefit from these results by optimizing the production effectiveness and safety through fewer collisions and higher output due to the guidance and explanation provided by the communication channels. Personnel exposed to these robots can experience less perceived stress due to the reduction of uncertainty and the improved collaboration relationship due to the social presence of the robot. This can help to increase an individual's willingness to effectively collaborate with the system and reduce negative stereotypes associated with robots and artificial intelligence, which are widespread among the population [144].

All in all, the conducted studies of this dissertation shed light on the important challenges of HRC presented in Section 1.1.2 and provide recommendations for action. Furthermore, this dissertation offers a basis for design decisions for future research and for design aspects in the industrial field of application.

7.3. Limitations

To contextualize the gathered results it is important to emphasize the general limitations of the hereby presented work regarding the methodological and technical constraints to test HRC concepts. Although the included publications already discussed the individual limitations of the respective studies, certain limitations found across all conducted studies in this work will be concluded in this section. A major limitation is the composition of the used sample. Since the majority of the participants from the studies reported in Chapters 2, 3, 4, and 6 consisted of STEM[1] students from the University of Applied Sciences Ruhr West[2], no external validity can be applied to the presented results. The same can be attributed to the study reported in Chapter 5, where insufficient demographic data were surveyed to enable conclusions about the composition of the sample. The skew in demographics, therefore, denies the application of the results gathered in this dissertation to the general population. Although the benefit of using students as participants, which form the workforce of tomorrow, was argued in the included studies presented in Chapters 2-6, the missing application of external validity remains. An inspection of similar HRC-related empirical studies reveals similar limitations in the composition of representative samples as well [29], which can alter the results gathered from these empirical studies, thus changing the conclusions to be drawn for future design guidelines for HRC. This necessitates additional studies in the future, that cover a more representative sample to reflect the diverse background of the general population across different cultures. The advantage of the VR HRC application compared to traditional lab settings is mobility. Without logistical constraints, the experimental procedure can be reproduced independently from a specific location, enabling future studies the increased freedom to recruit the necessary sample. However, one disadvantage of the VR approach is the exclusion of certain groups of participants. The use of VR can be restricted or ineligible for people with vision impairments such as stereoblindness, where a person can not distinguish stereoscopic images. Further limitations can occur with people with a low

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[1] The term STEM describes the academic disciplines of Science, technology, engineering, and mathematics.

[2] https://www.hochschule-ruhr-west.de

tolerance for motion sickness. Although, due to prior experiences with VR-related projects optimization strategies to minimize latency issues, which provoke motion sickness have been successfully applied, motion sickness might still occur in sensitive people. To acknowledge this, every questionnaire used in the described empirical studies queried motion sickness, to avoid any effect on the rating of the individual items. So far none of the participants across the conducted empirical studies and the adjacent research projects outlined in Section 1.3.3 reported impairments in the VR experience. Together with sophisticated guidelines for the development of VR and its usage that help to mitigate effects such as motion sickness [84], it can be argued that the advantages of the approach stated in this dissertation outweigh the potential restrictions.

To ensure comparability between the study results, the included publications in Chapters 2, 3, 4, and 6 follow the same experimental procedure. However, due to the ongoing COVID-19 pandemic at the time of this writing, the procedure for the study described in Chapter 5 was altered. While the changes in the procedure were justified in order to conduct the study, it breaks the comparability of the results with the rest of the studies included in this dissertation. It is therefore advised to repeat the hypotheses and research questions stated in Chapter 5 with an experimental procedure aligned with those found in Chapters 2, 3, 4, and 6.

Another limitation of this dissertation is the lack of an experimental study conducted with the real robot arm pendant to compare the empirical outcome. While the effectiveness of the VR technology as a tool to examine the situational behavior of a person has been outlined in Section 1.3.2, it is important to consider that a virtual setting, as immersive as it can be, always represents an approximation of reality. It is therefore possible that subjective impressions regarding the collaboration procedure and the robot arm can divert in a real setting compared to the virtual representation. As described in Chapters 2-6, great effort was spent to ensure that the VR application emulates a real HRC workplace as closely as possible in terms of representation, consistency, and immersion. However, the translation from reality to virtual reality is always accompanied by compromise. The best example of this is the lack of actual touch within the VR experience. Although the VR application uses the full spectrum of haptic force feedback to signal participants the occurrence of contact between the user's hands and a virtual object mentioned in Section 1.3.4, no actual tactile experience can be conveyed due to the lack of such a channel in current VR hardware. This is a major drawback, as intentional physical contact is one of the key modalities of HRC (cf. Section 1.1.1). This restricts the examination of physical-related research and its influence on the collaboration relationship. Future hardware solutions, such as dedicated VR gloves, might mitigate this limitation by extending the haptic and tactile capabilities of VR technology. Another limitation of the interaction mechanics is the inability to represent fine motor skills. This restricts the type of collaboration procedures that can be tested with the VR application. The current version of the VR application is adjusted to the capabilities of the Oculus series of touch controllers which are not suitable to translate fine motor skills.

Optical finger tracking could enhance precision by representing all ten fingers. However, this approach would remove the capability to signal a contact via the haptic force feedback, trading one compromise for another. Further tests with advanced VR hardware, i.e., the Valve Index controller could resolve this problem by offering precise full spectrum motion with haptic force feedback.

7.4. Future Research

The versatility of the VR application combined with the variety of challenges in HRC opens up a wide range of possible future perspectives. Potential future work can be divided into two categories, functionality extensions of the VR application and upcoming empirical studies. Extensions of the VR application involve functionalities and mechanics to expand the variety of potential scenarios the virtual setup can cover. One of these extensions that were already done is the previously stated adaption of the inverse kinematic system and the machine learning components for a dual-arm robot (cf. Section 1.3.5) [129]. Not only does this expand the library of robots that can be represented within the VR application, but it also allows the examination of new collaboration procedures. Considering that a dual-arm robot can mimic the movement of its human counterpart more closely than the already used single robot, new collaboration procedures, gestures, and communication arrangements can be examined. Also, the flexibility of the VR application to change the appearance of the robot while maintaining the collaboration procedure and all other parameters enables the direct comparison between multiple robot representations within the same context. This allows recreating the previously conducted studies reported in Chapters 2-6 with a robot equipped with two arms, investigating the emerging commonalities and differences. With the testing of different robot representations, patterns in the behavior of participants across the collaboration arrangements can be analyzed. This would help the HRC research community in determining guidelines and common methodologies in the design of collaboration setups. Additional functionality extensions could involve the integration of the Xsens MVN Avinda motion capture suit [152]. Preceding VR-related test projects utilized this motion capture suit to realize a full body representation of the user, enabling a more precise and accurate virtual experience. This could be used to feed the positioning of the user avatar to the agents, allowing the robot to detect the entire body of the user compared to the low-resolution implementation of merely the hands and head.

Besides the expansion of the technical functionality, the VR application can serve as the basis for further empirical studies. As of the time of this writing, two unpublished studies used the virtual representation of the Yumi IRB 14000 dual-arm robot shown in Figure **7-1** to investigate the perceptions users have, when the dual-arm robot uses human non-verbal gestures [137]. Based on the research of Straßmann et al. gestures for dominance and submissive behavior were applied to the virtual robot and for comparison, its real counterpart respectively [153]. The goal of the first study is, on the one hand, to examine the participants' impression of the robot's embodiment through human gestures, and on the other hand to investigate differences in the perception of the virtual robot compared to the real one. While the former goal contributes to the research effort of developing adequate gestures that comply with the expectation conformity, the latter is of interest to further strengthen, in addition to the research already mentioned in Section 1.3.2, the validity of the virtual simulation as a tool to explore HRC configurations.

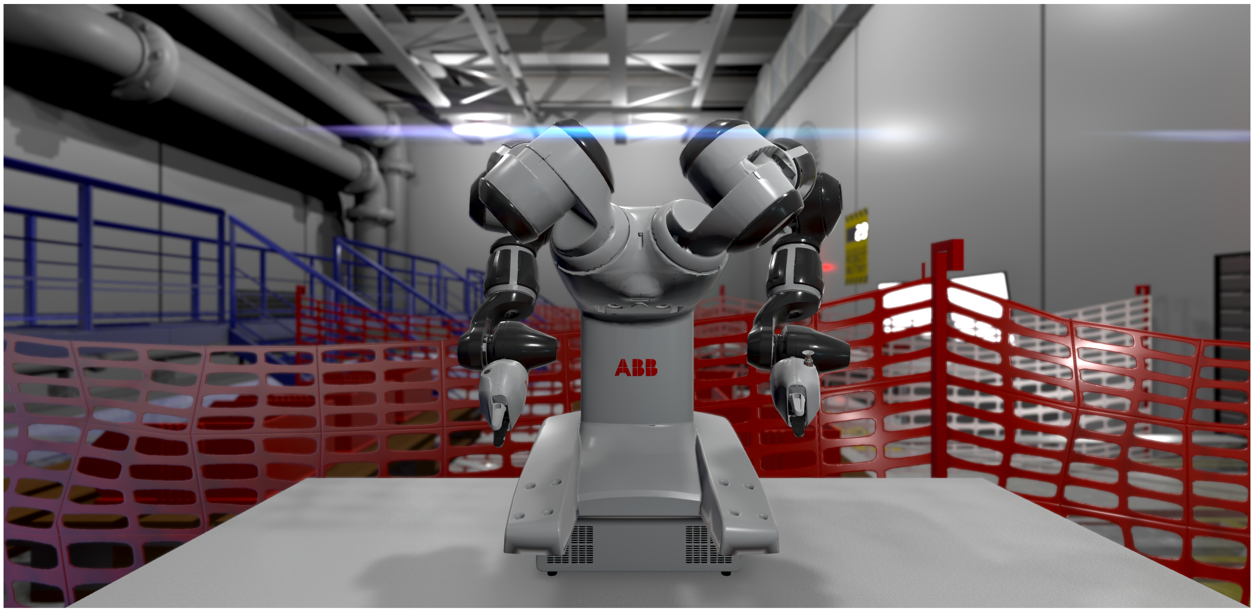

Figure **7-1**.: The virtual representation of the Yumi IRB 14000 dual-arm robot that was implemented in a successor version of the HRC VR application [129], [137].

A successor to the experimental setup involving a shared assembly task described in Chapters 3, 4, and 6 is currently, during the writing of this thesis, in preparation. The planned setup contains two teams, each consisting of a human collaborating with a robot. Both teams together are tasked to assemble a bicycle. While there is no example of bicycle manufacturing where HRC is involved, the task was conceptualized as it allows a complex enough procedure to occupy two teams. At the same time, the assembly processes of a bicycle are comprehensible enough to allow inexperienced participants to perform the task in collaboration with a robot. By combining multiple teams in shifting dependencies, roles, and hierarchies, the planned setup investigates aspects of HRC previously uncharted and almost unlikely to be explored through other means than the VR application presented in this thesis. To experiment with additional communication methods, new mechanics are currently in development, i.e., an interface to integrate Amazon Web Services into the application. The goal is to implement a verbal backchannel through the use of the Alexa Voice Service [154], where the robot can answer towards user input along a semantic chain across multiple requests. This opens up new possibilities regarding the working relationship between the human and the robot in terms of expectation conformity, perception, coordination, and working effectiveness (cf. Section 1.1.2).

Furthermore, the versatility of the VR application can be utilized as a training platform to educate personnel in existing scenarios or teach students about the various aspects of industrial robots and enable them to experiment in a fault-tolerant environment with the virtual robots for innovations in that area. Currently, at the time of writing this dissertation, a project is prepared to include additional educational functionalities to the VR HRC application. The goal is to use the best practices gained from prior VR learning applications (cf. Section 1.3.3) and provide students with a guided learning platform to explore various topics regarding industrial robots.

7.5. Conclusion

This dissertation aimed to explore selected challenges of HRC in empirical studies through the usage of a dedicated VR application, which was designed and developed as a sandbox for this purpose. Equipped with interaction mechanics, inverse kinematics, and machine learning functionalities, the VR application bears the capability to portray a wide variety of possible scenarios, which are difficult to realize otherwise due to safety or logistical concerns. Considering the challenges that are confronting HRC, refining the concept through empirical studies becomes paramount for successful implementation in industrial environments. The previously conducted studies described in Chapters 2-6 contribute to the HRC research effort by presenting valuable user impressions and feedback regarding the robot regarding aspects such as safety and expectation conformity. Furthermore, the studies revealed the various beneficial effects of using multi-modal communication channels during the collaboration procedure with an autonomous robot. In conclusion, the presented work delivers results, which help the HRC community to better understand the complex relationship and idiosyncrasies of humans collaborating with robots in industrial settings. In addition to the previously collected results, the developed application can be used as a basis for future research projects involving different robots, collaboration procedures, and settings, and thus opens up the opportunity to discover innovative concepts and ideas in the field of HRC. Taking into account the respective limitations of the VR technology and the application itself, the approach nevertheless provides a versatile tool for exploring and testing implementations for the collaboration between humans and robots before they become reality.

A. Questionnaire 1 (English Version)

This Appendix A contains the pre-questionnaire and post-questionnaire that were used in the experimental studies described in Chapters 3,4, and 6. The original pre-questionnaire and post-questionnaire were created in German and presented through the SoSciSurvey online platform during the respective experimental studies [155]. The formatting shown here does not correspond to the original presentation during the experimental setup of the studies described in Chapters 3,4, and 6 and was edited in the context of this dissertation.

A.1. Pre-questionnaire

Introduction

Welcome!

Dear participants,

*Thank you for your interest in this study. In this project of the **University of Applied Sciences Ruhr West in cooperation with the University of Duisburg-Essen**, we are investigating human-machine collaboration scenarios.*

*In total, the study will take about **45 minutes**. In an industrial environment simulated through virtual reality, you will be confronted with an assembly task that you are to perform successfully together with a robot arm.*

*In the questionnaire you will be shown a series of statements and questions. The questionnaire is about **your own opinion**. Therefore there are no "right" or "wrong" answers. Please do not think too long about a statement, but make a choice as **spontaneously** as possible.*

*Participation in the study is **voluntary**. You can terminate your participation at any time without giving any reason and without any disadvantages. The collected data and personal communications described above will be treated **confidentially**. Furthermore, the publication of the results will be in an anonymous form, i.e. your data can not be assigned to your person.*

The collection of your personal data described above will be done without asking for your name. Your answers and results will be stored under a ***personal code word****, which you will create yourself based on a rule at the beginning of the study and which nobody but you will know. This means that it is not possible for anyone to associate your data with your name.* ***After completion of the data collection, but no later than 31.12.2020, your code will be deleted****. Your data will then be anonymized. However, as long as the code exists, you can request the deletion of the data collected from you. To do so, you do not have to tell us your name, but only your code word. You will receive instructions for creating your code word. Please keep the code word carefully so that you can request the deletion of your data later if necessary. The anonymized data will be stored for at least 10 years.*

According to the General Data Protection Regulation (DS-GVO), you have the following rights:

- *Information about processing of personal data (Art 15).*
- *Revocation of consent given (Art 7)*
- *Correction (Art 16)*
- *Deletion (Art 17)*
- *Restriction of processing (Art 18)*

The retention period for the fully anonymized data is at least 10 years after data evaluation or at least 10 years after a publication on this study appears.

Students of course ***”competence development”*** *at the University of Applied Sciences Ruhr West can be compensated with the participation* ***45 FPM****. For this purpose, you will have the opportunity at the end of the study to provide your own password, which you can use to collect your FPM at the times communicated via Moodle.*

If you agree with everything and are ready for the study, please click ”Continue”.

Parent Code

At the beginning we need your parent code - please be sure to fill it in!

So that we can later relate your anonymized data from both parts of the experiment, we ask you to create an individualized subject identifier - the so-called parent code.

The parent code is composed of:

1. *The first two letters of your mother's first name (e.g.* ***An****nette =* ***AN****)*
2. *The day and month of your own birthday (e.g. August 27 =* ***2708****)*
3. *The first two letters of your father's first name (e.g.* ***Rü****diger =* ***RÜ****)*

Together this results in ***AN2708RÜ***

Table **A-1**.: The parent code that matched the participants' answers from their pre-questionnaire to the respective answers from the post-questionnaire was adopted from questionnaires conducted in previous research projects [17], [112].

Your parent code

Technological Affinity

First of all, we would like to know about your previous experience with technical equipment. Please rate yourself on the following characteristics.

Table **A-2**.: The Technological Affinity was measured through the Technology Commitment items created by Neyer et al. [156].

For each of the statements below, *please indicate the extent to which you agree with them.*					
(1 = Totally disagree; 5 = Fully agree)	**1**	**2**	**3**	**4**	**5**
I am very curious about new technical developments.					
For me, dealing with technical innovations is usually too much of a challenge.					
I find dealing with new technology difficult - I simply can't do it most of the time.					
It is up to me whether I succeed in using new technical developments - it has little to do with chance or luck.					
I am always interested in using the latest technical devices.					
When dealing with modern technology, I am often afraid of failing.					
If I have difficulties in dealing with technology, it ultimately depends solely on me to solve them.					
If I had the opportunity, I would use technical products much more often than I do at present.					
I am afraid of breaking new technical developments rather than using them properly.					
What happens when I engage with new technical developments is ultimately under my control.					
I quickly take a liking to new technical developments.					
I find it difficult to trust technical devices.					
Whether I am successful in using modern technology depends largely on me.					

Affect Grid

Please indicate how you currently feel in the grid below.
Tick a box for this purpose. Answer spontaneously and honestly from the current moment.

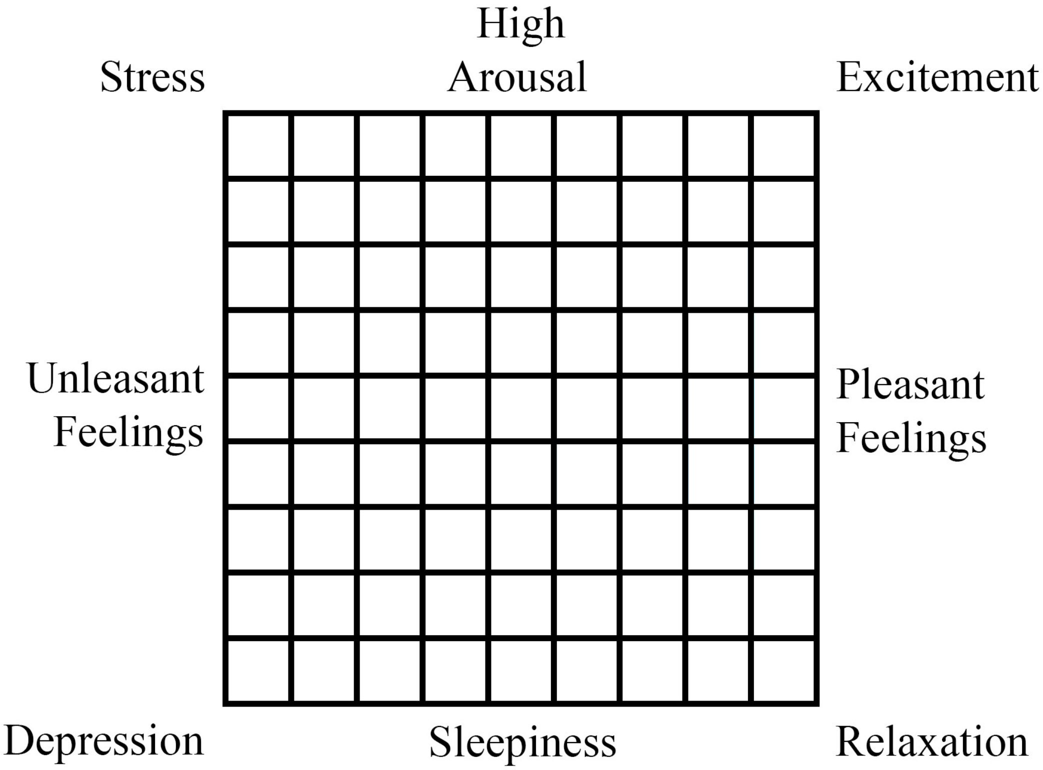

Figure **A-1**.: The Affect Grid is a single-item scale and is designed to determine the participants' subjective affect across the listed dimensions. It is based on the works by Russel [157] and was utilized in similar HRC related studies [24].

Negative Attitude Towards Robots

Table **A-3**.: The Negative Attitudes Toward Situations of Interaction With Robots sub-scale from the Negative Attitudes Towards Robots Scale by Nomura et al. [158].

How do you feel about the following statements about robots?							
(1 = Do not agree at all; 7 = Fully agree)	**1**	**2**	**3**	**4**	**5**	**6**	**7**
I would feel uneasy if I was given a job where I had to use robots.							
The word ”robot” means nothing to me.							
I would feel nervous operating a robot in front of other people.							
I would hate the idea that robots or artificial intelligences were making judgments about things.							
I would feel very nervous just standing in front of a robot.							

Table **A-4**.: The Negative Attitudes Toward the Social Influence of Robots sub-scale from the Negative Attitudes Towards Robots Scale by Nomura et al. [158].

How do you feel about the following statements about robots?							
(1 = Do not agree at all; 7 = Fully agree)	**1**	**2**	**3**	**4**	**5**	**6**	**7**
I would feel uneasy if robots really had emotions.							
Something bad might happen if robots developed into living beings.							
I feel that if I depend on robots too much, something bad might happen.							
I am concerned that robots would be a bad influence on children							
I feel that in the future society will be dominated by robots.							

Table **A-5**.: The Negative Attitudes Toward Emotions in Interaction With Robots sub-scale from the Negative Attitudes Towards Robots Scale by Nomura et al. [158].

How do you feel about the following statements about robots?							
(1 = Do not agree at all; 7 = Fully agree)	**1**	**2**	**3**	**4**	**5**	**6**	**7**
I would feel relaxed if I talked to robots.							
If robots had emotions, I could befriend them.							
I feel comforted to be with robots that have emotions.							

Previous Experience with Robotic Systems

*Do you already have previous experience with robotic systems? This refers to robot arms (see Figure **A-2**), which are used in the industry, e.g. for assembly tasks.*

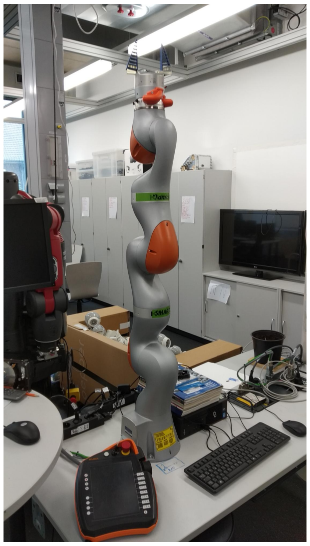

Figure **A-2**.: This photo was taken in the robotics laboratory at the University of Applied Sciences Ruhr West to be used within the experimental questionnaire.

Previous Experience with Virtual Reality

Table **A-6**.: Usage frequency of virtual reality formulated as a custom item lifted from the questionnaires of prior related VR projects [19], [103], [111].

How pronounced is your prior experience with VR devices?					
(1 = Not at all; 5 = Very often)	**1**	**2**	**3**	**4**	**5**
How often do you use VR devices?					

Table **A-7**.: The item regarding physical reactions during prior VR usage lifted from the questionnaires of prior related VR projects [19], [103], [111].

Physical reaction when using VR					
(1 = Never; 2 = Rarely; 3 = Sometimes; 4 = Frequently; 5 = Very often)	**1**	**2**	**3**	**4**	**5**
Have you ever experienced physical reactions (e.g. nausea, dizziness, etc.) when using VR devices?					

Socio-Demographics

Finally, we would like to know something about you.

Table **A-8**.: The item that was used to determine the participants' gender was adopted from prior experimental research projects [17], [112].

What is your gender?	
	Male
	Female
	Diverse

Table **A-9**.: The item that asked for the age of the participants' was lifted from prior experimental research projects [17], [112].

How old are you?		
I am		years old.

Table **A-10**.: The item, which determined the participants STEM background was taken from previous experimental studies [17], [112].

Is your current job/study in an engineering, science, or math-related field?	
	Yes
	No
	Not specified

What professional education do you have?

Table **A-11**.: The item, which determined the participants' vocational qualification was taken from previous experimental studies [17], [112].

Please select the highest educational qualification you have achieved so far

	No vocational training qualification
	Vocational training period with final certificate, but no apprenticeship
	Partial skilled worker qualification
	Completed industrial or agricultural apprenticeship
	Completed commercial apprenticeship
	Professional internship, traineeship
	Vocational school diploma
	Technical school diploma
	Master craftsman, technician or equivalent technical college degree
	University of applied sciences degree
	University degree
	Other degree, namely:

Table **A-12**.: The item that was used to ask for the participants' profession was taken from previous experimental studies [17], [112].

What do you do for a living?

	Pupil
	In training
	Student
	Salaried employee
	Civil servant
	Self-employed
	Unemployed/looking for work
	Other:

Closing Pre-Questionnaire

The survey part on the computer is now finished.
Please now contact the experimental supervisor, who will ask you a few more questions and explain the rest of the process.

Your answers have been saved, you can now close the browser window.

A.2. Post-questionnaire

Experimental Supervision

The contents on the following page are filled in by the experimental supervision and must not be seen by the test participants!

Table **A-13**.: This item was used by the experimenter to determine the participants' number.

Please always enter the participant number in the following way VP01,VP02.....

Table **A-14**.: This item was used by the experimental supervision to determine the experimental condition of the participant.

In which experimental condition is the participant assigned?	
	Robot with communication
	Robot without communication

Continuation

Welcome back!
This is the second part of the questionnaire.

Please read all the questions and instructions ***carefully*** *and try to give your answers* ***spontaneously****.If you agree with the collection of your data and would like to participate in this study, click* ***”Continue”.***

Thank you very much for your support.

Parent Code

At the beginning we need your parent code - please be sure to fill it in!

So that we can later correlate your anonymized data from both parts of the experiment, we ask that you re-enter your parent code here.

The parent code is composed of:

1. *The first two letters of your mother's first name (e.g.* ***An****nette =* ***AN****)*

2. *The day and month of your own birthday (e.g. August 27 =* ***2708****)*
3. *The first two letters of your father's first name (e.g.* ***Rü****diger =* ***RÜ****)*

Together this results in ***AN2708RÜ***

Table **A-15**.: The parent code matched answers from the pre-questionnaire to the respective answers from the post-questionnaire was lifted from prior experimental research projects [17], [112].

Your parent code

Affect Grid

Please indicate how you currently feel in the grid below.
Tick a box for this purpose. Answer spontaneously and honestly from the current moment.

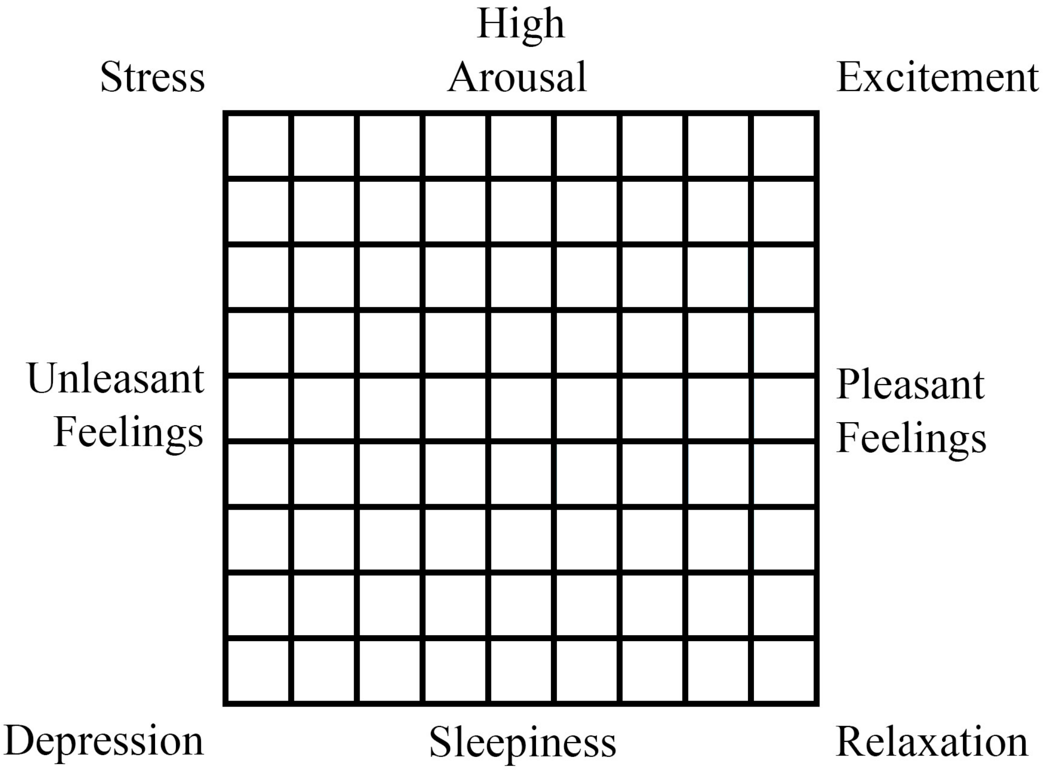

Figure **A-3**.: In accordance with the recommendations of Russel [157], the Affect Grid was again used in the post-questionnaire to determine a change in the subjective affect of the participants after being exposed to the stimulus material.

Task Load Index

Table **A-16**.: The item Mental Demand from the NASA Task Load Index [159].

Mental Demand																					
(1 = Very low; 20 = Very high)	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**
How mentally demanding was the task?																					

Table **A-17**.: The item Physical Demand from the NASA Task Load Index [159].

Physical Demand																					
(1 = Very low; 20 = Very high)	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**
How physically demanding was the task?																					

Table **A-18**.: The item Temporal Demand from the NASA Task Load Index [159].

Temporal Demand																					
(1 = Very low; 20 = Very high)	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**
How hurried or rushed was the pace of the task?																					

Table **A-19**.: The item Performance from the NASA Task Load Index [159].

Performance																					
(1 = Perfect; 20 = Failure)	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**
How successful were you in accomplishing what you were asked to do?																					

Table **A-20**.: The item Effort from the NASA Task Load Index [159].

Effort																					
(1 = Very low; 20 = Very high)	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**
How hard did you have to work to accomplish your level of performance?																					

Table **A-21**.: The item Frustration from the NASA Task Load Index [159].

Frustration																					
(1 = Very low; 20 = Very high)	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**
How insecure, discouraged, irritated, stressed, and annoyed were you?																					

Perceived Stress

Table **A-22.**: The slightly modified Perceived Stress Scale by Cohen [160], where the phrase *"In the last month"* was changed to *"In this experiment"* to better suit the context of the study.

In this experiment,...					
(1 = Never; 2 = Almost Never; 3 = Sometimes; 4 = Fairly Often; 5 = Very Often)	**1**	**2**	**3**	**4**	**5**
...how often have you been upset because of something that happened unexpectedly?					
...how often have you felt that you were unable to control the important things?					
...how often have you felt nervous and "stressed"?					
...how often have you felt confident about your ability to handle your personal problems?					
...how often have you felt that things were going your way?					
...how often have you found that you could not cope with all the things that you had to do?					
...how often have you been able to control irritations?					
...how often have you felt that you were on top of things?					
...how often have you been angered because of things that were outside of your control?					
...how often have you felt difficulties were piling up so high that you could not overcome them?					

Negative Attitude Towards Robots II

Considering the widespread misconceptions about robotics among the general population [144], it was of interest whether or not participants changed their attitude towards robots based on their exposure to the HRC scenario presented in the VR application. For this purpose, the Negative Attitude Towards Robots Scale was used again in the post-questionnaire.

Table **A-23**.: The Negative Attitudes Toward Situations of Interaction With Robots sub-scale from the Negative Attitudes Towards Robots Scale by Nomura et al. [158].

How do you feel about the following statements about robots?							
(1 = Do not agree at all; 7 = Fully agree)	**1**	**2**	**3**	**4**	**5**	**6**	**7**
I would feel uneasy if I was given a job where I had to use robots.							
The word ”robot” means nothing to me.							
I would feel nervous operating a robot in front of other people.							
I would hate the idea that robots or artificial intelligences were making judgments about things.							
I would feel very nervous just standing in front of a robot.							

Table **A-24**.: The Negative Attitudes Toward the Social Influence of Robots sub-scale from the Negative Attitudes Towards Robots Scale by Nomura et al. [158].

How do you feel about the following statements about robots?							
(1 = Do not agree at all; 7 = Fully agree)	**1**	**2**	**3**	**4**	**5**	**6**	**7**
I would feel uneasy if robots really had emotions.							
Something bad might happen if robots developed into living beings.							
I feel that if I depend on robots too much, something bad might happen.							
I am concerned that robots would be a bad influence on children							
I feel that in the future society will be dominated by robots.							

Table **A-25**.: The Negative Attitudes Toward Emotions in Interaction With Robots sub-scale from the Negative Attitudes Towards Robots Scale by Nomura et al. [158].

How do you feel about the following statements about robots?							
(1 = Do not agree at all; 7 = Fully agree)	**1**	**2**	**3**	**4**	**5**	**6**	**7**
I would feel relaxed if I talked to robots.							
If robots had emotions, I could befriend them.							
I feel comforted to be with robots that have emotions.							

Rating of the Robot

Table **A-26**.: The self-created items for the participants to rate the robot.

For each statement, please consider to what extent you think it applies.					
(1 = Do not agree at all; 5 = Fully agree)	**1**	**2**	**3**	**4**	**5**
I found the robot's movements pleasant.					
The robot adapted itself coherently to my way of working.					
I perceived the speed of the robot as pleasant.					
The robot reacted to me in the right way.					
The robot worked precisely.					
The text cues on the screen came from the robot.					
The robot worked well with me.					

Table **A-27**.: The self-created items for the participants to rate the communication of the robot.

For each statement, please consider to what extent you think it applies.					
(1 = Very bad; 2 = Bad; 3 = Average; 4 = Good; 5 = Very good)	**1**	**2**	**3**	**4**	**5**
In general, the robot's communication was...					
The robot's light signals were...					
The robot's text cues were....					
The robot's gestures were...					

Table **A-28**.: The self-created items for the participants to rate the competence of robot.

For each statement, please consider to what extent you think it applies.					
(1 = Not at all; 5 = Very much)	**1**	**2**	**3**	**4**	**5**
How useful was the robot?					
How competent was the robot?					
How knowledgeable was the robot?					
How analytical was the robot?					

Open Text - Negative Aspects of the Robot

Table **A-29**.: The open text box where participants stated their qualitative answers regarding the negative aspects of the robot.

Which aspects of the robot do you consider negative?	
	I don't think there were any negative aspects.

Satisfaction with the Workmate and Work Environment

Table **A-30**.: The self-created items for the participants to rate the satisfaction of the robot as a workmate, modified to fit the context of the study from the Work Environment Satisfaction Questionnaire by Carlopio [161].

For each statement, please consider to what extent you think it applies.					
(1 = Very dissatisfied; 5 = Very satisfied)	**1**	**2**	**3**	**4**	**5**
How satisfied were you with the robot's efficiency?					
How satisfied were you with the robot's effectiveness?					
How satisfied were you with the flexible working speed of the robot?					
How satisfied were you with the danger warnings you received from the robot?					
How satisfied were you with the way the robot tries to avoid accidents?					

Table **A-31**.: The self-created items for the participants to rate the work environment, modified to fit the context of the study from the Work Environment Satisfaction Questionnaire by Carlopio [161].

For each statement, please consider to what extent you think it applies.					
(1 = Very dissatisfied; 5 = Very satisfied)	**1**	**2**	**3**	**4**	**5**
How satisfied were you with the security arrangements at your virtual workspace?					
How satisfied were you with the overall design of your virtual workspace?					
How satisfied were you with the amount of time the robot gave you to complete the task?					
How satisfied were you with the amount of work you needed to complete the task?					
How satisfied were you with the way the robot tries to avoid accidents?					

Table **A-32**.: The item for the participants to rate the perceived safety of the robot based on the Survey Methods for Safe Human-Robot Interaction by Lasota et al. [162].

For each statement, please consider to what extent you think it applies.					
(1 = Totally disagree; 5 = Fully agree)	**1**	**2**	**3**	**4**	**5**
I believe that an accident with the robot (e.g. a collision) can happen or can happen again.					
I felt safe in the presence of the robot.					
I believe that other people feel safe in the presence of the robot.					
I would rather continue to work with the robot than without it.					

Open Text - Benefits of Collaborating with the Robot

Table **A-33**.: The open text box where participants stated their qualitative answers regarding the benefits of collaborating with the robot.

In your opinion, what benefits does the collaboration with the robot have in this shared task context?	
	I think there are no benefits.

Perceived Usefulness

Table **A-34**.: The Perceived Usefulness items adopted from Technology Acceptance Model 2 by Venkatesh and Davis [163].

Please answer the following questions							
(1 = Extremely Likely; 2 = Quite Likely; 3 = Slightly likely; 4 = Neither; 5 = Slightly Unlikely; 4 = Quite Unlikely; 7 = Extremely Unlikely)	**1**	**2**	**3**	**4**	**5**	**6**	**7**
Collaborating with the robot in my job would enable me to accomplish tasks more quickly.							
Collaborating with the robot would improve my job performance.							
Collaborating with the robot would increase my productivity.							
Collaborating with the robot would make it easier to do my job.							
I would find the collaboration with the robot useful in my job.							

Presence and Immersion

Table **A-35**.: The item to determine the presence derived from the Presence and Immersion Questionnaire by Witmer and Singer [164]. Questions that had no priority for the experimental study, i.e. locomotion aspects, were removed to reduce the length of the questionnaire, thus optimizing participants' responsiveness [165].

How do you perceived the virtual environment?							
(1 = Not at all; 4 = Somewhat; 7 = Completely)	**1**	**2**	**3**	**4**	**5**	**6**	**7**
How much were you able to control events?							
How responsive was the environment to actions that you initiated (or performed)?							
How natural did your interactions with the environment seem?							
How much did the visual aspects of the environment involve you?							
How compelling was your sense of objects moving through space?							
How much did your experiences in the virtual environment seem consistent with your real-world experiences?							
How completely were you able to actively survey or search the environment using vision?							
How involved were you in the virtual environment experience?							
How much delay did you experience between your actions and expected outcomes?							
How quickly did you adjust to the virtual environment experience?							
How proficient in moving and interacting with the virtual environment did you feel at the end of the experience?							
How much did the visual display quality interfere or distract you from performing assigned tasks or required activities?							
How much did the control devices interfere with the performance of assigned tasks or with other activities?							
How well could you concentrate on the assigned tasks or required activities rather than on the mechanisms used to perform those tasks or activities?							

Simulator Sickness

Table **A-36**.: Negative physical effects induced by the VR experience were gathered through the Simulator Sickness Scale by Kennedy et al. [166].

.

How much is each symptom below is affecting you right now?				
(1 = None; 2 = Slight; 3 = Moderate; 4 = Severe)	**1**	**2**	**3**	**4**
General discomfort.				
Fatigue.				
Headache.				
Eye strain.				
Difficulty focusing.				
Salivation increasing.				
Sweating.				
Nausea.				
Difficulty concentrating.				
Blurred vision.				
Dizziness with eyes open.				
Dizziness with eyes closed.				
Burping				

Debriefing

Dear participants!

Thank you very much *for participating in our study. Through your support, you have helped us greatly.*

All students at the University of Applied Sciences Ruhr West can receive credit for 45 research project minutes. To do so, please come to my office (Bottrop campus) (with your participation code) to fill out the receipt and participation list: 04.003.

Your task was to perform an assembly task together with a virtual robot and to answer various questions and evaluate statements in this context. The goal of our investigation is to find out how future human-machine collaboration scenarios have to be designed for optimal collaboration.

B. Questionnaire 2 (English Version)

This Appendix B presents the questionnaire that was used in the online study described in Chapter 5. As with Appendix A, the original questionnaire was formulated in German and distributed to the participants via the SoSciSurvey online platform [155]. Again, the formatting shown here is not identical to the original questionnaire layout and was edited to fit the style of this dissertation.

Introduction

Welcome!

Dear participants,

in the context of this study at the ***Institute of Computer Science at the University of Applied Sciences Ruhr West****, we are investigating the interaction of humans with robots. In total, participation will take about* ***20 minutes****. Since you will see a* ***video with sound****, please make sure you are in an environment where you can watch the video and play the sound.*

In the questionnaire, you will be shown a series of statements and questions. These are about your ***personal opinion****. Therefore, there are no "right" or "wrong" answers. Please do not think too long about a statement, but make a choice as* ***spontaneously*** *as possible.*

Participation in the study is voluntary. You can terminate your participation at any time without giving any reason and without any disadvantages. The collected data and personal communications described above will be treated confidentially. Furthermore, the publication of the results will be in an anonymous form, i.e. without your data being able to be assigned to your person.

The collection of the data described above will take place without asking for your name. Your answers and results will be stored under a ***personal code word****, which you will create yourself on the basis of a rule at the beginning of the study and which nobody but you will know. This means that it is not possible for anyone to associate your data with your name. After completion of the data collection,* ***but at the latest on 30.11.2020, your code will be***

deleted. *Your data will then be anonymized. However, as long as the code exists, you can request the deletion of the data collected from you. To do this, you do not have to tell us your name, but only your code word. You will receive instructions for creating your code word. Please keep the code word carefully so that you can request the deletion of your data later if necessary. The anonymized data will be stored for at least 10 years.*

According to the General Data Protection Regulation (DS-GVO), you have the following rights:

- *Information about processing of personal data (Art 15).*
- *Revocation of the consent given (Art 7)*
- *Correction (Art 16)*
- *Deletion (Art 17)*
- *Restriction of the processing (Art 18)*

The retention period for the anonymized data The retention period for the fully anonymized data is at least 10 years after data evaluation or at least 10 years after the appearance of a publication on this study.

Students of the University of Applied Sciences Ruhr West can acquire ***30 research project minutes*** *for participating in the study.*

If you agree with everything and are ready, please click ***"Continue"***.

Participation Code

So that we can later relate your anonymized data from both parts of the experiment, we ask you to create an individualized subject identifier - the so-called parent code.

The parent code is composed of:

1. *The last letter of your birthplace (e.g.* ***N*** *for BERLI**N**)*
2. *The second and last number of your date of birth (e.g. 77 for 0**7**.08.199**7**)*
3. *The first letter of your birth month (e.g.* ***A*** *for* ***A****UGUST)*
4. *The first letter of your eye color (e.g.* ***G*** *for* ***G****RAY)*

This results in the following example code: ***N77AG***

Table **B-1**.: The participation code that matched the participants' answers from their pre-questionnaire to the respective answers from the post-questionnaire was adopted from questionnaires conducted in previous research projects [17], [112].

Your participation code

Prior Experience with Robots

First, we ask you to answer the following questions truthfully. This is not about right or wrong answers, but about your very personal experiences.

Table **B-2**.: The self-created items for prior interactions with robots lifted from a adjacent research project [75].

How often have you interacted with the following robots?						
(1 = Never; 2 = Rarely; 3 = Sometimes; 4 = Regularly; 5 = Very often; 6 = I don't know what that is)	**1**	**2**	**3**	**4**	**5**	**6**
Household robots (e.g. vacuum cleaner robots, lawn mowing robots)						
Toy robots (e.g. Cozmo, Dash&Dot, Sphero)						
Pepper						
NAO						
Industrial robots (e.g. Kuka robot arm)						
Service robots (e.g. in hardware stores)						

Negative Attitude towards Robots

Table **B-3**.: The Negative Attitudes Toward Situations of Interaction With Robots sub-scale from the Negative Attitudes Towards Robots Scale by Nomura et al. [158].

How do you feel about the following statements about robots?							
(1 = Do not agree at all; 7 = Fully agree)	**1**	**2**	**3**	**4**	**5**	**6**	**7**
I would feel uneasy if I was given a job where I had to use robots.							
The word ”robot” means nothing to me.							
I would feel nervous operating a robot in front of other people.							
I would hate the idea that robots or artificial intelligences were making judgments about things.							
I would feel very nervous just standing in front of a robot.							

Table **B-4**.: The Negative Attitudes Toward the Social Influence of Robots sub-scale from the Negative Attitudes Towards Robots Scale by Nomura et al. [158].

How do you feel about the following statements about robots?							
(1 = Do not agree at all; 7 = Fully agree)	**1**	**2**	**3**	**4**	**5**	**6**	**7**
I would feel uneasy if robots really had emotions.							
Something bad might happen if robots developed into living beings.							
I feel that if I depend on robots too much, something bad might happen.							
I am concerned that robots would be a bad influence on children							
I feel that in the future society will be dominated by robots.							

Table **B-5**.: The Negative Attitudes Toward Emotions in Interaction With Robots sub-scale from the Negative Attitudes Towards Robots Scale by Nomura et al. [158].

How do you feel about the following statements about robots?							
(1 = Do not agree at all; 7 = Fully agree)	**1**	**2**	**3**	**4**	**5**	**6**	**7**
I would feel relaxed if I talked to robots.							
If robots had emotions, I could befriend them.							
I feel comforted to be with robots that have emotions.							

Video Briefing AI Robot - Randomized Assignment

In the following video, you will see an interaction in a virtual reality environment.

*It shows how a **human** and a **robot arm** equipped with **artificial intelligence** assemble a button together. The task consists of individual steps performed either by the robot arm equipped with artificial intelligence or by the human. The button can only be successfully assembled in collaboration.*

Please watch the video carefully and put yourself in the human's position. Please imagine that you are interacting with the robot arm and assembling the button together.

Video Briefing Non-AI Robot - Randomized Assignment

In the following video you will see an interaction in a virtual reality environment.

*It shows how a **human** and a **robot arm** assemble a button together. The task consists of individual steps that are performed either by the robot arm or by the human. The button can only be successfully assembled by working together.*

Please watch the video carefully and put yourself in the position of the human. Please imagine that you are interacting with the robot arm and assembling the button together.

After watching the video, we ask you to answer the following questions. Remember to keep imagining that you are in the role of the person from the video shown.

Table **B-6**.: The measures for blame and credit in the context of HRC adopted from the Attribution of Blame and Credit Scale by Kim & Hinds [148].

Please rate how much you agree or disagree with the statements below about the interaction shown in the video.					
(1 = Totally disagree; 5 = Fully agree)	**1**	**2**	**3**	**4**	**5**
The robot was responsible for any errors that were made in the task.					
The robot was to blame for most of the problems that were encountered in accomplishing this task.					
Success on this task was largely due to the things the robot did.					
The robot should get credit for most of what was accomplished on this task.					
I was responsible for any errors that were made in this task.					
I was to blame for most of the problems that were encountered in accomplishing this task.					
The success on this task was largely due to the things I did.					
I should get credit for most of what was accomplished on this task.					

Robot Assessment

Please rate your current impression of the robot using the following rating scale:

Table **B-7**.: The assessment of the robot was composed of the Anthropomorphism Animacy, Likeability, and Perceived Intelligence sub-scales adopted from the Godspeed scales developed by Bartneck et al. [167].

What do you think of the robot shown in the video?						
	1	**2**	**3**	**4**	**5**	
Fake						Natural
Machinelike						Humanlike
Unconscious						Conscious
Artificial						Lifelike
Moving rigidly						Moving elegant
Dead						Alive
Stagnant						Lively
Mechanical						Natural
Fake						Organic
Inert						Interactive
Apathetic						Responsive
Dislike						Like
Unfriendly						Friendly
Unkind						Kind
Unpleasant						Pleasant
Awful						Nice
Incompetent						Competent
Ignorant						Knowledgeable
Irresponsible						Responsible
Unintelligent						Intelligent
Foolish						Sensible
Uncooperative						Cooperative
Submissive						Dominant
Untrustworthy						Trustworthy
Eerie						Pleasant

Rating of the Collaboration

Table **B-8**.: The assessment of the collaboration was measured through a self-created scale that oriented itself on the Godspeed questionnaire series created by Bartneck et al. [167].

How would you rate the collaboration between you and the robot?						
	1	**2**	**3**	**4**	**5**	
Successful						Unsuccessful
Error-free						Faulty
Harmonious						Inharmonious
Satisfactory						Unsatisfactory
Tuned						Uncoordinated
Swift						Slow
Dynamic						Static

Robot Embodiment

What do you think about the robot shown? Indicate how much you agree with the statements.

Table **B-9**.: The items for the Embodiment of the robot were adapted from the EmpCorp Scale developed by Hoffmann et al. [168].

The robotic system shown ...					
(1 = Totally disagree; 5 = Fully agree)	**1**	**2**	**3**	**4**	**5**
...is able to recognize emotion.					
...is unrestricted in its movements.					
...is able to understand my behavior.					
...is able to carry objects.					
...is able to react to the same environmental stimuli as I do.					
...is able to immediately react to my actions.					
...is able to move in space.					
...is able to perform designated actions like brewing coffee or vacuuming.					
...is physically embodied.					
...is able to touch objects.					
...is unrestricted in its gestures.					
...is able to interpret (my) behaviors.					
...is able to move towards me.					
...is existent in the real world.					
...is able to autonomously navigate in space.					
...is able to perceive what I perceive.					
...is unrestricted in its actions.					
...is able to perceive what I perceive.					
...is real.					
...is unrestricted in its facial expression.					

Morality of the Robot

Table **B-10**.: The items for the Morality of the robot were adapted from the Perceived Moral Agency Scale created by Banks [169].

To what extent do the following statements apply to the robot shown in the video?					
(1 = Totally disagree; 5 = Fully agree)	**1**	**2**	**3**	**4**	**5**
This robot has a sense for what is right and wrong.					
This robot can think through whether an action is moral.					
This robot might feel obligated to behave in a moral way.					
This robot is capable of being rational about good and evil.					
This robot behaves according to moral rules.					
This robot would refrain from doing this that have painful repercussions.					

Dependency of the Robot

Table **B-11**.: The items for the Dependency of the robot were also adapted from the Perceived Moral Agency Scale created by Banks [169].

To what extent do the following statements apply to the robot shown in the video?					
(1 = Totally disagree; 5 = Fully agree)	**1**	**2**	**3**	**4**	**5**
This robot can only behave how it is programmed to behave.					
This robot's actions are the result of its programming.					
This robot can only do what humans tell it to do.					
This robot would never do anything it was not programmed to do.					

Robot Components - Communication Condition

Which of the components shown here are part of the robot?

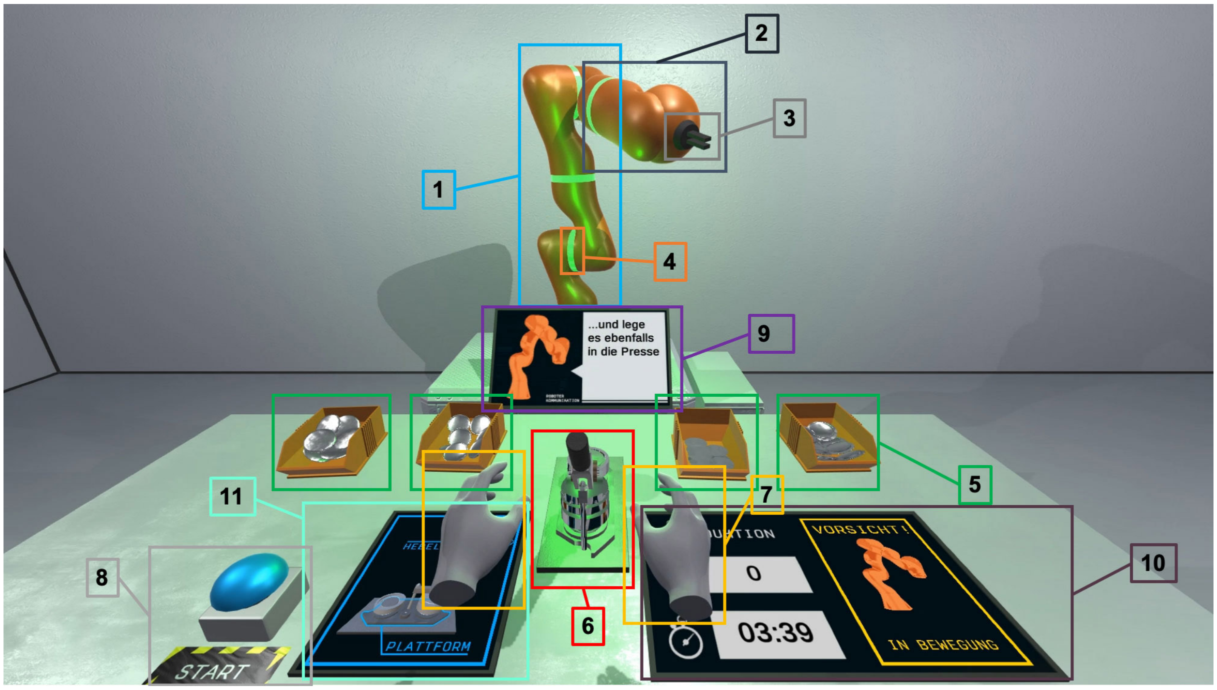

Figure **B-1**.: The collaboration setup from the communication condition.

Table **B-12**.: The respective components from the communication setup that the participants assigned to the robot were entered here.

This component is part of the robot...		
Component Number	**Yes**	**No**
1		
2		
3		
4		
5		
6		
7		
8		
9		
10		
11		

Robot Components - Non-Communication Condition

Which of the components shown here are part of the robot?

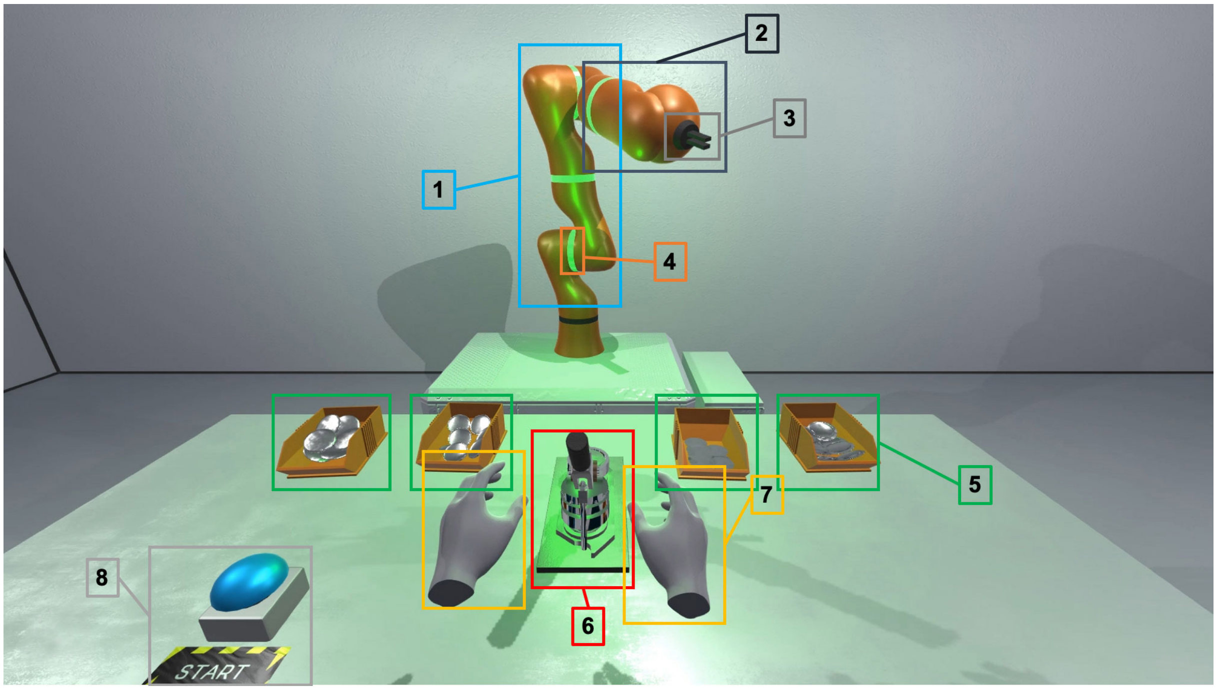

Figure **B-2**.: The collaboration setup from the non-communication condition.

Table **B-13**.: The respective components from the non-communication setup that the participants assigned to the robot were entered here.

This component is part of the robot...		
Component Number	**Yes**	**No**
1		
2		
3		
4		
5		
6		
7		
8		

Socio-Demographics

Finally, we have a few questions about yourself.

Table **B-14**.: The items determining the participants' gender were adopted from prior experimental research projects [17], [112].

What is your gender?	
	Male
	Female
	Diverse

Table **B-15**.: The item asking for the age of the participants' was lifted from preceding experimental research projects [17], [112].

How old are you?		
I am		years old.

What professional education do you have?

Table **B-16**.: The items, which determined the participants' vocational qualification were taken from prior experimental studies [17], [112].

Please select the highest educational qualification you have achieved so far

	No vocational training qualification
	Vocational training period with final certificate, but no apprenticeship
	Partial skilled worker qualification
	Completed industrial or agricultural apprenticeship
	Completed commercial apprenticeship
	Professional internship, traineeship
	Vocational school diploma
	Technical school diploma
	Master craftsman, technician or equivalent technical college degree
	University of applied sciences degree
	University degree
	Other degree, namely:

Table **B-17**.: The items used to ask for the participants' profession were taken from previous experimental studies [17], [112].

What do you do for a living?

	Pupil
	In training
	Student
	Salaried employee
	Civil servant
	Self-employed
	Unemployed/looking for work
	Other:

Table **B-18**.: The self-created items to ask for prior exposure of the participants with robots and artificial intelligence.

How much do you agree with the following statements?					
(1 = Totally disagree; 5 = Fully agree)	**1**	**2**	**3**	**4**	**5**
I am working intensively on the topic of industrial robots.					
I deal intensively with the topic of artificial intelligence.					
In my everyday life (professional/private), I deal a lot with topics related to industrial robots.					
In my everyday life (professional/private), I deal a lot with topics related to artificial intelligence.					

Additional Comments

Is there anything else you would like to say about this survey or to help you understand your answers?

Did you notice anything negative during your participation in this survey? Were the questions not clear at any point or did you feel uncomfortable answering them? Please briefly write a few keywords about this.

Table **B-19**.: Free form text-field for the participants to comment further remarks regarding the study.

Your comments

C. Qualitative Interview Questions (English Version)

This Appendix C lists the guiding questions that were used in the qualitative interviews described in chapter 2. Due to the nature of qualitative interviews, the experimenter has to respond to maintain the flow of the conversation. For this purpose, the guiding questions were formulated originally in German to structure the qualitative interview and allow for the comparability between the respective interviews based on the guidelines by Helfferich [170].

Introduction

My name is Alexander Arntz. As part of my Ph.D. thesis, I am investigating Human-Robot Collaboration scenarios that are using AI-enhanced robots. The interview consists of about 7 questions. Your statements will be recorded and then transcribed for analysis - but anonymized for further processing for publication in the form of a scientific paper. However, you can stop the interview at any time without any disadvantages.

Questions

1. How did you feel about the collaboration with the robot?

2. What expectations do you generally have of a collaboration partner?

3. Please describe how the robot communicated with you.

4. What additional forms of communication would you like to see if you had to collaborate with the robot?

5. What aspects of the robot did you find pleasant/unpleasant?

6. What characteristics should the robot have to evoke your perception of it as an intelligent system?

7. How stressful did you find working with the robot?

Auxiliary Questions

Additional guided questions to induce further responses from the participants and adapt to the flow of the conversation [170].

A. What was your impression of the (movement/behavior/speed/reaction/precision/adaption) of the robot?

B. What was your impression of the (text-panel/gestures) of the robot?

C. What characteristics would you attribute to the robot?

D. What forms of communication did you perceive from the robot?

Bibliography

[1] O. Bendel, "Die Maschine an Meiner Seite," in *Mensch-Roboter-Kollaboration*, H.-J. Buxbaum, Ed. Wiesbaden: Springer Fachmedien Wiesbaden, 2020, pp. 1–14.

[2] K. Goldberg, "Robots and the Return to Collaborative Intelligence," *Nature Machine Intelligence*, vol. 1, no. 1, pp. 2–4, 2019.

[3] R. Laurel D., "The Social Co-Robotics Problem Space: Six Key Challenges," 2014, pp. 13–17. [Online]. Available: http://arxiv.org/pdf/1402.3213v1

[4] A. Hentout, M. Aouache, A. Maoudj, and I. Akli, "Human–Robot Interaction in Industrial Collaborative Robotics: A Literature Review of the Decade 2008–2017," *Advanced Robotics*, vol. 33, no. 15-16, pp. 764–799, 2019.

[5] A. Isma and B. Brahim, "Time-Dependant Trajectory Generation for Tele-Operated Mobile Manipulator," in *2015 3rd International Conference on Control, Engineering & Information Technology (CEIT)*. IEEE, 2015, pp. 1–5.

[6] P. J. Koch, M. K. van Amstel, P. Debska, M. A. Thormann, A. J. Tetzlaff, S. Bøgh, and D. Chrysostomou, "A Skill-Based Robot Co-Worker for Industrial Maintenance Tasks," *Procedia Manufacturing*, vol. 11, pp. 83–90, 2017.

[7] B. Scassellati and B. Hayes, "Human-Robot Collaboration," *AI Matters*, vol. 1, no. 2, pp. 22–23, 2014.

[8] K. Wöllhaf, "Mensch-Roboter-Kollaboration – Wichtiges Zukunftsthema oder nur ein Hype?" in *Mensch-Roboter-Kollaboration*, H.-J. Buxbaum, Ed. Wiesbaden: Springer Fachmedien Wiesbaden, 2020, pp. 109–115.

[9] A. Vysocky and P. Novak, "Human–Robot Collaboration in Industry," *MM Science Journal*, vol. 2016, no. 02, pp. 903–906, 2016.

[10] F. Steinmetz and R. Weitschat, "Skill Parametrization Approaches and Skill Architecture for Human-Robot Interaction," in *2016 IEEE International Conference on Automation Science and Engineering (CASE)*. IEEE, 2016, pp. 280–285.

[11] C. Lenz and A. Knoll, "Mechanisms and Capabilities for Human Robot Collaboration," in *The 23rd IEEE International Symposium on Robot and Human Interactive Communication*. IEEE, 2014, pp. 666–671.

[12] M. El-Shamouty, X. Wu, S. Yang, M. Albus, and M. F. Huber, "Towards Safe Human-Robot Collaboration Using Deep Reinforcement Learning," in *2020 IEEE International Conference on Robotics and Automation (ICRA).* IEEE, 2020, pp. 4899–4905.

[13] K. Zakka, A. Zeng, J. Lee, and S. Song, "Form2Fit: Learning Shape Priors for Generalizable Assembly from Disassembly." [Online]. Available: http://arxiv.org/pdf/1910.13675v1

[14] G. Sóti, I. Mamaev, and B. Hein, "A Modular Deep Learning Architecture for Anomaly Detection in HRI," in *Interactive Collaborative Robotics*, ser. Lecture Notes in Computer Science, A. Ronzhin, G. Rigoll, and R. Meshcheryakov, Eds. Cham: Springer International Publishing, 2020, vol. 12336, pp. 295–307.

[15] Linda Onnasch, Xenia Maier, and Thomas Jürgensohn, "Mensch-Roboter-Interaktion - Eine Taxonomie für alle Anwendungsfälle."

[16] H.-J. Buxbaum and R. Häusler, "Ladenburger Thesen zur Zukünftigen Gestaltung der Mensch-Roboter-Kollaboration," in *Mensch-Roboter-Kollaboration*, H.-J. Buxbaum, Ed. Wiesbaden: Springer Fachmedien Wiesbaden, 2020, pp. 293–317.

[17] A. Arntz, S. Eimler, U. Handmann, and D. Keßler, *Teaching Practical Tasks with Virtual Reality and Augmented Reality: An Experimental Study Comparing Learning Outcomes*, F. Keusch, B. Struminskaya, O. Hellwig, C. Stützer, M. T. Thielsch, and A. Wachenfeld-Schell, Eds. Hürth: Deutsche Gesellschaft für Online-Forschung (DGOF) e.V, 2019. [Online]. Available: https://www.gor.de/wp-content/uploads/2019/03/GOR19_digital_conference_proceedings.pdf

[18] A. Arntz, D. Kessler, and S. C. Eimler, "Enlighten: A Photovoltaics Learning Environment in Virtual Reality," in *2021 International Conference on Advanced Learning Technologies (ICALT).* IEEE, 2021, pp. 221–223.

[19] D. Kesler, A. Arntz, J. Friedhoff, and S. C. Eimler, "Mill Instructor: Teaching Industrial CNC Procedures Using Virtual Reality," in *2020 IEEE International Conference on Artificial Intelligence and Virtual Reality (AIVR).* IEEE, 2020, pp. 231–234.

[20] J. Schmidtler, V. Knott, C. Hölzel, and K. Bengler, "Human Centered Assistance Applications for the Working Environment of the Future," *Occupational Ergonomics*, vol. 12, no. 3, pp. 83–95, 2015.

[21] H. C. Fang, S. K. Ong, and A. Y. C. Nee, "A Novel Augmented Reality-Based Interface for Robot Path Planning," *International Journal on Interactive Design and Manufacturing (IJIDeM)*, vol. 8, no. 1, pp. 33–42, 2014.

[22] A. Bicchi, M. A. Peshkin, and J. E. Colgate, *Safety for Physical Human–Robot Interaction*. Berlin, Heidelberg: Springer Berlin Heidelberg, 2008, ch. 57, pp. 1335–1348. [Online]. Available: https://doi.org/10.1007/978-3-540-30301-5_58

[23] R. Schiavi, A. Bicchi, and F. Flacco, "Integration of Active and Passive Compliance Control for Safe Human-Robot Coexistence," in *2009 IEEE International Conference on Robotics and Automation*. IEEE, 2009, pp. 259–264.

[24] S. L. Müller-Abdelrazeq, S. Stiehm, M. Haberstroh, and F. Hees, "Perceived Effects of Cycle Time in Human-Robot-Interaction," in *2018 IEEE Workshop on Advanced Robotics and its Social Impacts (ARSO)*. IEEE, 2018, pp. 25–30.

[25] "DIN EN ISO 10218-1:2012-01, Industrieroboter - Sicherheitsanforderungen - Teil 1: Roboter (ISO_10218-1:2011); Deutsche Fassung EN_ISO_10218-1:2011," Berlin.

[26] "DIN ISO/TS 15066:2017-04, Roboter und Robotikgeräte-Kollaborierende Roboter (ISO/TS_15066:2016)," Berlin.

[27] D. Kirschner, R. Velik, S. Yahyanejad, M. Brandstötter, and M. Hofbaur, "YuMi, Come and Play with Me! A Collaborative Robot for Piecing Together a Tangram Puzzle," in *Interactive Collaborative Robotics*, ser. Lecture Notes in Computer Science, A. Ronzhin, G. Rigoll, and R. Meshcheryakov, Eds. Cham: Springer International Publishing, 2016, vol. 9812, pp. 243–251.

[28] J. Roschelle and S. D. Teasley, "The Construction of Shared Knowledge in Collaborative Problem Solving," in *Computer Supported Collaborative Learning*, C. O'Malley, Ed. Berlin, Heidelberg: Springer Berlin Heidelberg, 1995, pp. 69–97.

[29] S. L. Müller-Abdelrazeq, K. Schönefeld, M. Haberstroh, and F. Hees, "Interacting with Collaborative Robots–A Study on Attitudes and Acceptance in Industrial Contexts," in *Social Robots: Technological, Societal and Ethical Aspects of Human-Robot Interaction*, ser. Human–Computer Interaction Series, O. Korn, Ed. Cham: Springer International Publishing, 2019, vol. 4, pp. 101–117.

[30] A. Mörtl, M. Lawitzky, A. Kucukyilmaz, M. Sezgin, C. Basdogan, and S. Hirche, "The Role of Roles: Physical Cooperation Between Humans and Robots," *The International Journal of Robotics Research*, vol. 31, no. 13, pp. 1656–1674, 2012.

[31] A. de Luca and F. Flacco, "Integrated Control for pHRI: Collision Avoidance, Detection, Reaction and Collaboration," in *2012 4th IEEE RAS & EMBS International Conference on Biomedical Robotics and Biomechatronics (BioRob)*. IEEE, 2012, pp. 288–295.

[32] A. Cherubini, R. Passama, A. Meline, A. Crosnier, and P. Fraisse, “Multimodal Control for Human-Robot Cooperation,” in *2013 IEEE/RSJ International Conference on Intelligent Robots and Systems.* IEEE, 2013, pp. 2202–2207.

[33] M. Indri, S. Trapani, and I. Lazzero, “Development of a Virtual Collision Sensor for Industrial Robots,” *Sensors (Basel, Switzerland)*, vol. 17, no. 5, 2017.

[34] M. Peshkin and J. Colgate, “Cobots,” *Industrial Robot: An International Journal*, vol. 26, no. 5, pp. 335–341, 1999.

[35] F. Ferland, A. Reveleau, F. Leconte, D. Létourneau, and F. Michaud, “Coordination Mechanism for Integrated Design of Human-Robot Interaction Scenarios,” *Paladyn, Journal of Behavioral Robotics*, vol. 8, no. 1, pp. 100–111, 2017.

[36] H. Bo, D. Menoth Mohan, M. Azhar, K. Sreekanth, and D. Campolo, “Human-Robot Collaboration for Tooling Path Guidance,” in *2016 6th IEEE International Conference on Biomedical Robotics and Biomechatronics (BioRob).* IEEE, 2016, pp. 1340–1345.

[37] H.-J. Buxbaum, S. Sen, and R. Häusler, “Theses on the Future Design of Human-Robot Collaboration,” in *Human-Computer Interaction. Multimodal and Natural Interaction*, ser. Lecture Notes in Computer Science, M. Kurosu, Ed. Cham: Springer International Publishing, 2020, vol. 12182, pp. 560–579.

[38] F. Courreges, M. A. Laribi, M. Arsicault, and S. Zeghloul, “Designing a Biomimetic Model of Non-Linear Elastic Safety Mechanism for Collaborative Robots,” in *2016 IEEE 14th International Conference on Industrial Informatics (INDIN).* IEEE, 2016, pp. 231–236.

[39] M. Vasic and A. Billard, “Safety Issues in Human-Robot Interactions,” in *2013 IEEE International Conference on Robotics and Automation.* IEEE, 2013, pp. 197–204.

[40] R. Meziane, M. J.-D. Otis, and H. Ezzaidi, “Human-Robot Collaboration While Sharing Production Activities in Dynamic Environment: SPADER System,” *Robotics and Computer-Integrated Manufacturing*, vol. 48, pp. 243–253, 2017.

[41] A. D. Santis, B. Siciliano, and N. Federico, “Safety Issues for Human-Robot Cooperation in Manufacturing Ssystems,” 2008.

[42] A. Bicchi, M. Bavaro, G. Boccadamo, D. de Carli, R. Filippini, G. Grioli, M. Piccigallo, A. Rosi, R. Schiavi, S. Sen, and G. Tonietti, “Physical Human-Robot Interaction: Dependability, Safety, and Performance,” in *2008 10th IEEE International Workshop on Advanced Motion Control.* IEEE, 2008, pp. 9–14.

[43] Y. Ayoubi, M. A. Laribi, F. Courreges, S. Zeghloul, and M. Arsicault, "A Complete Methodology to Design a Safety Mechanism for Prismatic Joint Implementation," in *2016 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*. IEEE, 2016, pp. 304–309.

[44] A. Pervez and J. Ryu, "Safe Physical Human Robot Interaction-Past, Present and Future," *Journal of Mechanical Science and Technology*, vol. 22, no. 3, pp. 469–483, 2008.

[45] S. Veselic, C. Zito, and D. Farina, *Human-Robot Interaction with Robust Prediction of Movement Intention Surpasses Manual Control*, 2020.

[46] F. Flacco, T. Kroger, A. de Luca, and O. Khatib, "A Depth Space Approach to Human-Robot Collision Avoidance," in *2012 IEEE International Conference on Robotics and Automation*. IEEE, 2012, pp. 338–345.

[47] N. Nikolakis, V. Maratos, and S. Makris, "A Cyber Physical System (CPS) Approach for Safe Human-Robot Collaboration in a Shared Workplace," *Robotics and Computer-Integrated Manufacturing*, vol. 56, pp. 233–243, 2019.

[48] R. E. Mohan, W. S. Wijesoma, C. A. Acosta Calderon, and C. Zhou, "False Alarm Metrics for Human–Robot Interactions in Service Robots," *Advanced Robotics*, vol. 24, no. 13, pp. 1841–1859, 2010.

[49] P. A. Lasota and J. A. Shah, "Analyzing the Effects of Human-Aware Motion Planning on Close-Proximity Human-Robot Collaboration," *Human factors*, vol. 57, no. 1, pp. 21–33, 2015.

[50] R. Galin and R. Meshcheryakov, "Review on Human–Robot Interaction During Collaboration in a Shared Workspace," in *Interactive Collaborative Robotics*, ser. Lecture Notes in Computer Science, A. Ronzhin, G. Rigoll, and R. Meshcheryakov, Eds. Cham: Springer International Publishing, 2019, vol. 11659, pp. 63–74.

[51] S. Robla-Gomez, V. M. Becerra, J. R. Llata, E. Gonzalez-Sarabia, C. Torre-Ferrero, and J. Perez-Oria, "Working Together: A Review on Safe Human-Robot Collaboration in Industrial Environments," *IEEE Access*, vol. 5, pp. 26 754–26 773, 2017.

[52] D. Massa, M. Callegari, and C. Cristalli, "Manual Guidance for Industrial Robot Programming," *Industrial Robot: An International Journal*, vol. 42, no. 5, pp. 457–465, 2015.

[53] N. Rußwinkel, "Antizipierende Interaktiv Lernende Autonome Agenten," in *Mensch-Roboter-Kollaboration*, H.-J. Buxbaum, Ed. Wiesbaden: Springer Fachmedien Wiesbaden, 2020, pp. 193–207.

[54] R. Galin, R. Meshcheryakov, and S. Kamesheva, “Distributing Tasks in Multi-Agent Robotic System for Human-Robot Interaction Applications,” in *Interactive Collaborative Robotics*, ser. Lecture Notes in Computer Science, A. Ronzhin, G. Rigoll, and R. Meshcheryakov, Eds. Cham: Springer International Publishing, 2020, vol. 12336, pp. 99–106.

[55] S. Zabihifar and A. Yuschenko, “Hybrid Force/Position Control of a Collaborative Parallel Robot Using Adaptive Neural Network,” in *Interactive Collaborative Robotics*, ser. Lecture Notes in Computer Science, A. Ronzhin, G. Rigoll, and R. Meshcheryakov, Eds. Cham: Springer International Publishing, 2018, vol. 11097, pp. 280–290.

[56] D. Wang, Q. Yang, A. Abdul, and B. Y. Lim, “Designing Theory-Driven User-Centric Explainable AI,” in *CHI 2019*, S. Brewster, G. Fitzpatrick, A. Cox, V. Kostakos, and A. L. Cox, Eds. New York, New York: The Association for Computing Machinery, 2019, pp. 1–15.

[57] M. Ragaglia, A. M. Zanchettin, and P. Rocco, “Trajectory Generation Algorithm for Safe Human-Robot Collaboration based on Multiple Depth Sensor Measurements,” *Mechatronics*, vol. 55, pp. 267–281, 2018.

[58] E. Aitygulov, G. Kiselev, and A. I. Panov, “Task and Spatial Planning by the Cognitive Agent with Human-Like Knowledge Representation,” in *Interactive Collaborative Robotics*, ser. Lecture Notes in Computer Science, A. Ronzhin, G. Rigoll, and R. Meshcheryakov, Eds. Cham: Springer International Publishing, 2018, vol. 11097, pp. 1–12.

[59] A. Sauppé and B. Mutlu, “The Social Impact of a Robot Co-Worker in Industrial Settings,” in *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems*, B. Begole, J. Kim, K. Inkpen, and W. Woo, Eds. New York, NY, USA: ACM, 2015, pp. 3613–3622.

[60] J. Bütepage and D. Kragic, “Human-Robot Collaboration: From Psychology to Social Robotics.” [Online]. Available: http://arxiv.org/pdf/1705.10146v1

[61] J. Mumm and B. Mutlu, “Human-Robot Proxemics,” in *Proceedings of the 6th international conference on Human-robot interaction - HRI ’11*, A. Billard, P. Kahn, J. A. Adams, and G. Trafton, Eds. New York, New York, USA: ACM Press, 2011, p. 331.

[62] O. Ogorodnikova, “Human Weaknesses and Strengths in Collaboration with Robots,” *Periodica Polytechnica Mechanical Engineering*, vol. 52, no. 1, p. 25, 2008.

[63] S. Glasauer, M. Huber, P. Basili, A. Knoll, and T. Brandt, “Interacting in Time and Space: Investigating Human-Human and Human-Robot Joint Action,” in *19th*

International Symposium in Robot and Human Interactive Communication. IEEE, 2010, pp. 252–257.

[64] G. Charalambous, S. Fletcher, and P. Webb, "Development of a Human Factors Roadmap for the Successful Implementation of Industrial Human-Robot Collaboration," in *Advances in Ergonomics of Manufacturing: Managing the Enterprise of the Future*, ser. Advances in Intelligent Systems and Computing, C. Schlick and S. Trzcieliński, Eds. Cham: Springer International Publishing, 2016, vol. 490, pp. 195–206.

[65] ——, "Identifying the Key Organisational Human Factors for Introducing Human-Robot Collaboration in Industry: an Exploratory Study," *The International Journal of Advanced Manufacturing Technology*, vol. 81, no. 9-12, pp. 2143–2155, 2015.

[66] C. Bröhl, J. Nelles, C. Brandl, A. Mertens, and V. Nitsch, "Human–Robot Collaboration Acceptance Model: Development and Comparison for Germany, Japan, China and the USA," *International Journal of Social Robotics*, vol. 11, no. 5, pp. 709–726, 2019.

[67] S. Augustsson, J. Olsson, L. G. Christiernin, and G. Bolmsjö, "How to Transfer Information Between Collaborating Human Operators and Industrial Robots in an Assembly," in *Proceedings of the 8th Nordic Conference on Human-Computer Interaction: Fun, Fast, Foundational*, V. Roto, J. Häkkilä, K. Väänänen-Vainio-Mattila, O. Juhlin, T. Olsson, and E. Hvannberg, Eds. New York, NY, USA: ACM, 2014, pp. 286–294.

[68] P. Barattini, C. Morand, and N. M. Robertson, "A Proposed Gesture set for the Control of Industrial Collaborative Robots," in *2012 IEEE RO-MAN: The 21st IEEE International Symposium on Robot and Human Interactive Communication.* IEEE, 2012, pp. 132–137.

[69] I. Maurtua, I. Fernández, A. Tellaeche, J. Kildal, L. Susperregi, A. Ibarguren, and B. Sierra, "Natural Multimodal Communication for Human–Robot Collaboration," *International Journal of Advanced Robotic Systems*, vol. 14, no. 4, p. 172988141771604, 2017.

[70] T. Kaupp, A. Makarenko, and H. Durrant-Whyte, "Human–Robot Communication for Collaborative Decision Making — A Probabilistic Approach," *Robotics and Autonomous Systems*, vol. 58, no. 5, pp. 444–456, 2010.

[71] A. L. Guzman, Ed., *Human-Machine Communication: Rethinking Communication, Technology and Ourselves*, ser. Digital formations. New York and Bern and Berlin: Peter Lang, 2018, vol. vol. 117.

[72] E. Bauzano, B. Estebanez, I. Garcia-Morales, and V. F. Munoz, "Collaborative Human–Robot System for HALS Suture Procedures," *IEEE Systems Journal*, vol. 10, no. 3, pp. 957–966, 2016.

[73] S. Nikolaidis, M. Kwon, J. Forlizzi, and S. Srinivasa, "Planning with Verbal Communication for Human-Robot Collaboration," *ACM Transactions on Human-Robot Interaction*, vol. 7, no. 3, pp. 1–21, 2018.

[74] M. Chen, S. Nikolaidis, H. Soh, D. Hsu, and S. Srinivasa, "Planning with Trust for Human-Robot Collaboration," in *Proceedings of the 2018 ACM/IEEE International Conference on Human-Robot Interaction*, T. Kanda, S. Ŝabanović, G. Hoffman, and A. Tapus, Eds. New York, NY, USA: ACM, 2018, pp. 307–315.

[75] C. Straßmann, A. Grewe, C. Kowalczyk, A. Arntz, and S. C. Eimler, "Moral Robots? How Uncertainty and Presence Affect Humans' Moral Decision Making," in *HCI International 2020 - Posters*, ser. Communications in Computer and Information Science, C. Stephanidis and M. Antona, Eds. Cham: Springer International Publishing, 2020, vol. 1224, pp. 488–495.

[76] C. Straßmann, S. C. Eimler, A. Arntz, A. Grewe, C. Kowalczyk, and S. Sommer, "Receiving Robot's Advice: Does it Matter When and for What?" in *Social Robotics*, ser. Lecture Notes in Computer Science, A. R. Wagner, D. Feil-Seifer, K. S. Haring, S. Rossi, T. Williams, H. He, and S. Sam Ge, Eds. Cham: Springer International Publishing, 2020, vol. 12483, pp. 271–283.

[77] S. A. Elprama, C. I. Jewell, A. Jacobs, I. El Makrini, and B. Vanderborght, "Attitudes of Factory Workers Towards Industrial and Collaborative Robots," in *Proceedings of the Companion of the 2017 ACM/IEEE International Conference on Human-Robot Interaction*, B. Mutlu, M. Tscheligi, A. Weiss, and J. E. Young, Eds. New York, NY, USA: ACM, 2017, pp. 113–114.

[78] H. Admoni, T. Weng, B. Hayes, and B. Scassellati, "Robot Nonverbal Behavior Improves Task Performance in Difficult Collaborations," in *2016 11th ACM/IEEE International Conference on Human-Robot Interaction (HRI)*. IEEE, 2016, pp. 51–58.

[79] P. Tsarouchi, S. Makris, and G. Chryssolouris, "Human–Robot Interaction Review and Challenges on Task Planning and Programming," *International Journal of Computer Integrated Manufacturing*, vol. 29, no. 8, pp. 916–931, 2016.

[80] S. Djezairi, I. Akli, R. B. Zamoum, and B. Bouzouia, "Mission Allocation and Execution for Human and Robot Agents in Industrial Environment," in *2018 27th IEEE International Symposium on Robot and Human Interactive Communication (RO-MAN)*. IEEE, 27.08.2018 - 31.08.2018, pp. 796–801.

[81] N. Jarrassé, V. Sanguineti, and E. Burdet, “Slaves no Longer: Review on Role Assignment for Human–Robot Joint Motor Action,” *Adaptive Behavior*, vol. 22, no. 1, pp. 70–82, 2014.

[82] A. Schepman and P. Rodway, “Initial Validation of the General Attitudes Towards Artificial Intelligence Scale,” *Computers in Human Behavior Reports*, vol. 1, p. 100014, 2020.

[83] J. Złotowski, D. Proudfoot, K. Yogeeswaran, and C. Bartneck, “Anthropomorphism: Opportunities and Challenges in Human–Robot Interaction,” *International Journal of Social Robotics*, vol. 7, no. 3, pp. 347–360, 2015.

[84] J. Jerald, *The VR Book: Human-Centered Design for Virtual Reality*, first edition ed., ser. ACM Books. New York, NY and San Rafael: Association for Computing Machinery and Morgan & Claypool Publishers, 2016, vol. 8. [Online]. Available: http://dl.acm.org/citation.cfm?id=2792790

[85] P. Smutny, M. Babiuch, and P. Foltynek, “A Review of the Virtual Reality Applications in Education and Training,” in *2019 20th International Carpathian Control Conference (ICCC)*. IEEE, 2019, pp. 1–4.

[86] J. Mazurek, P. Kiper, B. Cieślik, S. Rutkowski, K. Mehlich, A. Turolla, and J. Szczepańska-Gieracha, “Virtual Reality in Medicine: A Brief Overview and Future Research Directions,” *Human Movement*, vol. 20, no. 3, pp. 16–22, 2019.

[87] V. V. Kumar, D. Carberry, C. Beenfeldt, M. P. Andersson, S. S. Mansouri, and F. Gallucci, “Virtual Reality in Chemical and Biochemical Engineering Education and Training,” *Education for Chemical Engineers*, vol. 36, pp. 143–153, 2021.

[88] L. Gammieri, M. Schumann, L. Pelliccia, G. Di Gironimo, and P. Klimant, “Coupling of a Redundant Manipulator with a Virtual Reality Environment to Enhance Human-Robot Cooperation,” *Procedia CIRP*, vol. 62, pp. 618–623, 2017.

[89] C. Vogel, M. Fritzsche, and N. Elkmann, “Safe Human-Robot Cooperation with High-Payload Robots in Industrial Applications,” in *2016 11th ACM/IEEE International Conference on Human-Robot Interaction (HRI)*. IEEE, 2016, pp. 529–530.

[90] F. Hernoux, E. Nyiri, and O. Gibaru, “Virtual Reality for Improving Safety and Collaborative Control of Industrial Robots,” in *Proceedings of the 2015 Virtual Reality International Conference*. New York, NY, USA: ACM, 2015, pp. 1–6.

[91] J. Guhl, J. Hügle, and J. Krüger, “Enabling Human-Robot-Interaction via Virtual and Augmented Reality in Distributed Control Systems,” *Procedia CIRP*, vol. 76, pp. 167–170, 2018.

[92] E. Matsas and G.-C. Vosniakos, “Design of a Virtual Reality Training System for Human–Robot Collaboration in Manufacturing Tasks,” *International Journal on Interactive Design and Manufacturing (IJIDeM)*, vol. 11, no. 2, pp. 139–153, 2017.

[93] G. Di Gironimo, S. Patalano, and A. Tarallo, “Innovative Assembly Process for Modular Train and Feasibility Analysis in Virtual Environment,” *International Journal on Interactive Design and Manufacturing (IJIDeM)*, vol. 3, no. 2, pp. 93–101, 2009.

[94] A. de Giorgio, M. Romero, M. Onori, and L. Wang, “Human-Machine Collaboration in Virtual Reality for Adaptive Production Engineering,” *Procedia Manufacturing*, vol. 11, pp. 1279–1287, 2017.

[95] S. A. Green, J. G. Chase, X. Chen, and M. Billinghurst, “Evaluating the Augmented Reality Human-Robot Collaboration System,” *International Journal of Intelligent Systems Technologies and Applications*, vol. 8, no. 1/2/3/4, p. 130, 2010.

[96] Q. Wang, X. Fan, M. Luo, X. Yin, and W. Zhu, “Construction of Human-Robot Cooperation Assembly Simulation System Based on Augmented Reality,” in *Virtual, Augmented and Mixed Reality. Design and Interaction*, ser. Lecture Notes in Computer Science, J. Y. C. Chen and G. Fragomeni, Eds. Cham: Springer International Publishing, 2020, vol. 12190, pp. 629–642.

[97] J. Bailenson, *Experience on Demand: What Virtual Reality is, how it Works, and what it can do*, first edition ed. New York, NY and London: W.W. Norton & Company, 2018.

[98] A. van Loon, J. Bailenson, J. Zaki, J. Bostick, and R. Willer, “Virtual Reality Perspective-Taking Increases Cognitive Empathy for Specific Others,” *PloS one*, vol. 13, no. 8, p. e0202442, 2018.

[99] R. O. Roswell, C. D. Cogburn, J. Tocco, J. Martinez, C. Bangeranye, J. N. Bailenson, M. Wright, J. H. Mieres, and L. Smith, “Cultivating Empathy Through Virtual Reality: Advancing Conversations About Racism, Inequity, and Climate in Medicine,” *Academic medicine : journal of the Association of American Medical Colleges*, 2020.

[100] H. Gehlbach, G. Marietta, A. M. King, C. Karutz, J. N. Bailenson, and C. Dede, “Many Ways to Walk a Mile in Another’s Moccasins: Type of Social Perspective Taking and its Effect on Negotiation Outcomes,” *Computers in Human Behavior*, vol. 52, pp. 523–532, 2015.

[101] J. O. Bailey and J. N. Bailenson, “Immersive Virtual Reality and the Developing Child,” in *Cognitive Development in Digital Contexts*. Elsevier, 2017, pp. 181–200.

[102] N. Yee, J. N. Bailenson, and N. Ducheneaut, “The Proteus Effect,” *Communication Research*, vol. 36, no. 2, pp. 285–312, 2009.

[103] C. Straßmann, S. C. Eimler, A. Arntz, D. Keßler, S. Zielinski, G. Brandenberg, V. Dümpel, and U. Handmann, “Relax Yourself - Using Virtual Reality to Enhance Employees’ Mental Health and Work Performance,” in *Extended Abstracts of the 2019 CHI Conference on Human Factors in Computing Systems - CHI EA ’19*, S. Brewster, G. Fitzpatrick, A. Cox, and V. Kostakos, Eds. New York, New York, USA: ACM Press, 2019, pp. 1–6.

[104] G. C. Burdea and P. Coiffet, *Virtual Reality Technology*, 2nd ed. Hoboken, NJ: Wiley, 2003. [Online]. Available: http://www.loc.gov/catdir/description/wiley039/2002038088.html

[105] E. Rimer, L. V. Husby, and S. Solem, “Virtual Reality Exposure Therapy for Fear of Heights: Clinicians’ Attitudes Become More Positive After Trying VRET,” *Frontiers in psychology*, vol. 12, p. 671871, 2021.

[106] A. Arntz, D. Keßler, and S. Eimler, “Evaluation des Einflusses von Beleuchtung auf die Aufmerksamkeit Innerhalb von Virtual Reality Lernszenarien,” in *Mensch und Computer 2018 - Tagungsband*, R. Dachselt and G. Weber, Eds. Bonn: Gesellschaft für Informatik e.V., 2018.

[107] A. Helgert, S. C. Eimler, and A. Arntz, “Stop Catcalling - A Virtual Environment Educating Against Street Harassment,” in *2021 International Conference on Advanced Learning Technologies (ICALT)*. IEEE, 2021, pp. 419–421.

[108] ——, “Learning About Catcalling: An Interactive Virtual Gallery Concept Raising Awareness for Street Harassment,” in *2021 IEEE International Conference on Artificial Intelligence and Virtual Reality (AIVR)*. IEEE, 2021, pp. 287–294.

[109] A. Arntz, S. C. Eimler, D. Keßler, J. Thomas, A. Helgert, M. Rehm, E. Graf, S. Wientzek, and B. Budur, “Walking on the Bright Sight: Evaluating a Photovoltaics Virtual Reality Education Application,” in *2021 IEEE International Conference on Artificial Intelligence and Virtual Reality (AIVR)*, 2021, pp. 295–301.

[110] C. Strassmann, A. Arntz, and S. C. Eimler, “Under the (Plastic) Sea - Sensitizing People Toward Ecological Behavior Using Virtual Reality Controlled by Users’ Physical Activity,” in *2020 IEEE International Conference on Artificial Intelligence and Virtual Reality (AIVR)*. IEEE, 2020, pp. 166–173.

[111] ——, “Inspiring Movement — Physical Activity in a Virtual Sea as a Driver for Ecological Awareness,” *International Journal of Semantic Computing*, vol. 15, no. 04, pp. 539–559, 2021.

[112] A. Arntz, D. Keßler, N. Borgert, N. Zengeler, M. Jansen, U. Handmann, and S. C. Eimler, "Navigating a Heavy Industry Environment Using Augmented Reality - A Comparison of Two Indoor Navigation Designs," in *Virtual, Augmented and Mixed Reality. Industrial and Everyday Life Applications*, ser. Lecture Notes in Computer Science, J. Y. C. Chen and G. Fragomeni, Eds. Cham: Springer International Publishing, 2020, vol. 12191, pp. 3–18.

[113] A. Arntz, S. C. Eimler, D. Kesler, A. Nabokova, and S. Schadlich, "Thermodynamics Reloaded: Experiencing Heating, Ventilation and Air Conditioning in AR," in *2020 IEEE International Conference on Artificial Intelligence and Virtual Reality (AIVR)*. IEEE, 2020, pp. 319–322.

[114] Oculus, "Oculus Integration SDK," https://developer.oculus.com/downloads/package/unity-integration/, 2021.

[115] Unity, "Rigidbody," https://docs.unity3d.com/ScriptReference/Rigidbody.html, 2021.

[116] K. Group, "Open XR," https://www.khronos.org/openxr/, 2021.

[117] VRTK, "Virtual Reality Toolkit," https://vrtoolkit.readme.io/docs, 2021.

[118] S. Doliwa, "Inverse Kinematics of the KUKA lbr iiwa R800 (7 DoF)," 2020.

[119] KUKA, "KUKA lbr iiwa R800," https://www.kuka.com/en-gb/products/robotics-systems/industrial-robots/lbr-iiwa, 2021.

[120] I. Kresse, "Licensed under CC-BY-3.0 2010 © by Ingo Kresse, kresse@in.tum.de," https://creativecommons.org/licenses/by/3.0/., 2010.

[121] P. Artemiadis, "Closed-Form Inverse Kinematic Solution for Anthropomorphic Motion in Redundant Robot Arms," *Advances in Robotics & Automation*, vol. 02, no. 03, 2013.

[122] C. Faria, F. Ferreira, W. Erlhagen, S. Monteiro, and E. Bicho, "Position-Based Kinematics for 7-DoF Serial Manipulators with Global Configuration Control, Joint Limit and Singularity Avoidance," *Mechanism and Machine Theory*, vol. 121, pp. 317–334, 2018.

[123] I. Iossifidis and G. Schoner, "Dynamical Systems Approach for the Autonomous Avoidance of Obstacles and Joint-Limits for an Redundant Robot Arm," in *2006 IEEE/RSJ International Conference on Intelligent Robots and Systems*. IEEE, 2006, pp. 580–585.

[124] M. Alebooyeh and R. J. Urbanic, "Neural Network Model for Identifying Workspace, Forward and Inverse Kinematics of the 7-DoF YuMi 14000 ABB Collaborative Robot," *IFAC-PapersOnLine*, vol. 52, no. 10, pp. 176–181, 2019.

[125] G. K. Singh and J. Claassens, "An Analytical Solution for the Inverse Kinematics of a Redundant 7DoF Manipulator with Link Offsets," in *2010 IEEE/RSJ International Conference on Intelligent Robots and Systems.* IEEE, 2010, pp. 2976–2982.

[126] W. Liu, D. Chen, and J. Steil, "Analytical Inverse Kinematics Solver for Anthropomorphic 7-DoF Redundant Manipulators with Human-Like Configuration Constraints," *Journal of Intelligent & Robotic Systems*, vol. 86, no. 1, pp. 63–79, 2017.

[127] KUKA, "Sensitive Robotics lbr iiwa," https://www.kuka.com/-/media/kuka-downloads/imported/9cb8e311bfd744b4b0eab25ca883f6d3/kuka_sensitiverobotics_lbriiwa_insert_en.pdf?rev=82b2ad0795854609a53c500cb896eb3a&hash=742380F2B4D6B32C4A037EF5EBEE5C78, 2016.

[128] D. Tolani, A. Goswami, and N. I. Badler, "Real-Time Inverse Kinematics Techniques for Anthropomorphic Limbs," *Graphical models*, vol. 62, no. 5, pp. 353–388, 2000.

[129] A. Arntz, A. Di Dia, T. Riebner, and S. C. Eimler, "Machine Learning Concepts for Dual-Arm Robots within Virtual Reality," in *2021 IEEE International Conference on Artificial Intelligence and Virtual Reality (AIVR).* IEEE, 2021, pp. 168–172.

[130] A. Paszke, S. Gross, F. Massa, A. Lerer, J. Bradbury, G. Chanan, T. Killeen, Z. Lin, N. Gimelshein, L. Antiga, A. Desmaison, A. Köpf, E. Yang, Z. DeVito, M. Raison, A. Tejani, S. Chilamkurthy, B. Steiner, L. Fang, J. Bai, and S. Chintala, "Pytorch: An Imperative Style, High-Performance Deep Learning Library," 2019. [Online]. Available: http://arxiv.org/pdf/1912.01703v1

[131] Unity, "Unity ML-Agents," https://github.com/Unity-Technologies/ml-agents, 2021.

[132] A. Juliani, V.-P. Berges, E. Teng, A. Cohen, J. Harper, C. Elion, C. Goy, Y. Gao, H. Henry, M. Mattar, and D. Lange, "Unity: A General Platform for Intelligent Agents," http://arxiv.org/pdf/1809.02627v2, 2018.

[133] V. Mnih, K. Kavukcuoglu, D. Silver, A. A. Rusu, J. Veness, M. G. Bellemare, A. Graves, M. Riedmiller, A. K. Fidjeland, G. Ostrovski, S. Petersen, C. Beattie, A. Sadik, I. Antonoglou, H. King, D. Kumaran, D. Wierstra, S. Legg, and D. Hassabis, "Human-Level Control Through deep Reinforcement Learning," *Nature*, vol. 518, no. 7540, pp. 529–533, 2015.

[134] A. S. Kyaw, *Unity 4.x Game AI Programming*, second edition ed. Birmingham: Packt Publishing, 2013. [Online]. Available: https://search.ebscohost.com/login.aspx?direct=true&scope=site&db=nlebk&db=nlabk&AN=619975

[135] M. Toussaint, T. Munzer, Y. Mollard, L. Y. Wu, N. A. Vien, and M. Lopes, "Relational Activity Processes for Modeling Concurrent Cooperation," in *2016 IEEE International Conference on Robotics and Automation (ICRA).* IEEE, 2016, pp. 5505–5511.

[136] Unity, "Unity Mesh Collider," https://docs.unity3d.com/Manual/class-MeshCollider.html, 2021.

[137] ABB, "YuMi-irb 14000 — Collaborative Robot," https://new.abb.com/products/3HAC050778-001/irb-14000, 2015.

[138] Badgematic, "Badge Maker 900 Flexi 59 mm," https://www.badgematic.de/en/badge-maker-900-flexi-59-mm, 2020.

[139] A. Arntz and S. C. Eimler, "Experiencing AI in VR: A Qualitative Study on Designing a Human-Machine Collaboration Scenario," in *HCI International 2020 – Late Breaking Posters*, ser. Communications in Computer and Information Science, C. Stephanidis, M. Antona, and S. Ntoa, Eds. Cham: Springer International Publishing, 2020, vol. 1293, pp. 299–307.

[140] A. Arntz, S. C. Eimler, and H. U. Hoppe, ""The Robot-Arm Talks Back to Me" - Human Perception of Augmented Human-Robot Collaboration in Virtual Reality," in *2020 IEEE International Conference on Artificial Intelligence and Virtual Reality (AIVR).* IEEE, 2020, pp. 307–312.

[141] ——, "Augmenting the Human-Robot Communication Channel in Shared Task Environments," in *Collaboration Technologies and Social Computing*, ser. Lecture Notes in Computer Science, A. Nolte, C. Alvarez, R. Hishiyama, I.-A. Chounta, M. J. Rodríguez-Triana, and T. Inoue, Eds. Cham: Springer International Publishing, 2020, vol. 12324, pp. 20–34.

[142] ——, "A Virtual Sandbox Approach to Studying the Effect of Augmented Commmunication on Human-Robot Collaboration," *Frontiers in Robotics and AI*, vol. 8, p. 318, 2021. [Online]. Available: https://www.frontiersin.org/article/10.3389/frobt.2021.728961

[143] A. Arntz, S. C. Eimler, C. Straßmann, and H. U. Hoppe, "On the Influence of Autonomy and Transparency on Blame and Credit in Flawed Human-Robot Collaboration," in *Companion of the 2021 ACM/IEEE International Conference on Human-Robot Interaction*, C. Bethel, A. Paiva, E. Broadbent, D. Feil-Seifer, and D. Szafir, Eds. New York, NY, USA: ACM, 03082021, pp. 377–381.

[144] E. Union, "Special Eurobarometer 382: Public Attitudes Towards Robots," https://data.europa.eu/euodp/de/data/dataset/S1044_77_1_EBS382, 2014.

[145] N. H. Alsuraykh, M. L. Wilson, P. Tennent, and S. Sharples, "How Stress and Mental Workload are Connected," in *Proceedings of the 13th EAI International Conference on Pervasive Computing Technologies for Healthcare*, O. Mayora, S. Forti, J. Meyer, and L. Mamykina, Eds. New York, NY, USA: ACM, 2019, pp. 371–376.

[146] C. D. Cramton, "The Mutual Knowledge Problem and Its Consequences for Dispersed Collaboration," *Organization Science*, vol. 12, no. 3, pp. 346–371, 2001.

[147] M. Heerink, B. Krose, V. Evers, and B. Wielinga, "Influence of Social Presence on Acceptance of an Assistive Social Robot and Screen Agent by Elderly Users," *Advanced Robotics*, vol. 23, pp. 1909–1923, 10 2009.

[148] T. Kim and P. Hinds, "Who Should I Blame? Effects of Autonomy and Transparency on Attributions in Human-Robot Interaction," in *ROMAN 2006 - The 15th IEEE International Symposium on Robot and Human Interactive Communication.* IEEE, 06.09.2006 - 08.09.2006, pp. 80–85.

[149] Z. Institut, "Megatrend Silver Society," https://www.zukunftsinstitut.de/dossier/megatrend-silver-society/, 2022.

[150] ——, "Megatrend Gesundheit," https://www.zukunftsinstitut.de/dossier/megatrend-gesundheit/, 2022.

[151] B. A. Kadir, O. Broberg, and C. Da Souza Conceição, "Designing Human-Robot Collaborations in Industry 4.0: Explorative Case Studies," in *Proceedings of the DESIGN 2018 15th International Design Conference*, ser. Design Conference Proceedings. Faculty of Mechanical Engineering and Naval Architecture, University of Zagreb, Croatia and The Design Society, Glasgow, UK, 2018, pp. 601–610.

[152] XSens, "MVN Avinda," https://www.xsens.com/products/mvn-animate, 2021.

[153] C. Straßmann, A. R. von der Pütten, R. Yaghoubzadeh, R. Kaminski, and N. Krämer, "The Effect of an Intelligent Virtual Agent's Nonverbal Behavior with Regard to Dominance and Cooperativity," in *Intelligent virtual agents*, ser. Lecture Notes in Computer Science, D. Traum, W. Swartout, P. Khooshabeh, S. Kopp, S. Scherer, and A. Leuski, Eds. Cham: Springer, 2016, vol. 10011, pp. 15–28.

[154] A. Business, "AWS Device SDK," https://developer.amazon.com/en-US/alexa/devices/alexa-built-in/development-resources/sdk, 2021.

[155] S. Survey, "SoSci Survey – Die Lösung für eine Professionelle Onlinebefragung," 2022. [Online]. Available: https://www.soscisurvey.de/

[156] F. J. Neyer, J. Felber, and C. Gebhardt, "Kurzskala Technikbereitschaft (TB, Technology Commitment)."

[157] J. A. Russell, A. Weiss, and G. A. Mendelsohn, "Affect Grid: A Single-Item Scale of Pleasure and Arousal," *Journal of Personality and Social Psychology*, vol. 57, no. 3, pp. 493–502, 1989.

[158] T. Nomura, T. Suzuki, T. Kanda, and K. Kato, “Measurement of Negative Attitudes Toward Robots,” *Interaction Studies. Social Behaviour and Communication in Biological and Artificial Systems*, vol. 7, no. 3, pp. 437–454, 2006.

[159] S. G. Hart and L. E. Staveland, “Development of NASA-TLX (Task Load Index): Results of Empirical and Theoretical Research,” in *Human Mental Workload*, ser. Advances in Psychology. Elsevier, 1988, vol. 52, pp. 139–183.

[160] S. Cohen, T. Kamarck, and R. Mermelstein, *PsycTESTS Dataset*, 1983.

[161] J. R. Carlopio, “Construct Validity of a Physical Work Environment Satisfaction Questionnaire,” *Journal of occupational health psychology*, vol. 1, no. 3, pp. 330–344, 1996.

[162] P. A. Lasota, T. Fong, and J. A. Shah, “A Survey of Methods for Safe Human-Robot Interaction,” *Foundations and Trends in Robotics*, vol. 5, no. 3, pp. 261–349, 2017.

[163] V. Venkatesh and F. D. Davis, “A Theoretical Extension of the Technology Acceptance Model: Four Longitudinal Field Studies,” *Management Science*, vol. 46, no. 2, pp. 186–204, 2000.

[164] B. G. Witmer and M. J. Singer, “Measuring Presence in Virtual Environments: A Presence Questionnaire,” *Presence: Teleoperators and Virtual Environments*, vol. 7, no. 3, pp. 225–240, 1998.

[165] S. Sahlqvist, Y. Song, F. Bull, E. Adams, J. Preston, and D. Ogilvie, “Effect of Questionnaire Length, Personalisation and Reminder Type on Response Rate to a Complex Postal Survey: Randomised Controlled Trial,” *BMC medical research methodology*, vol. 11, p. 62, 2011.

[166] R. S. Kennedy, N. E. Lane, K. S. Berbaum, and M. G. Lilienthal, “Simulator Sickness Questionnaire: An Enhanced Method for Quantifying Simulator Sickness,” *The International Journal of Aviation Psychology*, vol. 3, no. 3, pp. 203–220, 1993.

[167] C. Bartneck, D. Kulić, E. Croft, and S. Zoghbi, “Measurement Instruments for the Anthropomorphism, Animacy, Likeability, Perceived Intelligence, and Perceived Safety of Robots,” *International Journal of Social Robotics*, vol. 1, no. 1, pp. 71–81, 2009.

[168] L. Hoffmann, N. Bock, and A. M. v.d. Rosenthal Pütten, “The Peculiarities of Robot Embodiment (EmCorp-Scale),” in *Proceedings of the 2018 ACM/IEEE International Conference on Human-Robot Interaction*, T. Kanda, S. Ŝabanović, G. Hoffman, and A. Tapus, Eds. New York, NY, USA: ACM, 2018, pp. 370–378.

[169] J. Banks, “A Perceived Moral Agency Scale: Development and Validation of a Metric for Humans and Social Machines,” *Computers in Human Behavior*, vol. 90, pp. 363–371, 2019.

[170] C. Helfferich, *Die Qualität Qualitativer Daten: Manual für die Durchführung Qualitativer Interviews*, 4th ed., ser. Lehrbuch. Wiesbaden: VS Verlag, 2011.

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