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Designing Authoring Tools for the Metaverse to Detect User Behavior

Doctoral Dissertation

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Abstract

Motivation: The industrial metaverse extends beyond the passive consumption of virtual content. In this context, employees without programming experience, referred to as citizen developers, create virtual objects within immersive environments that can be transformed into physical artifacts or processes. Conversely, citizen developers can also transform physical objects into virtual artifacts. Using authoring tools, these citizen developers are not only technically enabled to create metaverse content but also act as users who interact with and consume the content they or others created. We argue that the current design of these authoring tools remain incomplete. First, citizen developers must not only be able to use these tools but must be able to use them effectively to maximize their full benefits. Second, the citizen developers must not only be technically empowered to create metaverse content independently, but their intention to do so must be strengthened. Third, it is essential to deepen our understanding of how these tools are used, as such insights provide valuable guidance for the design of future authoring tools based on user behavior.

Research Approach: To address the identified research gaps, this thesis employs a Design Science Research (DSR) divided into three successive design cycles. The first cycle addresses the lack of design knowledge in metaverse content creation by focusing on AR interaction techniques within authoring tools, effectively enabling citizen developers to create AR-based industrial guidance. Two initial design principles are derived and evaluated in a laboratory experiment with 55 participants. The second design cycle investigates how AR authoring tools can foster both effective content creation and the intention to contribute content usable by peers, validating three design principles through two laboratory experiments and a case study involving 127 participants. The final design cycle examines users' psychological states during interaction with metaverse authoring tools by analyzing motor control in a laboratory experiment with 22 participants, using fraud as an illustrative case due to its relevance in anonymous environments.

Results: This thesis provides comprehensive prescriptive design knowledge. First, based on Effective Use Theory, we show that natural, consistent interaction and the ability to create both dynamic and static AR content increase transparent interaction and representational fidelity in AR interaction techniques. This leads to more effective use of the AR interaction techniques. Second, we propose a design theory based on the Social Cognitive Theory for future AR authoring tools, offering an abstract understanding of the principles and constructs that underlie their design. This design theory serves as a blueprint for the development of future AR authoring

tools in the industrial metaverse. Finally, we demonstrate that psychological states using fraud as an example affect users' human motor controls.

Contribution: This thesis makes several contributions to both theory and practice. We advance the conceptual understanding of the industrial metaverse as a socio-technical system that uniquely integrates virtual and physical environments. We contribute to the literature on Social Cognitive Theory by contextualizing the theory within the industrial metaverse. We also contribute to the field of affective computing by introducing the tracking of controller movements in the metaverse as a method for identifying user behavior. In addition, we contribute to the ongoing debate in cognitive psychology on whether truth or deception is the default mode of human communication. From a practical perspective, our findings provide insights for the design of future AR authoring tools and AR instructions within the industrial metaverse. We also highlight opportunities for small and medium-sized enterprises to extend their existing business models, and propose a method for detecting deceptive behavior in immersive virtual environments.

Limitations: This thesis is subject to several limitations. First, the findings relate to specific use cases, particularly the creation of AR instructions in the industrial metaverse, and therefore the design knowledge may only be transferable to other contexts to a limited extent. The proposed design principles, software artifacts, and the resulting nascent design theory are context-specific, and their generalizability to other interfaces or application scenarios remain uncertain. Additionally, both qualitative and quantitative methodological limitations, such as small sample sizes, potential biases introduced by study designs, and subjective interpretations in the qualitative analyzis, affect the validity and transferability of the results.

Future Research: Three directions for future research emerge from this thesis. First, as the industrial metaverse increasingly shifts work and processes into immersive environments, the design of dashboards and user interfaces becomes critically important. Immersive settings introduce novel design challenges that require new approaches to interface design. Second, the field of social computing is undergoing transformation through the rise of the industrial metaverse, particularly in the area of user-generated content, which has traditionally been explored on 2D screens. Investigating how such content is created, shared, and consumed in immersive 3D environments represents a promising line of research. Third, the emergence of industrial metaverse ecosystems raises new questions about platform dynamics, coordination, and governance, especially given of the complex, nested structures of meta-ecosystems.

Table of Contents

List of Figures

List of Tables

List of Abbreviations

ADCAT	Activation-Decision-Construction-Action Theory
ADR	Action Design Research
AR	Augmented Reality
CLT	Cognitive Load Theory
CON	Conference
CS	Case Studie
ECIS	European Conference on Information Systems
EUT	Effective Use Theory
EXP	Experiments
DOF	Degrees of Freedom
DP	Design Principles
DR	Design Research
DS	Design Science
DSR	Design Science Research
DSRIS	Design Science Research in Information Systems
DSRM	Design Science Research Methodology
GEM-MetAR	General content for the meta-design space - Industrial Metaverse Augmented Reality Development Tool
HCI	Human-Computer Interaction
HICSS	Hawaii International Conference on System Sciences
HMD	Head-Mounted Display
I	Issue
ICIS	International Conference on Information Systems
IS	Information System
JMIS	Journal of Management Information Systems
JNL	Journal
KYC	Know-Your-Customer
LR	Literature Review
MAD-MetAR	Merged AR development process - Industrial Metaverse Augmented Reality Development Tool
MR	Mixed Reality
MetAR	Industrial Metaverse Augmented Reality Development Tool
P	Publication
PGS	Process Guidance Systems
RQ	Research Question
SCMT	Self-Concept Maintenance Theory
SCT	Social Cognitive Theory
SME	Small and Medium-Sized Enterprise
UGC	User Generated Content
UMI	User-Metaverse Interface
VHB	German Academic Association for Business Research
VR	Virtual Reality
XR	eXtended Reality

List of Appendices

Part A

1 Introduction

"*The metaverse is here, and it's not only transforming how we see the world but how we participate in it – from the factory floor to the meeting room*" (Mehta 2021).

"*The economy in the metaverse [...] will be larger than the economy in the physical world*" (Haas 2022).

These quotes by Satya Nadella, CEO of Microsoft, and Jensen Huang, CEO of NVIDIA, underscore the transformative potential of the metaverse on everyday life, work, and value creation. This anticipated impact has led technology companies to invest over $120 billion in metaverse-related technologies and infrastructure by mid-2022, more than double the investment of the previous year (McKinsey & Company 2022).

Although the metaverse is often portrayed as a singular, immersive virtual environment, it can be more accurately conceptualized as comprising three distinct domains: the consumer metaverse, the enterprise metaverse, and the industrial metaverse. Given that information systems (IS) are fundamentally designed to improve organizational efficiency and effectiveness (Hevner et al. 2004) the industrial metaverse has attracted significant attention from leading companies such as Siemens, NVIDIA, and BMW (Diaz 2023; MIT Technology Review Insights 2023). For instance, BMW utilizes a fully virtual factory to plan new production lines, enabling engineers to simulate thousands of "what-if" scenarios and detect potential issues long before physical implementation (Diaz 2023).

Against this backdrop, IS research plays a critical role in shaping the design of interfaces and interaction mechanisms within the industrial metaverse. This thesis focuses on user interactions in this emerging environment, with a particular emphasis on the design of AR interaction techniques and authoring tools that empower users to actively contribute to industrial metaverse applications. Furthermore, the study explores analytical approaches for identifying interaction patterns to support the prediction of human behavior in the metaverse.

1.1 Motivation

The industrial metaverse refers to immersive meta-design spaces specifically tailored for industrial applications and virtual processes, enabling engineers to simulate, manage, and optimize operations to enhance physical value creation. The immersive nature of the industrial metaverse, along with the resulting fused environments, offers an unparalleled opportunity to observe, interact with, and analyze distinct spatial challenges encountered by industrial organizations (MIT Technology Review Insights 2023). Given its focus on physical human-machine interaction, industrial process simulations, and knowledge assessments, the fusion of virtual and physical elements into the employees' environment (Dwivedi et al. 2022) is a key aspect of the industrial metaverse. These fused environments semantically integrate people, spaces, and machines, both digitally and physically, creating opportunities for employees to develop and interact with content, processes, and machines, which is unique in this form in the industrial metaverse to this date. Organizations can leverage the industrial metaverse's capacity to seamlessly integrate immersive virtual experiences with physical realities, enabling employees to perform demanding physical tasks more effectively and safely. However, the concept of the industrial metaverse extends beyond passive consumption of immersive experiences, such as virtual training. Within the industrial metaverse, employees can create virtual objects in virtual environments that are then subsequently transformed back as physical artifacts or processes (Qu et al. 2022; Seidel et al. 2022). Conversely, employees can also create physical objects that are then transformed back into virtual artifacts in the industrial metaverse. Another peculiarity is that the immersive content within the industrial metaverse is not created by experts in immersive systems or programmers, but by engineers or service technicians (hereinafter referred to as *citizen developers*) (Ashtari et al. 2020; Krauß et al. 2021).

Augmented Reality (AR) authoring tools can help address these challenges. AR authoring tools are software programs that allow citizen developers to create and publish immersive AR content on different platforms, on different types of hardware (Konopka et al. 2022; Nebeling and Speicher 2018). AR authoring tools are used to simplify the complex development process of immersive content within the industrial metaverse (Krauß et al. 2021), but previous research has focused primarily on the actual immersive AR content to be created with these tools (Gattullo et al. 2020; Laviola et al. 2022). However, developing the immersive content is only one aspect of creating an application for the industrial metaverse. Another important aspect is that the citizen developers have to manually position and anchor the immersive content in the physical environment (Bräker et al. 2023a). This requires an interaction that allows a 3D movement of the AR content in the physical environment (henceforth referred to as *AR interaction technique*). Given the wide variety of application domains for immersive technologies in the industry (Dolata and Schwabe 2023), it is important to examine how different AR interaction techniques perform within specific use cases. While the general performance of existing AR interaction techniques is already well-researched (Goh et al. 2019; Liu et al. 2015), a closer look at the AR authoring tool landscape reveals that the AR authoring tools that require no programming knowledge to develop immersive AR content are mainly designed for a specific application domain (Damarowsky and Kühnel 2022; Laviola et al. 2022).

Therefore, for the first five publications (P1-P5) in this thesis, we focused on the application of process guidance systems (PGS) within an industrial context (Morana et al. 2017) as this is one of the most important use cases of AR in the industrial metaverse (Klinker et al. 2018; Kortekamp et al. 2019). PGS guides users step-by-step through their work to ensure process compliance. AR-based PGS, like an AR instruction, represents a novel approach to supporting physical tasks by providing necessary information precisely when and where it is required in the physical environment. Implementing these systems can generate significant savings for industrial organizations, such as reducing preparation times and minimizing error rates during the assembly of complex systems, like large aircraft (Serván et al. 2011). The selection of suitable AR interaction techniques is critical for AR authoring tools, as accurate and efficient placement of AR content within physical environments is fundamental to metaverse applications (Bräker et al. 2023a). However, existing literature lacks a clear consensus on which AR interaction techniques are most effective for translating traditional technical documentation into AR instructions for the industrial metaverse.

In recent years, an increasing number of design-oriented studies have explored the development of AR authoring tools. However, while these tools predominantly focus on the creation and presentation of immersive AR content, the design of AR interaction techniques is often treated superficially. References to interaction techniques in design principles are frequently limited to general phrases such as "*providing comprehensive user interaction*" or "*consider traditional interaction design*" (Bräker et al. 2023a; Damarowsky et al. 2023), without addressing the lack of a de facto standard for mobile AR interaction techniques (Goh et al. 2019). Furthermore, when designing such techniques, it is not sufficient for the underlying technology to be merely usable. Moreover, according to Effective Use Theory, it is essential that interaction techniques enable citizen developers to use them effectively, in order to fully realize their potential and practical value (Burton-Jones and Grange 2013).

While there is a growing trend to simplify AR authoring processes, minimizing the need for extensive programming knowledge or experience, similar to advancements in traditional software development (Matook et al. 2023) or the creation of AI-based systems (Elshan et al. 2023), recent research shows that AR authoring tools still often feature complex functions requiring advanced programming and strong spatial knowledge, making them primarily used by experienced software developers (Ashtari et al. 2020; Krauß et al. 2021; Nebeling and

Speicher 2018). Therefore, industrial organizations are increasingly adopting no-code tools to simplify AR content development, enabling citizen developers to create immersive AR content (Ashtari et al. 2020). These no-code AR authoring tools aim to reduce the need for programming skills and spatial knowledge, which are typically required to develop content for virtual environments such as the industrial metaverse. While existing design research has largely focused on the technical simplification of AR authoring tools, it often neglects how users actually engage with these tools. In particular, there is limited understanding of how to design AR authoring tools that not only lower technical barriers but also enhance citizen developers' confidence in their ability to create and share immersive AR content (Pace et al. 2020). This is especially important in the context of the industrial metaverse, where citizen developers must feel confident in their ability to translate domain-specific knowledge into immersive AR content that can be shared with their peers in the industrial metaverse (Funk et al. 2017; Zallio and Clarkson 2022). Therefore, drawing on Social Cognitive Theory (Bandura 1986), it is important to consider how AR authoring tools can be designed to foster users' self-efficacy and positive outcome expectations (Chiu et al. 2006; Hsu et al. 2007).

AR authoring tools represent a significant opportunity for industrial organizations, as they not only simplify access to immersive environments and enable the exploitation of significant efficiency potentials (Cohen et al. 2018; Serván et al. 2011) but also offer new analytical possibilities through the data collected by human-machine interaction devices, needed to access the metaverse. These tools allow organizations to optimize existing work processes in a human-centric manner (Michalos et al. 2018). In the industrial metaverse, citizen developers often interact with virtual reality (VR) controllers equipped with high-precision sensors that could provide valuable insights into user behavior. We argue that by recording and analyzing controller movements with millisecond accuracy, it is possible to infer the cognitive states of users. Demonstrating how and to what extent user's cognitive dynamics are influenced by emotions arising from different physiological states could enable the prediction of emotional and physiological states. This approach has the potential to improve key design and usability factors in the development of new industrial metaverse applications. For example, motion sickness could be mitigated by using controller motion data to accurately track when and under what circumstances it occurs, and to identify design elements that exacerbate the condition (Fernandes and Feiner 2016). Such insights could lead to improved user experiences and more effective application designs in the industrial metaverse.

In this thesis, we use the knowledge we have developed about how citizen developers interact with immersive content in the metaverse to analyze and uncover the cognitive dynamics of individuals in various psychological states. These insights serve as a foundation for developing additional design knowledge for future metaverse authoring tools (Hibbeln et al. 2017). As an example, we focus on the psychological state of fraud, where cognitive dynamics are particularly pronounced (Nuñez et al. 2005). Furthermore, identity theft, which is a form of fraud (Panicker et al. 2024), is of particular relevance in the metaverse (Dwivedi et al. 2023). Drawing on Self-Concept Maintenance Theory (SCMT) (Mazar et al. 2008), which suggests that individuals typically engage in fraudulent behavior when they stand to gain external benefits, but only to the extent that allows them to maintain a positive self-concept of their honesty. The effort to maintain a positive self-concept while harboring fraudulent intentions in order to gain external advantages leads to a motivational dilemma that individuals attempt to resolve in a predictable manner (Festinger 1957). This attempt to resolve the motivational dilemma and overcome the resulting cognitive dissonance can influence human motor control (Freeman et al. 2011; Wojnowicz et al. 2009). By examining these motor control dynamics, this thesis aims to shed light on the interplay between cognitive states and physical interactions within the metaverse. In doing so, it also contributes novel design knowledge that can inform the development of future metaverse authoring tools. For example, this method for detecting potentially fraudulent behavior could be integrated into these tools in an unobtrusive manner, offering a new layer of design knowledge to help preserve the integrity of virtual environments (Hibbeln et al. 2017; Weinmann et al. 2022).

1.2 Research Question

The overall goal of this thesis is to improve the design knowledge of the industrial metaverse and the interaction of citizen developers within the industrial metaverse. Despite growing research on the metaverse and the increasing importance of the industrial metaverse in practice, significant gaps remain regarding the industrial metaverse itself and the human behavior and interactions in the industrial metaverse. This thesis integrates literature from IS design and Human-Computer Interaction (HCI) on the metaverse and related interaction concepts. It employs both qualitative and quantitative data and applies a Design Science Research (DSR) approach. To address these gaps, we have formulated five research questions (RQ), which are answered through the six embedded publications presented in Part B. These RQs are described in more detail below.

To determine which AR interaction technique is most suitable for the industrial metaverse, RQ1 will be answered. To address this question, we considered one of the most important application domain of AR in the industrial metaverse, namely the creation of AR instructions, and conducted an experimental comparison of three different AR interaction techniques with 55 participants. The study evaluated trade-offs in performance, workload, and user satisfaction when positioning immersive AR content in designated positions across tasks essential for developing AR instructions. Furthermore, the study analyzed the strengths, weaknesses, opportunities, and risks associated with each AR interaction technique within this application domain. The tasks were derived from six information types used to convey traditional technical documentation into AR instructions. To enhance the generalizability and applicability of our findings, the research centered on AR interaction techniques suitable for standard handheld devices and employed the most common input methods in both practice and academia, namely, device-based and touch-based AR interactions. The insights gained regarding the AR interaction techniques most suitable for this application domain in the industrial metaverse serve as the foundation for addressing the next research question.

RQ1: *How does different AR interaction techniques on handheld devices affect performance, workload, and satisfaction when creating AR instructions?*

To contribute design knowledge on AR interaction techniques that empower citizen developers to independently and effectively create AR instructions with AR authoring tools, this thesis addresses RQ2. Specifically, we conducted a DSR project to explore how AR interaction techniques can be designed to support the effective creation of AR instructions without requiring programming skills or spatial knowledge. Drawing on Effective Use Theory and existing research on AR instructions, we derived two theoretically grounded design principles. These design principles were validated in a controlled laboratory experiment involving 55 participants. The findings gained as participants created AR instructions using the different AR interaction techniques informed the subsequent refinement of the final AR authoring tool in the next parts of this thesis.

RQ2: *How can an AR interaction technique be designed to improve transparent interaction and representational fidelity when placing AR content?*

To propose design knowledge for enabling citizen developers in the industrial metaverse to independently create immersive AR content and strengthen their intentions to do so, this thesis addresses RQ3 and RQ4. To achieve this, we conducted an additional extensive DSR project, developing a nascent design theory for AR authoring tools in the industrial metaverse. This design theory is grounded in Social Cognitive Theory and current research on AR authoring tools, and is built on three theoretically derived design principles that form its foundation. These design principles were validated through two evaluation episodes involving a total of 115 participants in two controlled lab experiments. Additionally, in a third evaluation episode, we assessed the utility of the design principles and the software artifact in a real-world scenario through a case study with 12 experts from two different industrial organizations. The findings gained about how citizen developers create and interact with immersive AR content in a metaverse environment provide a foundation for subsequent research questions.

RQ3: *How can an AR authoring tool be designed to enable citizen developers from the industrial metaverse to share their domain knowledge in the industrial metaverse while increasing their self-efficacy and outcome expectations?*

RQ4: *What are the drivers of citizen developers' self-efficacy and outcome expectations when creating and using metaverse applications for the industrial metaverse?*

To draw conclusions about users' psychological states by analyzing their interactions with immersive content in the metaverse in order to gain additional design knowledge for future metaverse authoring tools, this thesis addresses RQ5. We investigate the psychological state of fraudulent behavior as an example, using a single-factor controlled experimental study conducted in a VR setting with 22 participants. In this study, participants' VR controller movements were recorded and analyzed while they entered both honest and fraudulent inputs within a self-developed metaverse environment designed as a VR game. Participants were incentivized to enter fraudulent information through two established social mechanisms, rivalry and social incentives, without being explicitly prompted to do so. The study focused on identifying changes in human motor control, particularly in terms of controller distance and speed, associated with different phases of fraudulent behavior.

RQ5: *Does fraud action, activation, decision, and construction in the metaverse affect the controller distance and speed?*

1.3 Structure

This cumulative thesis is organized into three main parts. Part A establishes the foundation of the research, beginning with an introduction (Section 1) that outlines the motivation behind the study, presents the research questions, and provides an overview of the thesis structure. Section 2 then reviews the existing literature and theoretical framework, focusing on immersive technologies, (industrial) metaverse, and the underlying theories. The methodological framework is presented in Section 3, detailing both the research strategy and methods employed.

Part B forms the core of this cumulative thesis, consisting of six peer-reviewed publications (Sections 4-9) that represent the main research contributions. Each publication addresses specific aspects of the overall research agenda and has undergone independent peer review.

Part C synthesizes and concludes the research. It begins with a comprehensive summary of the findings from the six publications (Section 10), followed by an in-depth discussion of these results (Section 11). Section 12 explores the implications of the research for both theory and practice, while Section 13 acknowledges the limitations of the study. Section 14 identifies promising avenues for future research. The thesis concludes with a final synthesis of the work. Figure 1 provides a visual representation of this structure.

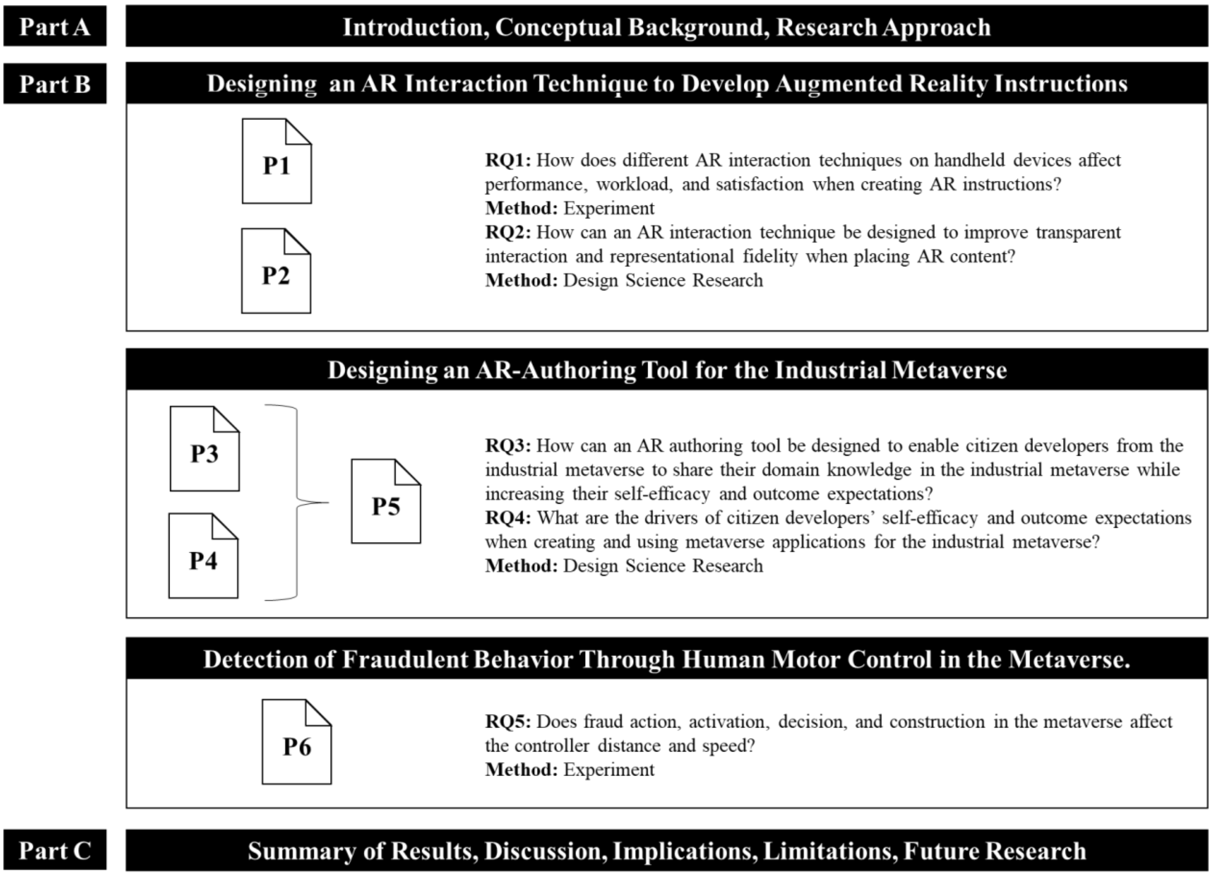

Figure 1. Structure of the Thesis

Table 1 provides an overview of the six peer-reviewed publications embedded in this thesis. The following sections outline each publication's (P) research problem, methodological approach, and main contribution.

P1: A Comparative Study of Handheld Augmented Reality Interaction Techniques for Developing AR-Instructions using AR Authoring Tools (Hönemann et al. 2025a). In this study, we analyze the performance of three handheld AR interaction techniques within the specific context of the industrial metaverse. While the performance of AR interaction techniques is well-documented in the HCI literature, prior evaluations have primarily been conducted using generic application domains. How these techniques perform in a specific domain, such as the creation of AR instructions in the industrial metaverse, remains unknown. To address this gap, we conducted an experimental comparison involving 55 participants, examining the performance trade-offs of positioning AR elements at designated locations in the physical environment across tasks essential for developing AR instructions. Based on our findings, we propose design guidelines to guide both practitioners and researchers in designing future AR development tools and AR instructions.

P2: Designing an Effective Augmented Reality Interaction Technique to Develop AR Instructions (Hönemann et al. 2025c). This study aims to investigate how AR interaction techniques can be designed to enable citizen developers, specifically, employees who are domain experts, such as service technicians, to effectively create AR instructions to use in the industrial metaverse. While prior design-oriented research on AR authoring has primarily focused on the AR content itself, interaction techniques are often addressed only marginally, with vague references such as "*consideration of traditional interaction design*" (Damarowsky et al. 2023). Notably, the absence of established standards for AR interaction techniques on handheld devices remains largely unaddressed. To bridge this gap, we conducted a design science study grounded in Effective Use Theory and informed by the current state of research on AR instructions. We proposed two theoretically grounded design principles, which were implemented in a software artifact and evaluated through a controlled laboratory study involving 55 participants. Our findings indicate that employing a device-based interaction technique enhances both transparent interaction and representational fidelity, thereby supporting the effective creation of AR instructions.

P3: Designing a User-Metaverse Interface for the Industrial-Metaverse (Hönemann et al. 2023a). In this study, we explore how a User Metaverse Interface (UMI), which serves as the interface to the industrial metaverse, can be designed. To achieve this, we employed an extensive design science research approach grounded in Social Cognitive Theory (SCT). SCT emphasizes the importance of user-generated metaverse content, as enabling citizen developers to create content through their own efforts enhances self-efficacy and engagement. Based on SCT, we propose two theoretically grounded design principles and develop a software artifact to operationalize these principles. The artifact is evaluated through a controlled laboratory experiment with 57 participants. Following the DSR Knowledge Contribution Framework, this research is classified as an improvement, as it presents a novel solution, a software artifact, to address a known problem.

P4: The Importance of Separation in the Creation and Usage Phases of Augmented Reality Content Using Social Cognitive Theory (Hönemann et al. 2024). This study aims to examine how the different sources of self-efficacy vary between the creation and usage phases of industrial metaverse content. To address this, we employed a design science research approach, also grounded in SCT. Understanding these distinctions is crucial for designing future AR development tools, as such tools are intended to support both industrial metaverse content creation and use, often by two distinct target groups with different objectives. Building on SCT, we propose a third theoretically grounded design principle and adapt the previously developed software artifact to operationalize this principle. To evaluate the artifact's utility and the validity of the third design principle, we conducted a case study with 12 domain experts from two different industrial organizations. The results highlight distinct sources of self-efficacy in the creation and use phases of metaverse content, emphasizing the importance of clearly separating these phases in future AR authoring tool designs.

P5: Designing an Augmented Reality Development Tool for Supporting Physical Process Guidance in the Industrial Metaverse. In this study, we examine how AR authoring tools can be designed to enable citizen developers, specifically, employees who are domain experts, to create virtual objects in the industrial metaverse, which then can be transformed back into physical artifacts and vice versa. Existing AR authoring tools often require programming skills and advanced spatial knowledge, creating technical barriers for citizen developers. This complexity can undermine the confidence of citizen developers in their ability to effectively integrate domain knowledge into processes designed for the industrial metaverse. To address this challenge, we propose a theory-driven design for AR authoring tools grounded in SCT. This approach aims to empower citizen developers to create metaverse content while enhancing their self-efficacy and outcome expectations. The proposed design was implemented in a software artifact and evaluated with 127 participants. The findings highlight that separating the AR development process, tailoring content to the meta-design space, and clearly distinguishing between the creation and usage phases of Metaverse applications significantly enhance the performance and self-efficacy of employees engaging with the industrial metaverse.

P6: Are you Telling the Truth? Detection of Identity Theft through Human Motor Control in the Metaverse (Hönemann et al. 2025b). This study examines whether insights into a user's psychological state can be derived by recording and analyzing human motor control, specifically VR controller movements, within the metaverse. We focus on the example of fraudulent behavior, particularly identity theft, which is highly relevant in the metaverse. Identity theft poses a significant risk because identity is central to access and interaction within the metaverse. However, verifying users' true identities is challenging, as traditional identification procedures are difficult to implement, and many metaverse users prioritize anonymity. To address this issue, we propose a method grounded in Self-Concept Maintenance Theory (SCMT) and Activation-Decision-Construction-Action Theory (ADCAT) for unobtrusive analyzis of motion data. This method aims to detect fraudulent behavior early by identifying altered cognitive dynamics. To validate this approach, we conducted a controlled single-factor experimental study in a VR environment with 22 participants. During the study, we recorded and analyzed VR controller movement data as participants input both honest and dishonest information.

No.	Authors	Title	Outlet	Type
P1	Hönemann, Konopka, Prilla, Wiesche	A Comparative Study of Handheld Augmented Reality Interaction Techniques for Developing AR-Instructions using AR Authoring Tools	Computers in Industry (*published 2024*)	JNL (VHB: B)
P2	Hönemann, Konopka, Wiesche	Designing an Effective Augmented Reality Interaction Technique to Develop AR Instructions	DESRIST2025	CON (VHB: B)
P3	Hönemann, Konopka, Thatcher, Wiesche	Designing a User-Metaverse Interface for the Industrial-Metaverse	ICIS2023	CON (VHB: A)
P4	Hönemann, Konopka, Wiesche	The Importance of Separation in the Creation and Usage Phases of Augmented Reality Content Using Social Cognitive Theory	HICSS2024	CON (VHB: B)
P5	Hönemann, Konopka, Thatcher, Wiesche	Designing an Augmented Reality Development Tool for Supporting Physical Process Guidance in the Industrial Metaverse	JMIS *(Revise and Resubmit)*	JNL (VHB: A)
P6	Hönemann, Konopka, Stundzig, Thatcher, Wiesche	Are you Telling the Truth? Detection of Identity Theft through Human Motor Control in the Metaverse	ECIS2025	CON (VHB: A)

Legend:
Outlet:
DESRIST: International Conference on Design Science Research in Information Systems and Technology
ECIS: European Conference on Information Systems
HICSS: Hawaii International Conference on System Sciences
ICIS: International Conference on Information Systems
JMIS: Journal of Management Information Systems

Type:
CON: Conference
JNL: Journal
VHB: German Academic Association for Business Research

Table 1. Overview on Embedded Publications

2 Conceptual Background

This section outlines the theoretical concepts that form the foundation of this thesis. First, the context of immersive technologies is described, with a clear distinction made between AR and VR. The concepts of immersive environments and the metaverse are then introduced, emphasizing the core characteristics of the metaverse and the specific characteristics of the industrial metaverse. Given that the first five publications (P1–P5) focus on content creation in the industrial metaverse, the concept of AR authoring tools is discussed in more detail. This includes an analyzis of the current status of AR interaction techniques and a review of existing AR-based process guidance systems.

In light of the thesis's emphasis on the effective use of AR authoring tools, the intentions of citizen developers when sharing domain knowledge in the industrial metaverse, and the influence of emotional states on human motor control, the section concludes by introducing the relevant kernel theories. These theories are examined in terms of their contributions to prior research in IS design and HCI studies, establishing the theoretical foundation for the empirical and design-oriented components of this work.

2.1 Immersive Technologies

Augmented reality (AR) is one of several immersive technologies, alongside virtual reality (VR) and mixed reality (MR). In the literature, the term *Extended Reality* (XR) is often used as an umbrella term for all reality-altering or reality-expanding technologies (Xi et al. 2023). Given the significant disagreement and ambiguity surrounding these terms in both practice and academic discourse, this thesis begins by presenting a coherent framework to consolidate existing perspectives (Flavián et al. 2019; Milgram and Kishino 1994; Rauschnabel et al. 2022; Wedel et al. 2020).

One of the most widely recognized frameworks addressing this challenge is the reality-virtuality continuum proposed by Milgram and Kishino (1994). This linear continuum spans the range from purely real environments to fully virtual ones (see Figure 2). Within this continuum, mixed reality is defined as a hybrid form of reality situated between augmented reality and augmented virtuality (Farshid et al., 2018; Flavián et al., 2019). However, the reality-virtuality continuum has limited capacity to capture the nuanced differences among modern immersive technologies (Flavián et al. 2019; Rauschnabel et al. 2022).

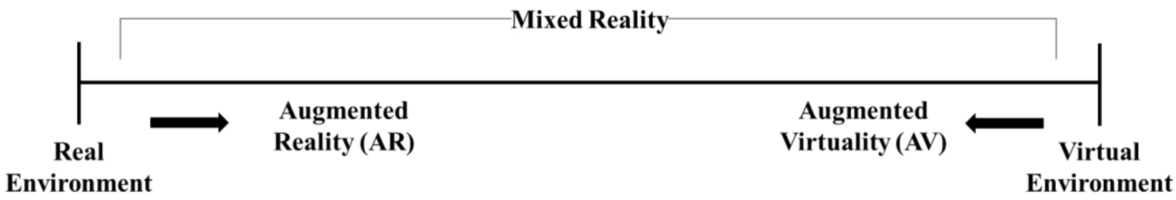

Figure 2. Reality-virtuality continuum proposed by (Milgram and Kishino 1994)

To address these limitations, Rauschnabel et al. (2022) propose a new framework that fundamentally differentiates immersive technologies such as AR and VR based on user experience and technical features. In this XR framework, the traditional term *Extended Reality* is replaced with *xReality*, where *X* acts as a variable representing different reality formats (Rauschnabel et al. 2022). Immersive technologies such as AR and VR are categorized along distinct continuums within this framework (see Figure 3).

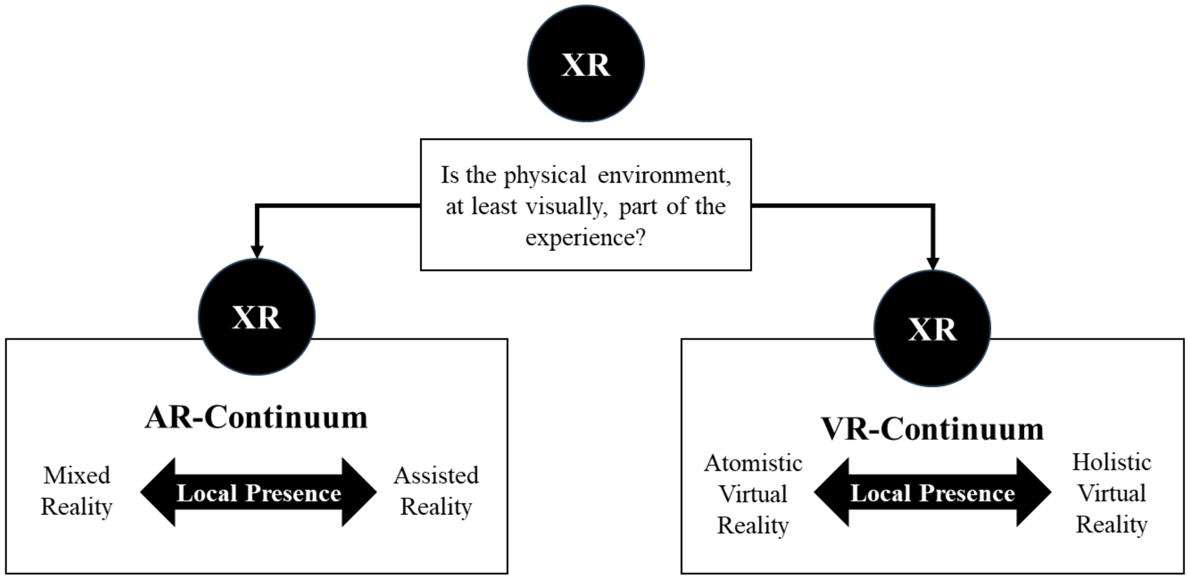

Figure 3. Simplified xReality Framework proposed by (Rauschnabel et al. 2022)

The first decision point in the XR framework is whether the physical environment is at least visually part of the experience. If so, the AR continuum is applied. This continuum ranges from *Assisted Reality*, which offers minimal interaction and low local presence, to *Mixed Reality*. In *Assisted Reality*, immersive content is perceived as artificial and overlaid, meaning it is not experienced as actually present. In contrast, *Mixed Reality* seamlessly and interactively combines the physical and virtual environments, allowing users to perceive immersive elements as genuinely present in their surroundings (Rauschnabel et al. 2022).

If the physical environment is not visually part of the experience, the VR continuum is used. This ranges from *Atomistic VR*, characterized by task-oriented environments with secondary telepresence, to *Holistic VR*. In *Atomistic VR*, user experience quality is often subordinate to achieving specific goals, making telepresence less central. *Holistic VR*, on the other hand, offers fully immersive and experiential virtual worlds that prioritize the user's perception of presence in the virtual environment (Rauschnabel et al. 2022).

2.1.1 Augmented Reality

AR is broadly defined as any case in which the physical environment is augmented with virtual, computer-generated objects (Milgram and Kishino 1994). The most widely accepted definition of AR comes from Azuma (1997), who identifies three central characteristics of an AR system: 1) the integration of physical and virtual content, 2) interactivity in real time, and 3) the registration of virtual content in three dimensions (3D). This definition excludes cases like films where physical and virtual objects are combined, as these involve only a recording of the physical environment for overlay purposes. Since such examples lack real-time interactivity, do not allow user interaction, and do not feature 3D registration of virtual content, they do not meet the criteria for an AR system. A key advantage of AR is that it does not require users to be fully immersed in virtual worlds. This flexibility allows for the implementation of AR across a wide range of technologies that vary in their levels of interactivity and technical complexity (Steffen et al. 2019).

AR-based Process Guidance Systems

Process Guidance Systems (PGS) are commonly employed to assist employees in executing digital processes in a manner that aligns with established workflows (Morana et al. 2017). However, in industrial settings, numerous physical tasks limit the applicability of digital PGS. To address this, researchers have developed and evaluated AR-based PGS (Bräker et al. 2023a; Kammerer et al. 2018; Konopka et al. 2022). These systems allow employees to access context-relevant information precisely when and where it is needed, seamlessly integrated into their physical environment.

Due to the continuous implementation of cyber-physical systems, more and more data is available to employees. This rising flood of data leads to a fundamental disconnection from the physical environment (Porter and Heppelmann 2017). Thus, some researchers argue that while the physical environment is three-dimensional, the data we use daily to make new decisions are trapped in two-dimensional spaces like displays. The gap between the real and virtual environment hinders the ability to make the best possible decisions (Porter and Heppelmann 2017). Researchers and practitioners are already well aware of this gap, which is why one of the biggest use cases for AR is to provide process guidance based on data directly in situ (Klinker et al. 2018). Kortekamp et al. (2019) identified that this use case is the most frequently applied in the manufacturing environment. In this use case, information is displayed to the employees in situ, which is required for a process conform execution. For example, service technicians need to know the sequence of maintenance steps and how to perform them.

AR is used especially for complex tasks in the field of aerospace technology to complete the work in a process-compliant manner. For example, authors Chen et al. (2019) initiated and evaluated an AR application that guides service technicians through the assembly process of cables in large spacecraft components. In another AR application, service technicians are guided through the process of installing an aircraft's wiring harness. Using AR reduced the time required to identify the parts to be installed. As a result, maintenance time was reduced by 90% (Serván et al. 2011). These are just two examples of how AR can be used to support complex tasks. Many more AR applications in this context exist in the literature (Choi et al. 2022; Tang et al. 2003). In addition to the AR applications, researchers have identified six classes of information types (i.e., identity, location, way-to, notification, order, and orientation) with which a maintenance manual can be fully represented in AR (Gattullo et al. 2020).

AR Authoring

AR authoring tools provide a framework for designing, developing, and managing AR applications by integrating virtual objects with the physical environment, requiring the creation and manipulation of AR elements (Nebeling and Speicher 2018). Research on AR authoring tools, particularly in the human-computer interaction field, has focused on authoring tools designed for developers with varying skill levels and for different stages of application fidelity (Ashtari et al. 2020; Krauß et al. 2021). A systematic literature review of databases, including Scopus, IEEE Xplore, ACM Digital Library, and AIS eLibrary, focusing on publications since 2017, identified 60 distinct AR authoring tools (vom Brocke et al. 2009). These tools were analyzed and classified into two main clusters based on their complexity and versatility.

The first cluster includes highly complex tools requiring programming and scripting expertise (Carmigniani et al. 2011). These tools are highly versatile and capable of creating custom AR applications tailored to nearly any requirement. Development using these tools typically occurs on desktop platforms with gizmo-based interactions. Common examples include Unity and Unreal Engine, which are predominantly developed and marketed by large companies such as Snap Inc., Apple, and Google.

The second cluster comprises less complex tools that require minimal or no programming skills. However, these tools are more limited in functionality and are often tailored to specific application domains. Development with these tools typically occurs on handheld devices or head-mounted displays, using interaction techniques such as touch-based interactions (Rajaram and Nebeling 2022), device-based interactions (Konopka et al. 2022), or mid-air gesture interactions (Damarowsky and Kühnel 2022). A practical example is Microsoft Dynamics 365 Guides, which is used to create AR instructions (Lavric et al. 2022). Focusing on the second cluster, it becomes evident that AR interaction techniques, like AR content, should be tailored to the specific use case and evaluated accordingly to maximize their effectiveness.

AR Interaction Techniques

This thesis focuses on handheld devices for AR, which are particularly relevant for small and medium-sized enterprises (SMEs) due to their widespread availability and low cost. Additionally, recent research has demonstrated that handheld devices are well-suited for AR development in industrial contexts. Unlike the use of AR instructions, these devices do not require hands-free operation when creating AR instructions (Hönemann et al. 2024).

In AR, 3D interaction is a fundamental concept, as defined in its early definitions (Azuma 1997). These interactions involve controlling six degrees of freedom (6DOF), with 3DOF relating to object translation and 3DOF to object rotation. For handheld mobile AR, 3D interactions for virtual object manipulation can be categorized into three main techniques: (1) *touch-based interaction*, (2) *device-based interaction techniques*, and (3) *mid-air gesture-based interactions*. This section provides a detailed explanation of these three AR interaction techniques. Figure 4 provides a graphical overview of the three main AR interaction techniques for handheld devices.

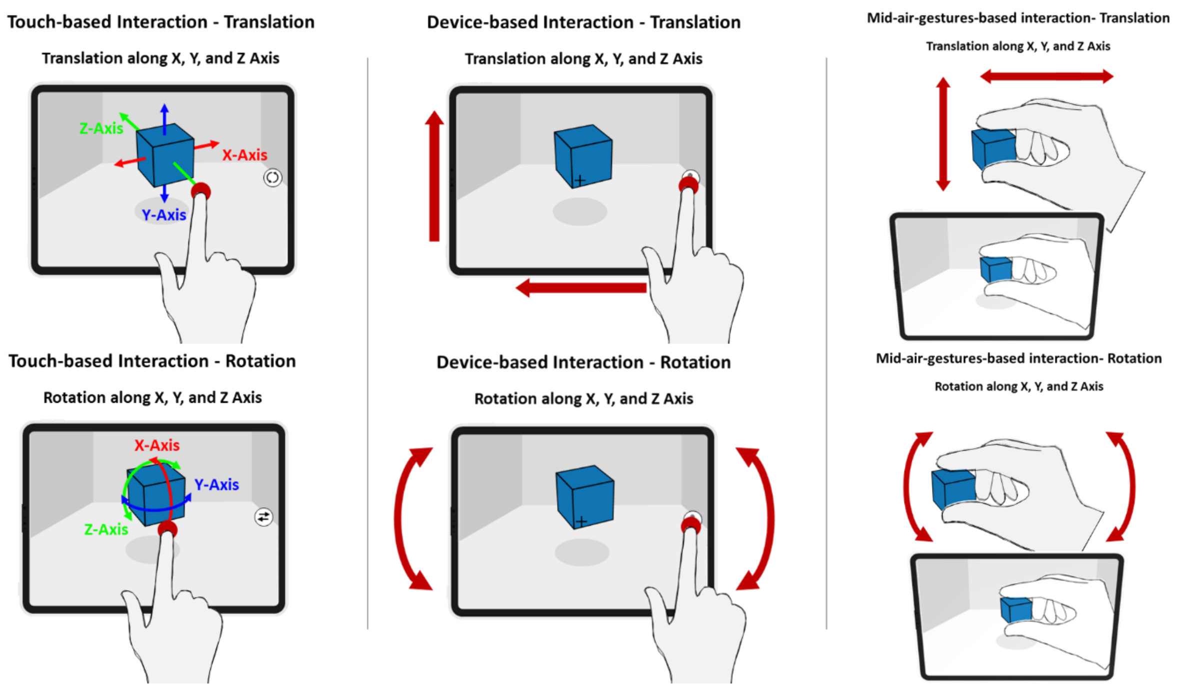

Figure 4. Examples of the three AR interaction techniques

Touch-based interaction: Touch-based interaction involves using on-screen touch inputs via fingertips to manipulate 3D objects (Goh et al. 2019). A key challenge with this interaction method is translating 2D touch points on the screen into 3D attributes to enable full 3D object manipulation, which requires controlling 6DOF (Martinet et al. 2010). To address the need for additional depth information for manipulating objects along the Z-axis, three approaches can be considered: One solution is integrating additional hardware capable of capturing depth information. For example, Wilson et al. (2008) proposed a camera that provides depth per pixel, allowing for the creation of detailed 3D models of the hand and enabling new interaction possibilities. However, incorporating additional hardware often increases costs. Another approach involves touch-based interactions using two fingers. (Liu et al. 2012) introduced a concept enabling 6DOF manipulation by using two fingers simultaneously on the screen. In this method, 3DOF translation and 1DOF rotation can be achieved by moving both fingers together, while an additional 2DOF rotation can be performed by moving one finger while the other remains stationary. A third option is utilizing translation and rotation gizmos, which enable complete 6DOF manipulation with a single finger. This method simplifies interactions while maintaining full 3D control (Drey et al. 2023).

Device-based interaction: Device-based interactions involve using the physical attributes of handheld mobile devices, such as rotation, tilting, skewing, and movement, to manipulate 3D objects (Goh et al. 2019). This interaction method offers several advantages, including the ability to hold the device with both hands, freedom from occlusion (Tanikawa et al. 2015), and generally faster manipulation of 3D objects compared to touch-based interactions (Marzo et al. 2014; Mossel et al. 2013). However, there are also notable limitations. One major drawback is the difficulty of performing large rotations (over 90°), which may require significant effort or may not be possible at all. To address this, Samini and Palmerius (2016) introduced a hold function, allowing larger rotations by fixing the object at different positions. Another limitation is the inability to perform translation and rotation separately, as these movements are inherently linked, any displacement includes rotation and vice versa. To overcome this issue, Polvi et al. (2016) implemented a method combining ray casting with epipolar geometry. This approach leverages the device's built-in positioning capabilities by aligning the camera's position with the 3D object to track movement. However, this technique does not allow for object rotation, which was supplemented by integrating touch-based interaction for rotational adjustments (Polvi et al. 2016).

Mid-air-gestures-based interaction: Mid-air gesture-based interactions involve tracking bare hands or finger gestures as input methods for manipulating 3D objects (Goh et al. 2019). This approach provides the most natural and intuitive way to interact with 3D objects. Similar to touch-based interactions, two main options are available to achieve full 6DOF manipulation: One approach is to incorporate additional hardware, such as data glove sensor systems. For example, Wang and Popović (2009) proposed a system that uses a single camera and a color-coded cloth glove. The color coding simplifies pose estimation, enabling the use of a nearest-neighbor approach to track the hand's movements. Another option leverages computer vision to recognize gestures. For instance Song et al. (2012), introduced a handle metaphor that visually links the user's hand gestures with corresponding virtual object manipulation actions. By tracking the relative 3D motion of both hands, this method enables precise 3D object control, even with low-resolution image data.

2.1.2 Virtual Reality

While early definitions of VR primarily focused on the underlying hardware (Steuer 1992), this thesis adopts a hardware-independent definition. Such an approach is more adaptable to technological advancements and avoids being overly tied to specific technical systems (Steffen et al. 2019). One definition of VR is based on the concept of telepresence, which refers to the experience of being present in a specific environment facilitated by technology. In this context, VR can be understood as a physical or virtual environment where users experience telepresence. Another essential feature of VR is immersion, which describes the perception of an interactive, computer-generated virtual environment presented in real-time and designed to mimic the characteristics of the physical world (Klein 2009). This concept is aptly summarized by the statement: "*As long as you can see the screen, you are not in virtual reality. When the screen disappears, and you see an imaginary scene [...] then you are in virtual reality*" (Pimentel and Teixeira 1993).

2.2 Metaverse

The metaverse offers users significant interpretational flexibility, which is unlikely to evolve in predictable patterns due to the intricate interplay between virtual and physical environments. These interactions foster dynamic social behaviors that vary across application contexts, often resulting in unforeseen outcomes (Dolata and Schwabe 2023). To build a better understanding of such interactions in the metaverse, IS research needs to develop a contextualized understanding of the metaverse's capabilities, components, and technologies for specific sectors (Dolata and Schwabe 2023; Dwivedi et al. 2022; Peukert et al. 2022). A sectoral perspective is important, as the social and technological requirements differ greatly across applications in different industries (Schöbel et al. 2023). By realizing a deeper understanding of how sectors influence requirements for the metaverse, companies can develop metaverse applications and strategies that strengthen their competitiveness (Dwivedi et al. 2022). To establish a shared understanding of the metaverse, this discussion explores its general applications across sectors and highlights the unique characteristics of the industrial metaverse.

2.2.1 General Metaverse Characteristics

First, the metaverse integrates virtual, augmented, and physical environments, enabling the exchange of information, actions, and interactions across these environments. This interplay allows users to create virtual content and transform it back into the physical environment as tangible physical artifacts or processes and vice versa (Schöbel and Leimeister 2023; Seidel et al. 2022). A purely virtual environment is typically of limited practical use, as certain tasks cannot be fully performed virtually. Similarly, augmented environments face challenges, such as locational constraints. In physical environments, decision-making data is typically available only in digital form. By intertwining these three environments, the metaverse exploits their complementary strengths while addressing their individual limitations.

Second, the metaverse nests the various environments in interconnected meta-design spaces (Seidel et al. 2022). One application on its own is not a metaverse As can be seen in Figure 5, the metaverse is an ecosystem consisting of interconnected meta-design spaces, and users should be able to move between the individual meta-design spaces in a natural and frictionless way (Nickerson et al. 2022b; Schöbel and Leimeister 2023; Seidel et al. 2022). Meta-design spaces consist of different metaverse applications (design spaces), each representing a solution to a specific problem. Thus, each meta-design space leads to a different experience (Seidel et al. 2022). Within an organization, design spaces are assigned, while meta-design spaces extend across multiple companies.

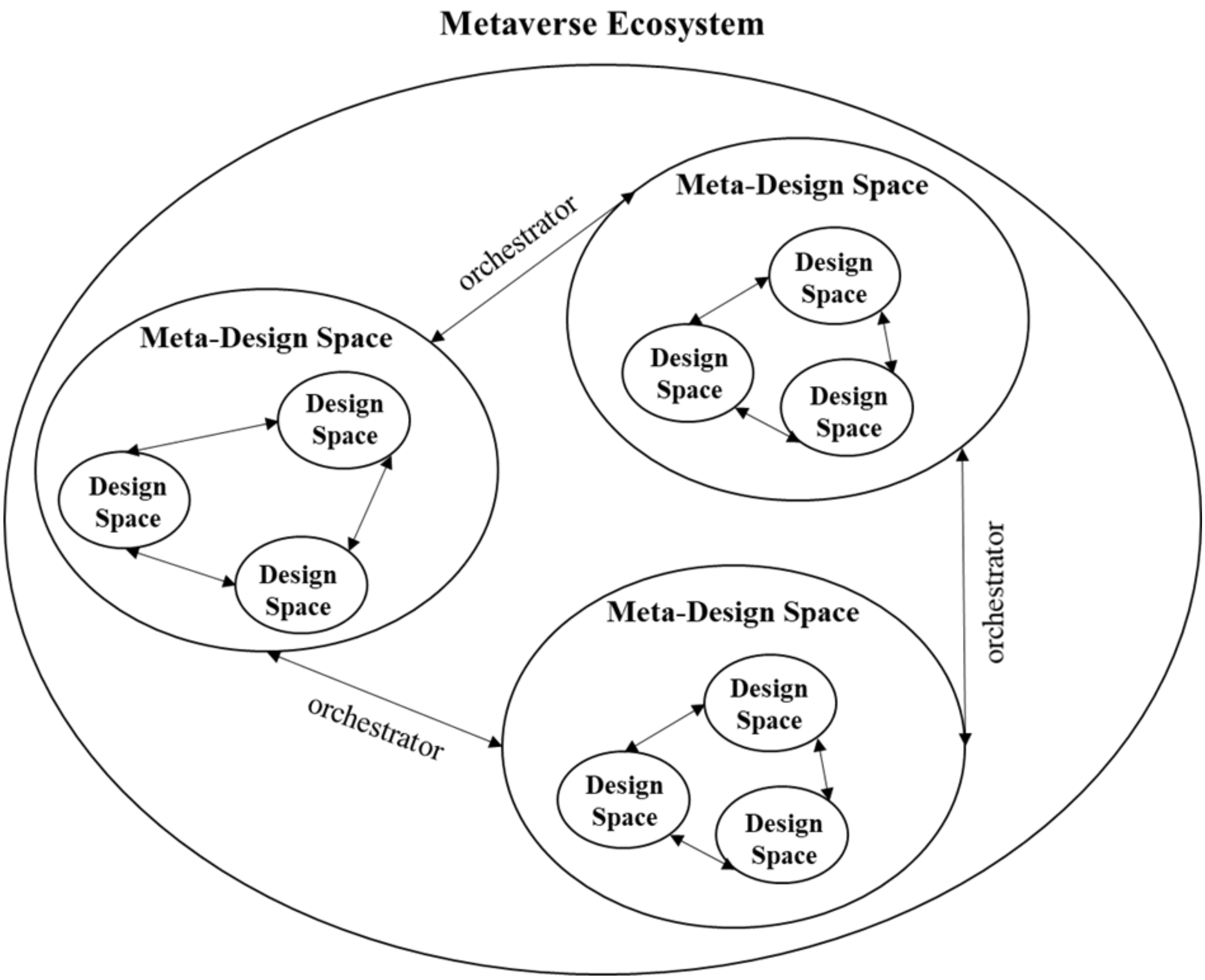

Figure 5. The metaverse ecosystem

Third, user immersion in the metaverse not only facilitates transitions between virtual, augmented, and physical environments (Nickerson et al. 2022b; Schöbel et al. 2023; Schöbel and Leimeister 2023; Seidel et al. 2022), but it is also essential to enter these environments, actively participate in them, and take advantage of their benefits. The most frequently discussed way to achieve this immersion and to enter the metaverse is through Augmented Reality (AR) or Virtual Reality (VR) interfaces (Dwivedi et al. 2022). Choosing the appropriate AR/VR interface for a specific metaverse application is crucial and should be guided by the application's context.

2.2.2 Industrial Metaverse Characteristics

While the metaverse encompasses consumer, enterprise, and industrial domains, the industrial metaverse is distinct in several key aspects. First, whereas the consumer and enterprise metaverse primarily aim to enhance social value (Duan et al. 2021), the industrial metaverse focuses on generating measurable industrial value. This shift requires research in the industrial metaverse to emphasize the interaction between physical environments and virtual or augmented environments, supporting operations in the physical industry, unlike the social interaction focus of consumer and enterprise metaverses (Yang et al. 2022).

Second, virtual or augmented environments' requirements for representational fidelity vary significantly across these realms (Park and Kim 2022). Drawing on the design tensions identified by Seidel et al. (2022), spatial and artificial tensions make these differences apparent. In the consumer metaverse, environments are designed for unrestricted movement (spatial tension = open-ended), enabling users to experience imaginative, metaphysical spaces without physical constraints, such as avatars flying (Dwivedi et al. 2022). These environments also feature detailed representations of imagined worlds (artificial tension with high imagination and fidelity) (Park and Kim 2022).

In contrast, enterprise metaverse environments are more restricted. For instance, users may collaborate in virtual offices where movement is confined to defined spaces (spatial tension = closed). These environments are often simpler in design, with lower levels of imagination and fidelity (artificial tension = low imagination and fidelity).

The industrial metaverse is fundamentally different, focusing on integrating virtual elements with physical machinery (Siyaev and Jo 2021). It demands high representational fidelity to replicate the physical environment and its properties, such as air resistance, enabling precise simulation of real-world processes (Dwivedi et al. 2022). These environments operate under strict rules, closely mirroring the physical world. Similar to the enterprise metaverse, spatial restrictions apply (spatial tension = closed), but these limitations stem from the user's physical environment rather than a virtual boundary. Industrial metaverse environments typically prioritize exact replication of the physical world (artificial tension = low imagination and high fidelity) (Burghardt et al. 2020).

Table 2 highlights the differences between these three metaverse realms based on the characteristics defined by Park and Kim (2022) Park and Kim (2021) and the design tensions outlined by Seidel et al. (2022).

Metaverse Realms			
	Consumer metaverse	**Enterprise metaverse**	**Industrial metaverse**
Definition	Create immersive experiences for entertainment and gaming purposes.	Create immersive communication and collaboration in the workplace and immersive business environments for company interactions with customers and other businesses.	Create interactions between the physical world and the virtual world to broaden the operations in the physical industry.

Application domain		Games and entertainment	White-collar work Knowledge work	Blue-collar work Manual labor
Value		Social value creation	Social + business value creation	Industrial value creation
Focus		Social interaction between people in the form of avatars	Social interaction between people in the form of avatars	Interaction between humans and physical assets
Environment	**Spatial tension**	Predominantly open-ended	Predominantly closed	Closed
	Artificial tension	High imagination, high fidelity	Low imagination, low fidelity	Low imagination, high fidelity
Requirements for content creation		High user experience through high-fidelity content	Support exchange between users in a virtual environment	Anchoring in situ domain knowledge in the physical and virtual environment

Table 2. Metaverse Realms Key Characteristics

2.2.3 From Virtual Objects to Physical Artifacts and Processes and Vice Versa

The industrial metaverse extends beyond the mere creation of immersive content, encompassing a broader framework that integrates virtual and physical domains seamlessly. This paradigm shift empowers employees to design and manipulate virtual objects within fused environments, which can subsequently be transformed into tangible physical artifacts or processes (Rajaram and Nebeling 2022; Seidel et al. 2022). A prime example of this transformation in the industrial metaverse is the concept of the digital twin.

A digital twin is a highly detailed virtual representation of a real-world object, mirroring it in every aspect and integrating data across its entire lifecycle (Dietz and Pernul 2020). Within the industrial metaverse, the development of digital twins focuses on creating objects that are not only photorealistic but also AI-enabled and physics-based. These advanced digital twins provide employees with immersive, on-site-like experiences, facilitating precise simulations and testing. The integration of digital twins in the industrial metaverse enables employees to conduct simulations in real-time without the constraints of cost or risk. Through this process, digital twins can be iteratively refined and customized based on simulation outcomes, eliminating the need for physical prototypes (MIT Technology Review Insights 2023). Once optimized, the digital twin serves as a blueprint for building the corresponding physical artifact or implementing the process exactly as tested in the virtual environment. In this way, the virtual object becomes a physical artifact or process within an industrial organization.

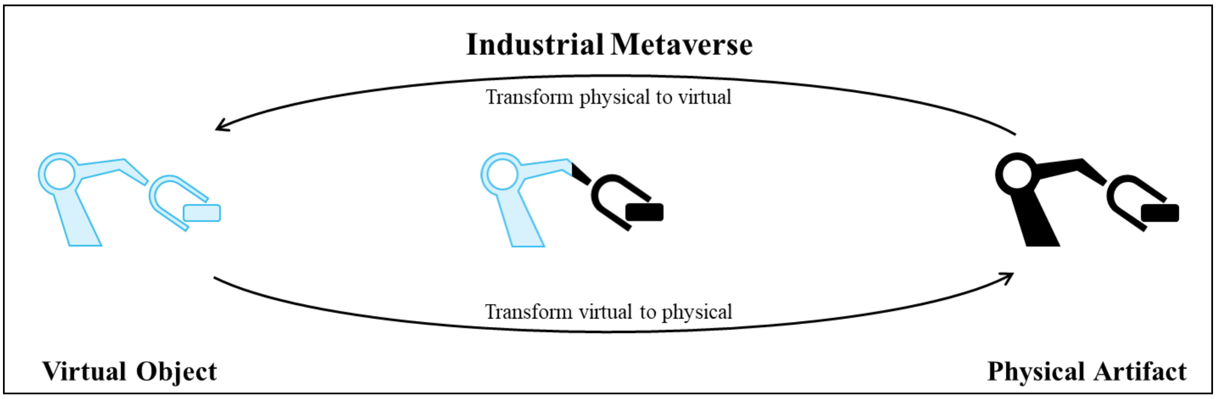

Figure 6. Transform virtual objects into physical artifacts and vice versa

Conversely, as shown in Figure 6, in the industrial metaverse, the employees must also be able to create physical artifacts or processes that can be transformed into virtual objects, enabling seamless sharing and collaboration with colleagues within the metaverse (Laviola et al. 2022). A notable application of this transformation is the development of AR-based process guidance systems, which bridge physical and virtual environments. These process guidance systems are information systems designed to support employees by offering structured guidance for decision-making, problem-solving, and task execution, often functioning as decision-support systems (Morana et al. 2017).

AR-based process guidance systems provide a novel approach to enhancing physical workflows by delivering real-time, contextual information directly within the employee's physical workspace at the moment it is needed (Azuma 1997). In manufacturing, the implementation of such process guidance systems offers substantial potential for cost savings and efficiency improvements. For instance, in large-scale manufacturing processes such as aircraft assembly, AR-based process guidance systems have been shown to reduce preparation times and minimize error rates (Cohen et al. 2018; Porter and Heppelmann 2017; Serván et al. 2011).

These process guidance systems map and virtualize physical processes such as machine repair, maintenance, or assembly, creating digital documentation that can be utilized within the industrial metaverse for various purposes. For example, they can be shared with their peers in the industrial metaverse and function as comprehensive training modules, allowing new employees to practice complex tasks like repair or maintenance in a risk-free virtual environment. Beyond training, these systems have practical applications in real-world scenarios, providing step-by-step guidance for complicated tasks such as assembly or maintenance, thereby reducing errors and improving efficiency. This integration effectively transforms physical artifacts into virtual objects or processes within the industrial metaverse.

2.2.4 Metaverse Identity Theft

Since in the final part of this thesis, we apply the knowledge gained about how citizen developers interact with immersive content in the metaverse to analyze and uncover their cognitive dynamics in various psychological states, using fraud as an example. To provide context, this section outlines the conceptual background and current state of metaverse identity theft, a specific form of fraud (Panicker et al. 2024).

Cybersecurity experts and organizations like UNICEF have emphasized the urgent need for research on identity theft in the metaverse (Vosloo et al. 2023), a threat that poses significant risks for everyday users, such as in countries like the United States and the United Kingdom (van Schaik et al. 2017). Since digital identity is central to accessing and interacting within the metaverse, users face heightened vulnerabilities to the theft or misuse of personal data (Sharma et al. 2024; Tariq et al. 2023). UNICEF has highlighted these risks, reporting an increase in cyberattacks targeting children, where stolen identity credentials and biometric data can lead to severe and long-term consequences (Pauwels 2022).

In cases of identity theft, fraudsters exploit stolen usernames, passwords, and biometric profiles to impersonate victims in virtual environments. This allows them to operate anonymously, adopting both the name and photorealistic avatar of the victim. Moreover, they can use the stolen identity to gather additional personal information from the victim’s social circle (Yang et al. 2023).

The risk of identity theft is particularly high in the metaverse, as verifying true identities is challenging due to the lack of traditional physical identification methods in virtual spaces. The appeal of anonymity in the metaverse, where users’ real identities are distinct from their virtual avatars, further complicates the implementation of verification procedures, such as Know-Your-Customer (KYC) processes commonly used in banking (Aygun et al. 2022; Sharma et al. 2024). While various identification methods have been proposed (Jaber 2022; Li et al. 2023; Ryu et al. 2022), many users value anonymity and may circumvent these processes even without fraudulent intent (Sharma et al. 2024; Vernaza et al. 2012).

To address these challenges and mitigate the growing threat of identity theft, in P5 we propose a method for unobtrusive and scalable analyzis of controller movement data. This approach enables early detection of fraudulent behavior. If suspicious activity is identified, the affected account can be temporarily restricted until the user completes an identification check to restore access.

2.3 Associated Theories

Since the first design cycle of this thesis focuses on the creation of metaverse content, Effective Use Theory (EUT) and its associated dimensions, transparent interaction and representational fidelity, are of particular relevance for developing an initial understanding of how AR interaction techniques can be used effectively by citizen developers in the industrial metaverse to create AR instructions (Burton-Jones and Grange 2013). According to EUT, it is not sufficient for systems to be merely used; they must be used effectively to maximize their benefits (Burton-Jones and Grange 2013). Figure 7 illustrates the theories employed throughout the thesis and their alignment with the respective design cycles of the overall design science research project.

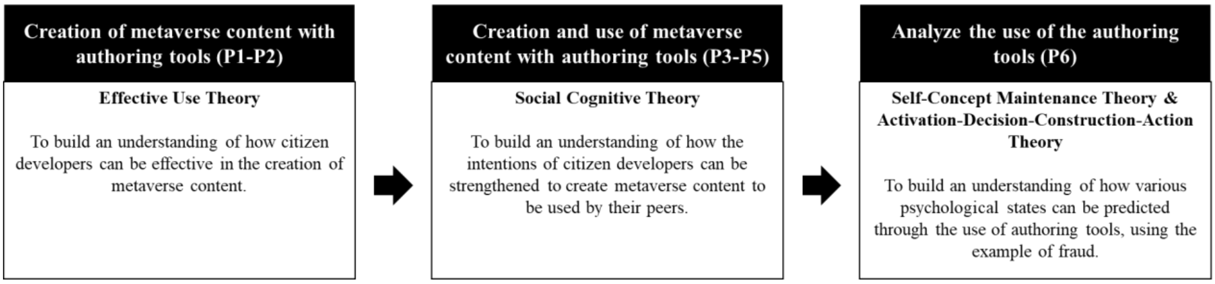

Figure 7. Applied theories along the design cycles

The second design cycle extends the focus from content creation to the actual use of the developed metaverse content. In this context, it is not enough to enable citizen developers to create content from a purely technical perspective. Their motivation and intention to engage in content creation must also be supported, particularly since the creation of industrial metaverse content represents a form of knowledge sharing (Funk et al. 2017; Zallio and Clarkson 2022). Citizen developers encode their domain expertise into immersive content that can be shared with their peers. To understand how AR authoring tools can strengthen this intention, Social Cognitive Theory (SCT) (Bandura 1986) is used as a kernel theory. The SCT emphasizes the importance of self-efficacy, which has been shown to influence users' intentions to engage in knowledge-sharing behavior (Chiu et al. 2006; Hsu et al. 2007).

The third design cycle focuses on analyzing user behavior during the use of AR authoring tools in order to inform adaptive design recommendations for future tools. This design cycle examines how different psychological states affect interaction within the metaverse, with a particular focus on the psychological state of fraud. To explore the cognitive implications of fraudulent behavior on human motor control, this thesis draws on Self-Concept Maintenance Theory (SCMT), which explains the internal conflict individuals experience when engaging in dishonest actions while attempting to preserve a positive self-image (Mazar et al. 2008). Additionally, the Activation-Decision-Construction-Action Theory (ADCAT) is employed to further examine the processual nature of fraud, offering a nuanced understanding of the cognitive dynamics at each stage of a fraudulent act (Walczyk et al. 2014).

2.3.1 Effective Use Theory

Burton-Jones and Grange (2013) emphasizes that it is not sufficient for systems to be used, they must be used effectively to maximize their benefits. To address this, the authors introduced Effective Use Theory (EUT), grounded in representation theory. EUT defines effective use as the extent to which an IS supports users in achieving their goals. The theory comprises three hierarchical dimensions derived from representation theory: (1) transparent interaction, (2) representational fidelity, and (3) informed action (Burton-Jones and Grange 2013).

Each lower-level dimension is necessary but not sufficient for achieving the next higher-level dimension. Consequently, if users cannot interact transparently with an IS, their ability to obtain a faithful representation, and ultimately to act in an informed manner, is significantly reduced or prevented (Burton-Jones and Grange 2013). For this reason, the present thesis focuses on the first two dimensions: transparent interaction and representational fidelity. Transparent interaction refers to the degree to which users can access system representations without obstruction from the interface or its physical form. Representational fidelity denotes the extent to which the system's representations accurately reflect the underlying real-world domain (Burton-Jones and Grange 2013).

EUT has been widely applied in IS research, particularly in design-oriented studies aiming to improve system usability and understand user interaction. For instance, Ruoff et al. (2023) applied EUT to investigate how dashboard information can be designed to support effective decision-making in crisis scenarios. Similarly, Abouzahra and Ghasemaghaei (2022) used EUT to examine the effectiveness of wearable devices for seniors, highlighting their potential to enhance health outcomes.

2.3.2 Social Cognitive Theory

To explain the intentions of citizen developers when sharing their domain knowledge as virtual artifacts with peers in the industrial metaverse, we draw on SCT (Bandura 1986) as a kernel theory to conceptualize and develop design principles (DP) for an AR authoring tool. SCT posits that human behavior is determined by the continuous reciprocal interaction between behavioral, cognitive, and environmental factors. Specifically, it examines how environmental and cognitive factors influence behavior in a given context (Bandura 1986).

Two core tenets of the SCT, the self-efficacy and the outcome expectations, are particularly relevant to this thesis. Self-efficacy refers to an individual's self-assessment of their ability to perform specific tasks, influencing decisions about which behaviors to engage in and the amount of effort and persistence to apply when faced with challenges. Those with higher self-efficacy are likelier to engage in certain behaviors than those with lower self-efficacy (Bandura 1997). Outcome expectations, the second core tenet, involve an individual's anticipation of the consequences of their actions, which guides behavior based on the expected results in a given situation (Bandura 1997).

SCT is particularly well-suited as a kernel theory in this context because self-efficacy has proven critical to enabling behavior in both virtual and physical environments within industrial organizations. This is evident across domains such as knowledge sharing and acquisition (Chiu et al. 2006; Kim et al. 2011; Lin 2010). In virtual communities, self-efficacy is essential for knowledge sharing, as users who believe in their ability to share knowledge are more likely to do so (Hsu et al. 2007).

Creating immersive content for the industrial metaverse constitutes a form of knowledge exchange where domain experts (i.e., citizen developers) map their expertise into AR content to share it with other metaverse users (Funk et al. 2017; Zallio and Clarkson 2022). For experts to effectively share their domain knowledge in the industrial metaverse, their intentions to do so must be strengthened. A proven approach to encouraging participation in virtual communities (Hsu et al. 2007) and motivating content creation (Gangadharbatla 2008) is to enhance the self-efficacy of the citizen developers. Individuals with high self-efficacy are more likely to explore and engage with new virtual environments because they trust their ability to learn and adapt to new tasks and challenges (Buchholz et al. 2022; Chiu et al. 2006; Pellas 2014). Strengthening self-efficacy can thus play a pivotal role in enabling citizen developers to create and share immersive content within the industrial metaverse.

2.3.3 Self-Concept Maintenance Theory

To explain how the fraudulent behavior of individuals affects human motor control, we draw on the SCMT (Mazar et al. 2008). SCMT posits that individuals value honesty as a fundamental part of their internal reward system. Being honest allows individuals to act morally and sustain a positive self-concept, their perception of themselves (Griffin and Ross 1991; Sanitioso et al. 1990). When individuals fail to meet their internal standards of honesty, they face the need to adjust their self-concept, often leading to negative self-perception (Bénabou and Tirole 2004).

To avoid this, individuals strive to maintain their internal standards, thereby preventing negative updates to their self-concept and preserving a positive self-image.

SCMT has been widely applied to IS studies on fraudulent behavior. For example, it has been used to explore how students justify using AI tools for academic dishonesty, helping researchers understand how students perceive certain behaviors as acceptable if they can maintain a positive self-image despite engaging in unethical acts (Bergström et al. 2024). Another application examined how awareness of moral standards influences adherence to safety guidelines, where the theory was used to show that priming individuals with moral cues could reduce unethical behaviors like safety policy violations (DePaula and Goel 2016).

According to SCMT, individuals may act dishonestly to gain external benefits but only to the extent that they can still preserve a positive self-concept. This creates a motivational conflict where individuals must balance two competing goals: pursuing external rewards (e.g., financial or social benefits) and maintaining their self-perception as honest (Mazar et al. 2008). This internal conflict makes fraudulent behavior cognitively more demanding than telling the truth (Christ et al. 2009; Suchotzki et al. 2017; Vrij et al. 2006).

2.3.4 Activation-Decision-Construction-Action Theory

To explain how individuals' fraudulent behavior impacts human motor control and how it can be distinguished from fraudulent intentions, this thesis draws additionally on the ADCAT (Walczyk et al. 2014). The ADCAT provides a framework for understanding how fraudulent individuals respond to demands for honesty, particularly in high-risk situations or those with significant consequences. It describes the cognitive and emotional resources involved in those fraudulent situations and how these demands fluctuate across different stages of the fraud process (Walczyk et al. 2014).

ADCAT offers a cognitive explanation of the fraud process by integrating established constructs from cognitive science, such as working memory and executive function. The framework divides deception into four distinct phases: (1) the activation of fraud, (2) the decision to commit fraud, (3) the construction of the fraudulent act, and (4) the execution of the fraud (Walczyk et al. 2014). Central to this framework is the Theory of Mind, which encompasses the social-cognitive processes through which the deceiver assesses and interprets the mental states of their target (Walczyk and Cockrell 2022).

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Throughout these phases, the individual's primary objective is to create the impression of honesty while maintaining fraudulent intentions. A critical aspect of this process is minimizing the outwardly visible cognitive effort to appear effortlessly honest (Walczyk et al. 2014). Successfully reducing the observable cognitive load is essential for maintaining the illusion of honesty during deception (Walczyk et al., 2014a; Colwell et al., 2006). This theoretical framework provides valuable insights into the cognitive demands of deception, helping to distinguish fraudulent intentions from actual fraudulent actions.

3 Research Approach

3.1 Research Strategy

This section outlines the research design of this thesis. To address the five research questions, we employed a comprehensive design science research (DSR) approach (Hevner et al. 2004), focusing on the design of innovative artifacts for real-world problems (Gregor and Hevner 2013). We opted for a design-oriented approach because it provides an abstract understanding of what was learned during the development of a software artifact and can serve as a template for the development of similar artifacts (Piirainen and Briggs 2011). We have adapted the approach of Kuechler and Vaishnavi (2008) and divided the entire DSR process into three successive design cycles (see Figure 8). In the following sections, the overall study design is presented along the three design cycles.

	First Design Cycle – Creation of metaverse content with authoring tools (P1-P2)	Second Design Cycle – Creation and use of metaverse content with authoring tools (P3-P5)	Third Design Cycle – Analyze the use of the authoring tools (P6)
Problem Awareness	Literature Review on AR interaction techniques and the effective use theory	Literature Review on AR authoring tools and the social cognitive theory	Literature Review on metaverse identity theft and the self concept maintenance theory
Suggestion	Formulation of the design principles for AR interaction techniques to effectively create AR instructions	Formulation of the design principles for AR Authoring tools to independently create metaverse content	Formulation of initial design hypothesis for detecting user behavior using authoring tools
Development	Instantiation of initial design principles as a software artifact in the form of an AR interaction technique	Instantiation of initial design principles as a software artifact in the form of an AR authoring	Developing an authoring tool that allows us to track human motor control to test our hypothesis
Evaluation	Evaluation of the software artifact in a laboratory experiment with 55 participants	Evaluation of the software artifact in a laboratory experiment with 115 participants + a utility check in a field study with 12 experts	Evaluation of our hypothesis in a laboratory experiment with 22 participants
Conclusion	Reflection on design principles and evaluation results	Reflection on design principles and evaluation results	Design suggestions for the design of future authoring tools based on the evaluation results

Figure 8. Overview of the design science approach of this thesis

First Design Cycle – Creation of metaverse content with authoring tools

The first design cycle addressed the lack of design knowledge related to metaverse content creation, with a specific focus on AR interaction techniques within AR authoring tools. The aim was to enable citizen developers to effectively create AR instructions for the industrial metaverse. The research process began with the *problem awareness* phase, in which a real-world problem motivating this thesis was identified. A literature review on AR interaction techniques (P1–P2) and Effective Use Theory (P2) informed the formulation of a set of meta-requirements (MR). In the *suggestion phase*, two design principles (DPs) for an effective AR interaction technique in the industrial metaverse were derived based on these MRs. In the *development phase*, we instantiated the DPs in a software artifact, an AR interaction technique.

This artifact served as a means to present and communicate the DPs and the nascent design theory, and it also functioned as an artifact for empirical testing (Jones and Gregor 2007). During the *evaluation phase*, we conducted a laboratory experiment to assess the performance of the developed AR interaction technique in comparison to two conventional techniques (P1) and to validate the proposed DPs (P2). A laboratory setting provided a controlled, formative evaluation environment that supported the comparison of design alternatives and allowed us to examine whether the proposed DPs enhanced transparent interaction and representational fidelity (Niehaves and Ortbach 2016; Venable et al. 2016). In the *conclusion phase* of the first design cycle, the findings and implications of the DPs, along with the software artifact, formed the foundation for the second design cycle.

Second Design Cycle – Creation and use of metaverse content with authoring tools

The second design cycle addressed the lack of design knowledge on how to develop AR authoring tools that not only enabled citizen developers to create metaverse content effectively but also strengthened their intention to do so, ensuring that the content they created could be used by peers within the industrial metaverse. Additionally, this cycle focused on integrating the design implications from both the first and second cycles into a nascent design theory for AR authoring tools, following the guidelines of Jones and Gregor (2007). As in the first cycle, the research process began with the *problem awareness phase*. Here, we conducted a literature review on AR authoring tools and Social Cognitive Theory (P3–P5) to derive an adapted set of MRs. These MRs represented the first component of a design theory by describing a class of goals to which the theory applied (Walls et al. 1992). In the *suggestion phase*, we developed three theoretically grounded DPs for AR authoring tools based on these MRs. In the *development phase*, we implemented the three DPs we proposed in a software artifact, an AR authoring tool. During the *evaluation phase*, we conducted two laboratory experiments to assess the validity of the first two DPs (P3, P5). To evaluate the third DP and the practical utility of the AR authoring tool, we conducted a case study in two industrial organizations (P4, P5). This included expert interviews with citizen developers who used the tool in their real work environments. We selected expert interviews as they served as a form of naturalistic evaluation, well-suited for validating theoretical artifacts within organizational contexts (Venable et al. 2016). In *the conclusion phase*, we synthesized the findings from this cycle into a nascent design theory, following the guidelines proposed by (Jones and Gregor 2007).

Third Design Cycle – Analyze the use of the authoring tools

The third and final design cycle of this thesis addressed the lack of design knowledge related to the psychological states of users when interacting with authoring tools in the metaverse. The objective was to analyze users' motor control movements to predict different psychological states, using fraud as an illustrative case, as it is a highly relevant case in the anonymous metaverse (Dwivedi et al. 2023) in order to derive design recommendations for future authoring tools. As in the previous design cycles, this cycle began with the *problem awareness phase*, during which we conducted a literature review on metaverse identity theft, Self-Concept Maintenance Theory, and Activation-Decision-Construction-Action Theory. In the *suggestion phase*, we formulated initial hypotheses to predict user behavior in the metaverse when using authoring tools, based on insights from the literature. During the *development phase*, we designed and implemented a software artifact, an authoring tool, to evaluate these hypotheses. In the *evaluation phase*, we evaluated the authoring tool in a laboratory experiment to assess the predictive value of motor control data in identifying fraudulent behavior. Finally, in the conclusion phase, we derived design recommendations for future metaverse authoring tools that aimed to detect potential fraudulent behavior at an early stage and without affecting users' interactions.

3.2 Research Methods

While the overall research procedure follows a design science approach, different quantitative and qualitative methods are applied across the various phases of each design cycle, including the problem awareness and evaluation phases. Although each individual study provides detailed information about the specific methods used, the following section offers a brief overview of the methodological approaches employed throughout the thesis. Table 3 summarizes which methods are applied in each design cycle of the overall design science research approach.

	First Design Cycle	Second Design Cycle	Third Design Cycle
LR	○	○	○
EXP	●	●	●
CS		●	
LR: Literature Review EXP: Experiment CS: Case Study	**Legend:** ○ Method used problem awareness phase of the DSR process ● Method used evaluation phase of the DSR process		

Table 3. Overview of Research Methods Applied in Embedded Publications

3.2.1 Design Science Research

Design Science Research (DSR) is a problem-solving research paradigm that aims to extend human and organizational capabilities through the creation of innovative software artifacts (Hevner et al. 2004). At its core, DSR seeks to generate and validate prescriptive knowledge by designing and applying artifacts to achieve defined objectives. Within IS research, DSR focuses on innovations that improve organizational effectiveness and efficiency by analyzing, designing, implementing, managing, and utilizing information systems (Hevner et al. 2004). The DSR paradigm incorporates two key dimensions: Design Science (DS), which emphasizes methodological rigor in the design and evaluation of artifacts at a meta-level, and Design Research (DR), which focuses on the practical development and assessment of specific artifacts to address real-world challenges (Winter 2008). Given that this dissertation involves a DSR project aimed at evaluating software artifacts to solve practical problems, the emphasis is placed specifically on DR projects.

Central to DSR is the concept of artifacts, which may take the form of constructs, models, methods, or instantiations intended to resolve identified organizational challenges (Hevner, 2004). The design process in DSR typically follows an iterative cycle that includes problem identification and motivation, defining solution objectives, artifact design and development, demonstration and evaluation, and the communication of results (Hevner et al. 2004; Kuechler and Vaishnavi 2008). DSR thus contributes to knowledge expansion by creating practical solutions and generating design knowledge to support systematic artifact development in future research and practice (Gregor and Hevner 2013).

Within the DSR paradigm, researchers apply methodological frameworks to structure their research activities effectively. Notable frameworks include Action Design Research (ADR) (Sein et al. 2011), the Design Science Research Methodology (DSRM) (Peffers et al. 2007), and Design Science Research in Information Systems (DSRIS) (Kuechler and Vaishnavi 2008). This thesis adopts the DSRIS methodology proposed by Kuechler and Vaishnavi (2008), as it aligns closely with the project's objective of developing a prescriptive design theory for a particular class of IS artifacts.

3.2.2 Literature Review

The review and analyzis of existing research literature is a key step in the problem awareness phase across all three design cycles and serves as the foundation for subsequent design phases. The purpose of a literature review is to identify publications relevant to the research topic, to uncover gaps and tensions in the existing body of knowledge that motivate the design cycles (Kuechler and Vaishnavi 2008) and to derive future research questions (Webster & Watson, 2002). Several guidelines for conducting literature reviews have been established, including those by Webster and Watson (2022) and vom Brocke et al. (2009).

In conducting the literature search, scientific databases are reviewed using selected keywords. Both backward and forward searches are then performed to expand the initial set of publications identified (Webster and Watson 2022). The selection of keywords is based on the unit of analyzis and may be refined iteratively during the review process. In the backward search, references cited in the initially identified publications are examined for further relevant sources. In the forward search, publications that cite the initially identified publications are reviewed to uncover additional relevant publications (Levy and J. Ellis 2006). Finally, the selected publications are screened for relevance by coding key findings to key aspects using a concept matrix to structure and support the analyzis (vom Brocke et al. 2009; Webster and Watson 2022).

3.2.3 Experiments

The method of experiments plays a central role in the fields of IS research and DSR, as it serves as an effective approach for establishing cause-and-effect relationships between variables (Lazar et al. 2017; Recker 2021; Venable et al. 2016). Defined broadly, an experiment is a systematic investigation in which researchers intentionally introduce a treatment or manipulation to observe its effect on outcome variables. The manipulation of independent variables, control over intervening variables, and measurement of dependent variables are essential core elements of this method (Recker 2021). A crucial distinction exists between true experiments, which involve the random assignment of participants, and quasi-experiments, which lack randomization and therefore offer weaker causal inferences (Shadish et al. 2002).

The quality of experimental research largely depends on the careful definition and operationalization of variables and the precise formulation of hypotheses. Hypotheses serve as a framework to guide the research process and allow for the testing of specific predictions regarding relationships between variables (Lazar et al. 2017). Equally important are the concepts of internal validity, which ensures that the independent variable is the actual cause of the observed effect, and external validity, which concerns the generalizability of the results (Lazar et al. 2017).

In the context of the DSR paradigm, experiments prove particularly valuable because they are well-suited for testing different design principles embedded in alternative design solutions (Niehaves and Ortbach 2016). As an artificial and formative evaluation method, experiments also make it possible to assess early on whether proposed design principles improve key target variables derived from kernel theories, such as self-efficacy or effective use of developed artifacts (Venable et al. 2016).

3.2.4 Case Studies

Case studies are rich empirical investigations that examine and describe specific instances of a phenomenon within their real-life context (Yin 2009). This method is particularly useful when the phenomenon under study is broad and deeply embedded in its organizational environment (Benbasat et al. 1987). The strength of case studies lies in their use of multiple data sources, such as documents, archival records, interviews, observations, and physical artifacts, which enables researchers to explain causal relationships, describe phenomena within real-world settings, and illustrate theoretical arguments (Wiesche 2014). A distinction is made between single-case studies, which are appropriate for testing existing theories in unique or typical cases, and multi-case studies, which examine different contexts (Dyer and Wilkins 1991).

Within the DSR paradigm, single-case studies, particularly in the form of expert interviews, serve as a naturalistic evaluation method that is especially valuable for validating theoretical artifacts in organizational contexts (Venable et al. 2016). In IS research, interviews are considered one of the most important data collection techniques in qualitative studies, as they enable the gathering of detailed information on specific topics (Myers and Avison 2002). Semi-structured interviews, which use a flexible guide with open-ended questions, allow researchers to systematically capture subjective experiences, opinions, and knowledge from interviewees. This approach is particularly valuable for gaining a deep understanding of individuals' perspectives on developed software artifacts, technologies, and their organizational impact, and for illuminating complex phenomena from the viewpoint of those directly involved (Myers 1997).

Part B

4 A Comparative Study of Handheld Augmented Reality Interaction Techniques for Developing AR-Instructions using AR Authoring Tools (P1)

Title	A Comparative Study of Handheld Augmented Reality Interaction Techniques for Developing AR-Instructions Using AR Authoring Tools
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Publication	Computers in Industry (2024)
Status	Published
Contribution of first author	The first author was responsible for Methodology, Investigation, Formal analyzis, Conceptualization, problem definition, research design, data collection and analyzis, interpretation, and conceptual development and reporting. He further significantly contributed to the creation of the manuscript.
Citation	Hönemann, K., Konopka, B., Prilla, M., and Wiesche, M. (2025) "A Comparative Study of Handheld Augmented Reality Interaction Techniques for Developing AR Instructions using AR Authoring Tools," Computers in Industry (164), https://doi.org/10.1016/j.compind.2024.104205

Table 4. Fact Sheet Publication P1

Abstract: AR instructions offer companies tremendous savings potential. However, developing these AR instructions has traditionally been challenging due to the need for programming skills and spatial knowledge. To address this complexity, industry and academia are working to simplify AR development. A crucial aspect of this process is the accurate positioning of AR content within the physical environment, which requires effective AR interaction techniques that enable full 3D manipulation of AR elements. In this study, we conducted an experimental comparison of three different AR interaction techniques with 55 participants to empirically assess their performance, workload, and user satisfaction across tasks related to AR instruction development. Our findings contribute to the design of future AR instructions and AR authoring tools, emphasizing the importance of evaluating AR interaction techniques that can be utilized

by users without programming experience tailored to the specific needs of the intended application domain.

4.1 Introduction

Over the past three decades, numerous studies have demonstrated that augmented reality (AR) is a powerful and innovative technology that supports various industrial operations, including maintenance (Henderson and Feiner 2011) or quality control (Krenzer et al. 2019). One of the most significant use cases for AR in the industry is the utilization of AR instructions for process support (Klinker et al. 2018; Kortekamp et al. 2019). This application domain frequently leverages AR technology due to its substantial cost-saving potential. For example, implementing AR in Boeing's cable assembly processes resulted in a 40% productivity increase and a 25% reduction in wiring production time (Cohen et al. 2018). These savings drive industrial organizations to transition from traditional technical documentation to AR instructions (Porter and Heppelmann 2017). Traditional technical documentation, often presented as printed or electronic manuals, relies on comprehensive text and images (Geng et al. 2020), making it challenging to relate to the physical environment and the tasks involved (Chen et al. 2019). In contrast, AR-based technical instructions provide users with the necessary contextual information directly in the physical environment at the appropriate time (Azuma 1997). However, as AR applications become more widespread, so do the associated challenges. One of the most significant challenges in the industry is the complexity of developing AR applications. In addition to technical expertise, advanced programming skills are required, and virtual objects and their physical placements must be created within programming environments (Ashtari et al. 2020; Nebeling and Speicher 2018). Moreover, manually positioning AR elements in the physical environment requires AR interaction techniques that are unfamiliar to many users and demand extensive spatial knowledge (Azuma 2016; Bräker et al. 2023a). The complexity of developing AR applications has led to approximately 64% of AR applications in the industry being custom-built solutions (Palmarini et al. 2018). These custom-built solutions developments are often impractical for small and medium-sized enterprises, as even minor changes can result in significant development costs, thereby slowing the adoption of AR in the industry (Konopka et al. 2024).

While there is a trend to ease the AR development processes so that no extensive programming knowledge or experience is required, such as in traditional software development (Matook et al. 2023) or for developing AI-based systems (Elshan et al. 2023) recent research shows that the AR authoring tools are still mainly used by experienced software developers (Ashtari et al.

2020; Krauß et al. 2021; Nebeling and Speicher 2018). To further streamline the AR development process and empower domain experts, such as service technicians, to independently create AR instructions, previous research on AR development tools has primarily focused on simplifying the creation of AR content (Fortuna et al. 2024; Scurati et al. 2018). This approach enables domain experts to utilize pre-built 3D models, animations, and annotations to generate on-site AR instructions without requiring programming skills (Nebeling and Speicher 2018). However, while the development of AR content is a critical component of these authoring tools, another crucial aspect is the need for domain experts without programming expertise to manually anchor or position the AR content within the physical environment (Bräker et al. 2023a).

This task requires an interaction that allows the 3D movement of AR elements within the physical environment (henceforth referred to as the AR interaction technique). AR interaction techniques encompass the methods and mechanisms that enable users to manipulate AR elements anchored in the physical environment. While the field of human-computer interaction (HCI) broadly defines interaction as a reciprocal exchange between a user and a system, in this paper, we focus specifically on the actions a user actively performs, namely, the inputs users make within an immersive AR system (Hertel et al. 2021). Selecting the appropriate AR interaction technique is crucial for AR authoring tools, as precise and efficient positioning of AR content in the physical environment is a core component of AR instructions (Bräker et al. 2023a). Although the general performance of existing AR interaction techniques has been extensively studied (Geng et al. 2020; Goh et al. 2019), an examination of current AR authoring tools reveals that those not requiring programming knowledge are typically tailored to specific application domains (Damarowsky and Kühnel 2022; Laviola et al. 2022). Given the wide variation in application domains for immersive technologies in the industry (Buchholz et al. 2022; Dolata and Schwabe 2023), evaluating how different AR interaction techniques perform when applied to specific use cases is important. Our study focuses on handheld devices for AR, as their widespread availability and lower costs, compared to wearable devices, make them particularly accessible and appealing for small and medium-sized enterprises (SMEs). Additionally, current research has shown that handheld devices are well-suited as AR authoring tools in the industry, as they do not require hands-free operation during the development of AR instructions, unlike their use for executing AR instructions (Hönemann et al. 2024). To the best of our knowledge, there is no clear consensus on which AR interaction technique is best suited to convert traditional technical documentation into AR instructions. Therefore, we aim to address the following research questions:

RQ1: *What are the performance, workload, and satisfaction trade-offs of AR interaction techniques for conveying traditional technical documentation into AR instructions?*

RQ2: *What are the strengths, weaknesses, opportunities, and risks of using the different AR interaction techniques when creating AR instructions?*

To address these research questions, we conducted an experimental comparison of three different AR interaction techniques with a total of 55 participants, aiming to empirically evaluate the trade-offs in terms of performance, workload, and user satisfaction when positioning AR elements in designated locations across tasks necessary for developing AR instructions. Satisfaction refers to the user's satisfaction with the process and the final positioning of the 3D elements in the physical environment. Additionally, we assessed the strengths, weaknesses, opportunities, and risks associated with each AR interaction technique within the specific application domain. The tasks were derived from the six information types used to convert traditional technical documentation into AR instructions (Gattullo et al. 2020). To ensure that our results are generalizable and broadly applicable, we focused on AR interaction techniques suitable for standard handheld devices and based on the most common input methods in both practice and academia, namely, device-based and touch-based interactions (Goh et al. 2019). We compared three AR interaction methods: two touch-based interactions, *Gizmo-based* and *Plane-based*, and one *Device-based* interaction. *Gizmo-based* interaction represents a widely used 3D manipulation technique found in 3D modeling tools such as Unity (Unity Technologies 2024). *Plane-based* interaction is commonly employed in commercial AR applications like IKEA Place (IKEA 2017). The third method, *Device-based* interaction, relies on the movement of hardware rather than touch input and is utilized in commercial applications like the Apple Measure app (Apple 2024).

Our study contributes to the design of future AR instructions by identifying the tasks that participants found particularly challenging when creating AR instructions. Additionally, our qualitative findings provide insights into which AR interaction techniques may be suitable for applications beyond the domain of AR instructions and the risks associated with each technique. We also present empirical performance, workload, and user satisfaction data for the three AR interaction techniques evaluated. Finally, our results underscore the need to assess AR interaction techniques within AR authoring tools that are intended for users without programming experience, specifically tailored to their intended application domains.

This paper is organized as follows. First, we review the related work on AR interaction techniques, AR authoring tools, and the information types used to convey technical documentation into AR instructions. Next, we describe the laboratory experiment procedure and present the results. Finally, we conclude with a discussion of the findings.

4.2 Related Work

We have organized the related work into three sections: (1) Types of AR interaction techniques on handheld devices, (2) Augmented Reality Instructions, and (3) Augmented Reality Authoring Tools.

4.2.1 Types of AR Interaction Techniques on Handheld Devices

In AR, 3D interaction is a fundamental concept, as emphasized in its definition (Azuma 1997). These 3D interactions require control over six degrees of freedom (6DOF), with 3DOF for object translation and 3DOF for object rotation. In handheld mobile AR, virtual object manipulation techniques can be broadly categorized into two main types widely used in science and practice: (1) Touch-based interaction and (2) Device-based interaction techniques. This section provides a detailed description of these two handheld AR interaction techniques.

Touch-based interaction: Touch-based interaction involves using on-screen touch inputs via fingertips to manipulate 3D objects (Goh et al. 2019). A key challenge with this interaction type is mapping 2D touch points on a screen to 3D attributes, allowing for complete 3D object manipulation consisting of 6DOF (Martinet et al. 2010). Three approaches can be considered to obtain the additional depth information necessary for manipulating objects along the Z-axis. The first approach involves using additional hardware. For instance, Wilson et al. (2008) proposed a camera capable of providing depth information per pixel, which could be used to create a comprehensive 3D model of the hand, thereby expanding interaction possibilities. However, the need for additional hardware often leads to increased costs. The second approach to achieving full 3D object manipulation is through touch-based interaction using two fingers. For example, (Liu et al. 2012) proposed an interaction concept that enables 6DOF manipulation by using two fingers on the screen. This allows for 3DOF translation and 1DOF rotation with simultaneous finger movement, while an additional gesture involving one moving finger and one stationary finger can achieve 2DOF rotation. The third approach involves using translation and rotation gizmos, enabling 6DOF interaction with just one finger (Drey et al. 2023).

Device-based interaction: Device-based interaction refers to techniques that utilize the physical attributes of handheld mobile devices to manipulate 3D objects. Users control 3D objects by rotating, tilting, skewing, and moving the mobile device (Goh et al. 2019). This interaction category offers several advantages: the device can be held with both hands, it is free from occlusion (Tanikawa et al. 2015), and 3D objects can generally be manipulated more quickly compared to touch-based interactions (Marzo et al. 2014; Mossel et al. 2013). However, there are also notable drawbacks. For example, larger rotations (beyond 90°) are either difficult to perform or impossible without significant effort. To address this issue, Samini and Palmerius (2016) proposed an interaction method with a hold function, allowing larger rotations by fixing the object at various positions. Another challenge is that translation and rotation cannot be performed independently, a rotation accompanies each translation, and vice versa. To mitigate this, Polvi et al. (2016) employed ray casting in conjunction with epipolar geometry, integrating the device's existing positioning technique, which tracks the device's movement by aligning the built-in camera's position with the 3D object. Object rotation is impossible in this method, so a touch-based interaction was used as a complementary technique (Polvi et al. 2016).

4.2.2 Augmented Reality Instructions

One of the most important use cases of AR in the industry is the application of AR as a process guidance system, which is an AR instruction (Klinker et al. 2018; Kortekamp et al. 2019). These systems provide users with the right information at the right time and place in the physical environment, supporting them in performing their daily tasks in a process-compliant manner (Morana et al. 2017). These process guidance systems, in the form of AR instructions, are crucial in industrial settings due to their immense potential to facilitate the execution of complex and unfamiliar tasks (Hoffmann et al. 2020). For example, Serván et al. (2011) demonstrated a 90% reduction in preparation time using AR instructions, which assisted service operators in wiring harness installation by displaying both the tasks to be performed and the essential operating parameters directly in the operators' physical environment. Beyond cost savings, research has also shown that AR instructions can reduce the user's mental workload (Tang et al. 2003).

The information in an AR instruction can vary in type, and no standard classification exists. Gattullo et al. (2020) proposed six information types to convey traditional technical documentation in an AR instruction to streamline the development of AR instructions and identify the necessary AR content. A unique characteristic of these information types is their inclusion of dynamic content, such as animations, alongside static content, such as 3D models. In addition to the system model, an AR instruction typically includes both 3D and 2D elements (Gattullo et al. 2020; Mohr et al. 2015). Table 5 provides an overview of these six types of information and their respective characteristics.

Information Type	Description	System Models	Spatial Models	Example
Identity	To display the identity of an object	Static	2D	An image of the object
Location	To determine or highlight the location of an object in the user's physical environment	Static	3D	An arrow pointing at the object
Way-To	To visualize the operation to be carried out	Dynamic	3D	An animation showing how to move the object
Notification	To display additional information which are necessary for an assembly step, but also for different conditions or other quality indications	Static	2D	A text that displays a hint
Order	To visualize the assembly sequence	Static	2D	A number that indicates the assembly sequence
Orientation	To visualize the alignment of an object	Static	3D	A 3D model of the object

Table 5. Information types in AR instructions proposed by Gattullo et al. (2020)

4.2.3 Augmented Reality Authoring Tools

AR authoring tools provide an environment for designing, developing, and managing AR applications and experiences by integrating virtual objects with the physical environment, which involves developing and manipulating AR elements (Nebeling and Speicher 2018). These tools target developers with varying skill levels and address different stages of application fidelity (Ashtari et al. 2020; Krauß et al. 2021). By analyzing 60 different AR authoring tools from both scientific and practical contexts, we classified the landscape of AR authoring tools into two distinct clusters, as illustrated in Figure 9. The left side of Figure 9 presents a selective overview of various AR authoring tools identified in our analyzis. The left-hand coordinate system in Figure 9 classifies a selection of AR authoring tools based on their complexity (ranging from 1 – no programming knowledge required to 5 – advanced programming knowledge required) and their versatility in developing AR applications (ranging from 1 – suitable for one use case only to 5 – suitable for unlimited use cases). The right-hand coordinate system in Figure 9 shows the distribution of AR authoring tools, where the dark blue/grey areas represent coordinates with several tools assigned, and the lighter areas indicate coordinates with only a few tools assigned.

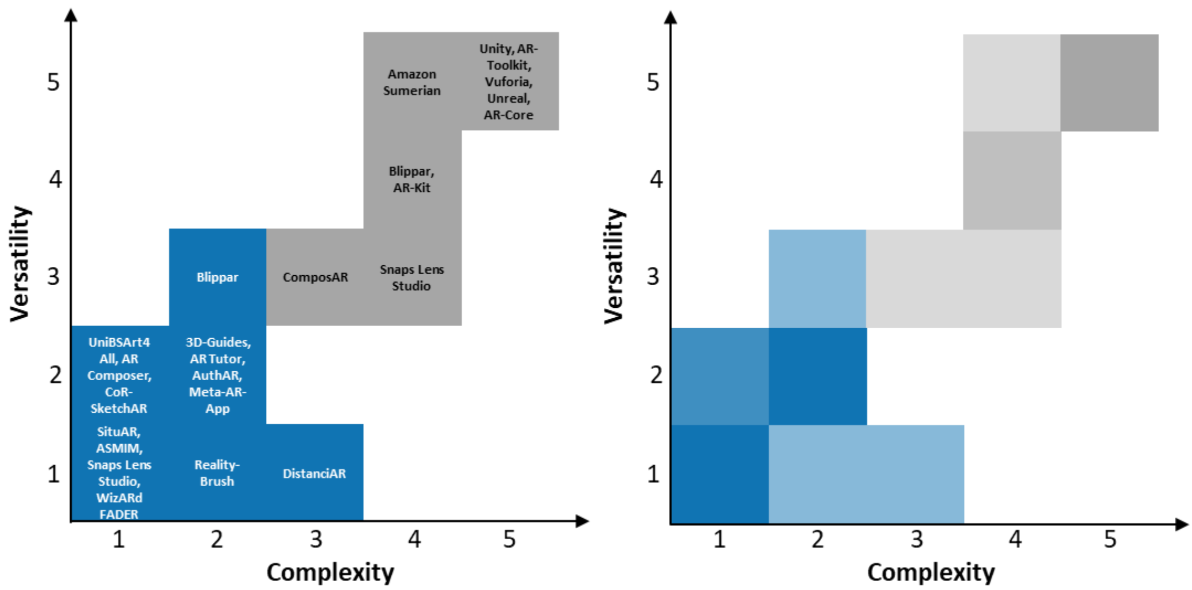

Figure 9. Clusters of AR authoring tools

The first cluster (grey) consists of highly complex tools that require programming and scripting knowledge (Carmigniani et al. 2011). Despite their complexity, these powerful tools can develop highly customized AR applications that can meet almost any requirement. As a result, both the complexity and versatility of these tools are very high. Developers often use gizmo interactions on desktops when creating AR applications with these tools. In practice, tools like Unity (Unity Technologies 2024) or Unreal (Unreal Engine 2024) are commonly used. Notably, though unsurprisingly, most of these tools are developed and marketed by large companies such as Snap Inc., Apple, and Google.

Tools in the second cluster (blue) consist of less complex tools that require little to no programming skills. However, these tools are limited in functionality and scope, often focusing on value creation within a specific application domain. Consequently, both the complexity and versatility of these tools are relatively low. The development of AR applications with tools from this cluster typically occurs on handheld devices or head-mounted displays using various interaction techniques, such as touch-based interactions (Rajaram and Nebeling 2022) or device-based interactions (Konopka et al. 2022). An example of a tool used in practice is Microsoft Dynamics 365 Guides, which can be used to develop AR instructions (Lavric et al. 2022).

A closer examination of the second cluster reveals that, just as developers tailor AR content to specific use cases, they should also tailor the AR interaction technique to the specific use case and evaluate it accordingly.

4.3 Method

To investigate the AR interaction techniques and the assumptions outlined in the previous section, we designed a laboratory experiment to compare three AR interaction techniques across a set of information types used to convey technical documentation into AR instructions. We first provided an overview of the (1) study design, (2) measures collected, and (3) study sample. We then detailed the (4) study procedure, (5) the three AR interaction techniques (*Plane-based*, G*izmo-based,* and D*evice-based*), and the lab experiment (6) tasks (*Order*, *Orientation*, *Way-To*, and *Location*).

4.3.1 Study Design

In designing this study, we adhered to the guidelines outlined by Bergström et al. (2021) for evaluating AR interaction techniques. We employed a repeated-measures within-subject design, where participants used each manipulation technique in a randomized sequence. We utilized a Latin Square design to ensure balance in the sequence of AR interaction techniques among participants.

Bergström et al. (2021) suggest limiting the number of independent variables to three, as this minimizes the influence of interpersonal variability on performance in low-level tasks. In alignment with these recommendations, we focused on two independent variables: A*R interaction techniques* (*Plane*, *Gizmo*, *Device*) and *task types* (*Order*, *Orientation*, *Way-To*, and *Location*).

Additionally, Bergström et al. (2021) recommend setting a threshold for object placement in manipulation tasks. In our study, this threshold was self-determined by participants, who positioned the AR element and confirmed the final position with a button press. A transparent version of the 3D object was used to visualize colocation, as suggested by Bergström et al. (2021). These transparent 3D objects are displayed on a virtual object that imitates the real environment to simulate an AR application.

The study also emphasized using low-level tasks, as Bergström et al. (2021) recommended, which involves separating pointing and selection from translation and rotation. Thus, our study focused exclusively on rotation and translation tasks. Furthermore, a discrete task setup was employed to maintain control over task distance, with manipulation objects starting from a consistent initial position.

Each participant used each AR interaction technique for tasks presented in a random order, except for task order, which followed realistic technical documentation. Participants began with the *Order* task (determining the assembly order of a cylinder), proceeded to the *Orientation* task (correctly positioning pistons), followed by the *Way-To* task (placing a piston on the connecting rod from the starting position), and concluded with the *Location* task (connecting the cylinder to the connecting rod with a pin). Each task included one practice trial followed by two evaluation trials.

In summary, participants engaged with three AR interaction techniques across four tasks per technique. Each task comprised three trials, including one practice trial and two evaluation trials. Thus, participants completed a total of 36 trials, with 24 designated as evaluation trials.

4.3.2 Measures

Through a post-survey, we collected demographic data such as age and gender to characterize the participants and assess their experience with AR, providing insight into their proficiency with AR technology. Additionally, we inquired about their 3D modeling experience to gauge their familiarity with the different AR interaction techniques.

The participants' workload and satisfaction with each AR interaction technique were assessed through a survey. Participants rated the AR interaction techniques using a seven-point Likert scale for satisfaction and a ten-point survey scale for workload. We measured workload using the RAW-TLX questionnaire (Hart 2006) and satisfaction using the questionnaire developed by Venkatesh et al. (2011). The measurement items for satisfaction are presented in Table 6.

I am … with the use of the **interaction technique.**		
SAT1	Extremely displeased . . .	Extremely pleased.
SAT2	Extremely frustrated . . .	Extremely contented.
SAT3	Extremely dissatisfied . . .	Extremely satisfied.

Table 6. Satisfaction measurement items (Venkatesh et al. 2011)

Following the guidelines of Bergström et al. (2021), we collected four performance measures for each evaluated trial: (1) Threshold time, the time from spawning the AR object to reaching the threshold accuracy; (2) Distance error, the deviation in millimeters (X, Y, and Z axes); (3) Path error, the path deviation in millimeters (X, Y, and Z axes); and (4) Rotation error, the deviation in degrees (X, Y, and Z axes).

We conducted a semi-structured interview to evaluate the strengths, weaknesses, opportunities, and risks associated with using the three AR interaction techniques in relation to the tasks. During the interviews, participants were asked to share their initial impressions of each AR interaction technique, including perceived strengths and weaknesses. We then asked them to identify potential opportunities and threats related to the AR interaction technique. The interviews were recorded and subsequently transcribed.

4.3.3 Participants

We selected a student sample comprising undergraduate, graduate, and postgraduate students from the fields of business economics and engineering, as they represent future domain experts in the industry. We recruited 57 participants for our lab experiment, excluding two participants due to incomplete performance data resulting from a technical error. Thus, our study included a total of 55 participants. The gender distribution was as follows: 53% (29 of 55) were male, 44% (24 of 55) were female, and 3% (2 of 55) chose not to disclose their gender. The average age of the participants was 28.7 years (SD = 9.76), with all participants providing their age information. The participants had a rather balanced overall *AR Experience*. When asked about their AR experience on a scale of 1-7 (1-No experience, 7-A lot of experience), only seven participants indicated that they had no AR experience (2: n=10; 3: n=14; 4: n=13; 5: n=4; 6: n=5; 7: n=2). The *3D Modeling Experience* of the participants, however, is somewhat lower. For example, 14 participants stated they had no 3D modeling experience at all (2: n=12; 3: n=9; 4: n=11; 5: n=5; 6: n=1; 7: n=3). Each participant received a gift of 15 euros as an incentive for participation. Additionally, to further motivate participants, the top three performers, those with the lowest average threshold time, distance error, rotation error, and path error across all AR interaction techniques and tasks, received an additional gift of 20 euros.

4.3.4 Procedure

At the beginning of each experimental session, participants were informed about the research objective: to evaluate three different AR interaction techniques across various information types to transform technical documentation into AR instructions. The experimental procedure was also explained to them. Participants were reminded to complete the tasks as quickly and accurately as possible. Following this introduction, the experiment commenced.

At the start of the experiment, the experimenter selected the initial AR interaction technique for each participant and placed a pre-built 3D model, serving as the task foundation, on a flat surface in the participant's physical environment. Participants were then provided with a tablet device to use during the tasks. Each of the four tasks began with a practice trial that participants could initiate independently. During the practice trial, participants were encouraged to take their time to familiarize themselves with the AR interaction technique and the task at hand. They were allowed to ask the experimenter questions regarding the task and the AR interaction technique if needed. The practice trials were marked as such in the application. Following the practice trial, participants proceeded with the evaluated trials. Figure 10 provides an overview of the study procedure in the laboratory environment.

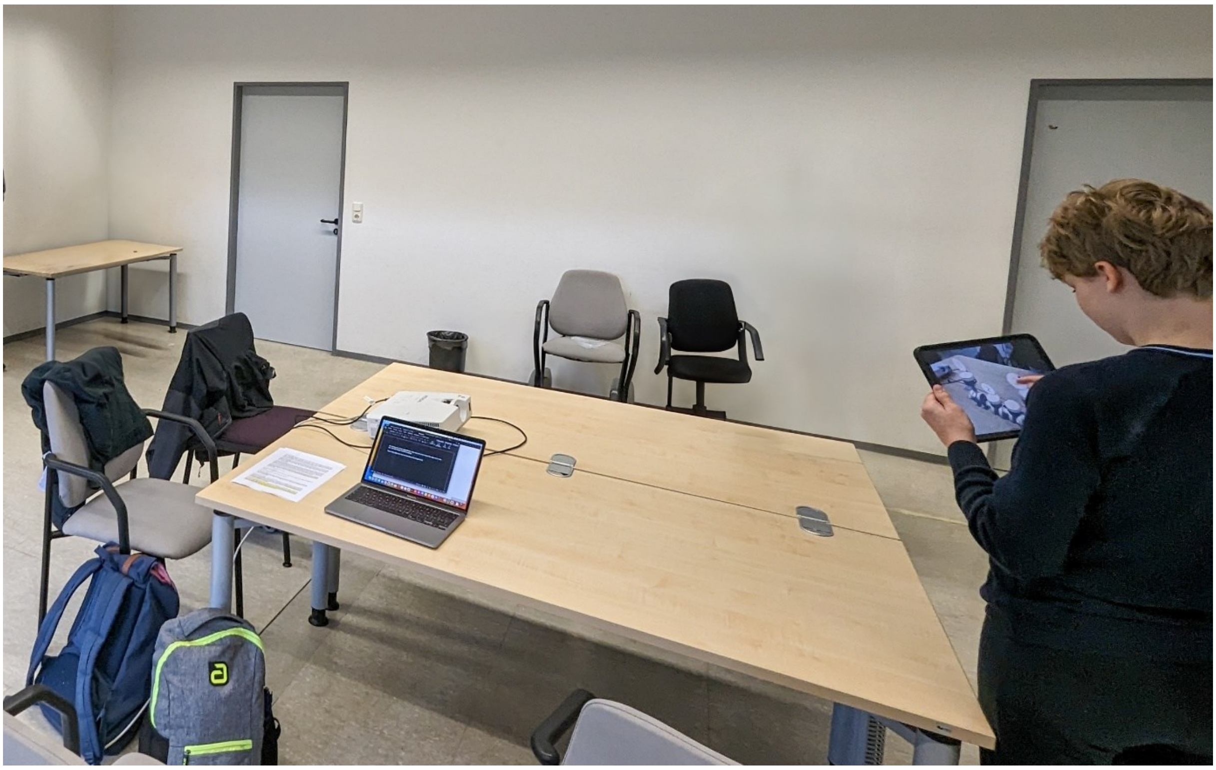

Figure 10. Conducting the study in the laboratory environment

Upon completing all four tasks using a specific AR interaction technique, a semi-structured interview was conducted. After the interview, participants were asked to complete a questionnaire assessing their workload and satisfaction of using the AR interaction techniques to complete the tasks (i.e., positioning the AR elements to the designated position). Once all tasks with all AR interaction techniques were completed, participants completed a final questionnaire collecting demographic data, AR experience, and 3D modelling experience. The entire lab experiment lasted between 45 and 60 minutes, depending on the speed at which participants completed the tasks and questionnaires.

4.3.5 AR Interaction Techniques

In our laboratory experiment, we compared three AR interaction techniques: two representing touch-based interaction and one representing device-based interaction. These AR interaction techniques are widely referenced and utilized in both scientific research (Goh et al. 2019) and practical applications in manufacturing and service. We focused on the following three AR interaction techniques, as illustrated in Figure 11.

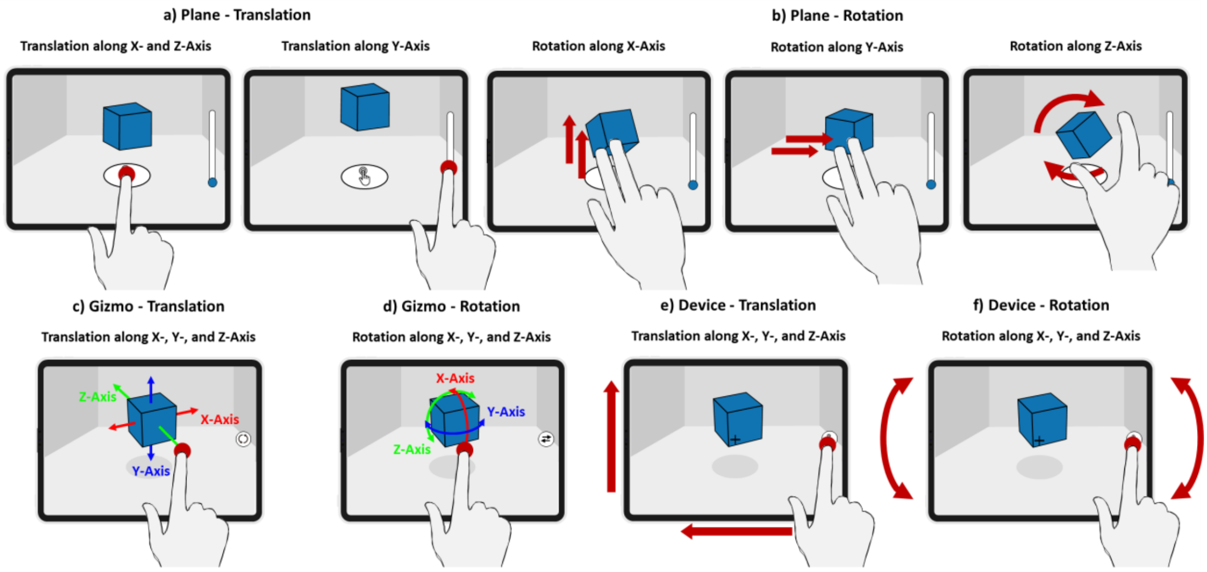

Figure 11. Three AR interaction techniques

Plane-based (Plane): In this technique, AR objects were moved along a surface detected by the device. By touching the plane beneath the AR objects, users could move them along the surface. As shown in Figure 11(a), only 2DOF (degrees of freedom) was possible when translating along a surface, so we implemented a slider that allowed the object to be moved vertically (1DOF). The surface always served as the origin, and moving the object below the surface was impossible. If a new surface was detected and the AR object was moved from one surface to another, the new surface became the starting point. Rotation in this technique was achieved through a 3D touch technique. Figure 11(b) illustrates the touch gestures that allowed AR objects to be rotated along all three axes. A horizontal movement with two fingers rotated the AR object along the Y-axis, while a vertical movement with two fingers rotated it along the X-axis. When fingers were moved diagonally, the AR object rotated along either the X or Y axis, depending on which axis the diagonal movement was closer to. The AR object rotated around the Z-axis when a rotation gesture was performed with two fingers, with the distance between the fingers determining the rotation speed, the closer the fingers, the slower the rotation. We chose this AR interaction because it is one of the most commonly used interactions in practice and is featured in several AR authoring tools (Nebeling and Speicher 2018). Practical examples include furnishing apps like IKEA Place (IKEA 2017) or messaging apps like Snapchat (Snap AR 2024).

Gizmo-based (Gizmo): In this technique, AR objects were translated and rotated using gizmos. As shown in Figure 11(c) and Figure 11(d), the AR objects could be moved and rotated by interacting with the different gizmos attached to the objects. Given the limited screen space on the device and to simplify the interaction for participants, we separated translation and rotation functions. A button allowed users to switch between translation and rotation modes. We selected this AR interaction technique because it represents a widely used 3D object manipulation method in AR authoring tools from the first cluster described in the previous section (Unity Technologies 2024; Unreal Engine 2024) and is also frequently utilized in AR authoring tools referenced in academic literature (Rajaram and Nebeling 2022).

Device-based (Device): In this technique, the device's own attributes were used, with the device serving as a controller for the interaction. As shown in Figure 11(e) and Figure 11(f), to translate or rotate an AR object, participants had to align the crosshair in the center of the display with the AR object they wished to manipulate. Pressing a button initiated the interaction, and releasing the button stopped it. X, Y, and Z translations were performed by physically moving the device along the desired axis; for instance, participants could move the AR object along the Z-axis by stepping forward or backward. X, Y, and Z rotations were achieved by rotating the device along the corresponding axis, such as simulating a steering wheel movement to rotate the AR object around the Z-axis. Due to ergonomic constraints, AR objects could only be rotated by approximately 90° at a time. To achieve a full 180° rotation, participants needed to rotate the object 90°, stop the interaction, return the device to the starting position, and then perform another 90° rotation. We selected this AR interaction technique because it is widely used in practice, such as in measurement apps like Apple's Measure app (Apple 2024), and is also featured in many AR authoring tools discussed in academic literature (Konopka et al. 2022).

4.3.6 Task

The six information types presented in the related work section served as the foundation for the tasks in our lab experiment. We focused on four of the six information types for the experiment. The two information types, ***Identify*** and ***Notification***, were excluded from the laboratory experiment because they are displayed in AR instructions using simple 2D elements without any reference to the physical environment. As a result, these types neither required nor allowed for 3D manipulation. In practice, the ***Identify*** information type is typically represented by a photo or illustration of the object, while ***Notification*** is usually conveyed through simple text. The Order task addresses manipulating 2D texts or images in the physical environment. We designed a practical and realistic task relevant to an industrial context for each of the four selected information types, as illustrated in Figure 12.

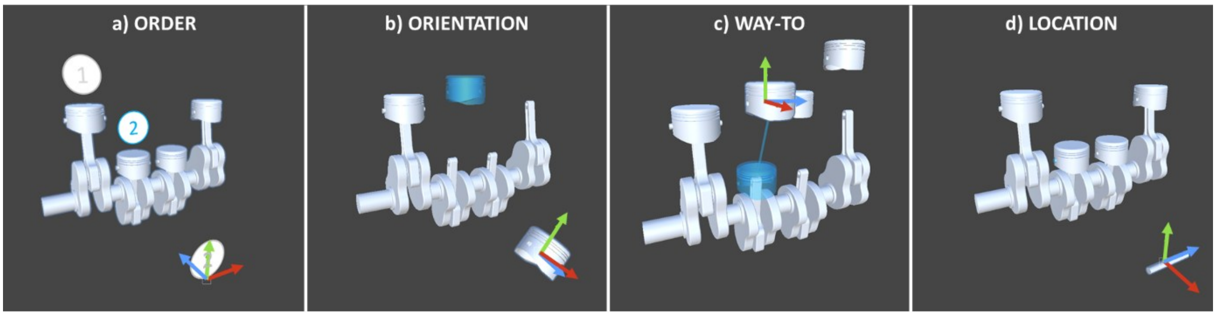

Figure 12. Four tasks to convey technical documentation in AR instructions

Order: As shown in Figure 12(a), this task required participants to attach a 2D object (a number) to a specified location (highlighted in blue) on the model, which would later be used to visualize the assembly process. Performance in this task was evaluated based on the accuracy of the 2D object placement in the designated locations.

Orientation: As shown in Figure 12(b), this task required participants to place a 3D object (a piston) in a specified location (highlighted in blue) relative to the model, ensuring that the 3D object's orientation would serve as the starting point for the next assembly step. Performance in this task was evaluated based on the precise placement of the 3D object in the designated location.

Way-To: As shown in Figure 12(c), this task required participants to move a 3D object (a piston) along a specified pathway (highlighted in blue), representing the creation of an animation (attaching a piston to the connecting rod). Performance in this task was evaluated based on the accuracy of the 3D object's movement along the designated pathway.

Location: As shown in Figure 12(d), this task required participants to place a 3D object (a connector pin) in a specified location (highlighted in blue) within another object, indicating the position for an assembly step. Unlike the *Orientation* task, this task involved placing objects inside another object, necessitating occluded interaction. Performance in this task was evaluated based on the precise placement of the 3D object in the designated location.

4.4 Results

The results section is structured as follows: (1) an analyzis of the performance data collected during the evaluated trials, (2) an analyzis of the workload and satisfaction data provided by participants in the questionnaire, and (3) participants' evaluations of the three AR interaction techniques in terms of strengths, weaknesses, opportunities, and risks.

4.4.1 Performance

We conducted a statistical analyzis of the dependent variables collected during our lab experiment. To compare the effects on nonparametric data, such as performance, we utilized the Aligned Rank Transform (ART) method, as proposed by Wobbrock et al. (2011). This approach enabled us to perform a three-way repeated measures ANOVA with factors for AR Interaction Technique, Task, and Time. In the ART method, data is first aligned for each effect before being ranked, making it suitable for non-normally distributed data (Wobbrock et al. 2011). The variable *Time* consisted of the first and second evaluated trials. Following this, we applied Bonferroni post-hoc tests for pairwise comparisons to identify significant differences between the AR interaction techniques. When Mauchly's test indicated a violation of the sphericity assumption, we applied Greenhouse-Geisser corrections in our analyzis.

Threshold time: Figure 13 shows the estimated marginal means of threshold time for the three interaction techniques across the four tasks during the first evaluated trial. We found a significant main effect for the variables *Task* and *Interaction*. Additionally, we observed a significant three-way interaction for *Task x Interaction x Time* ($F(6,324) = 9.04$, $p < 0.001$). Significant two-way interactions were identified for *Task x Interaction* in both the first evaluated trial ($F(6,324) = 3.12$, $p = 0.009$) and the second evaluated trial ($F(6,324) = 2.80$, $p < 0.020$).

In the first evaluated trial, there was a significant simple main effect for all tasks in reaching the threshold time across the AR interaction techniques ($p < 0.001$). Specifically, in the *Order* task, there was a significant difference between the *Device* and *Plane* interactions and between the *Device* and *Gizmo* interactions. For the *Orientation* task, significant differences were observed between the *Plane* and *Gizmo* interactions and between the *Gizmo* and *Device* interactions. Significant differences were found between all three interaction techniques in the Way-To task. For the *Location* task, significant differences were identified between the *Plane* and *Gizmo* interactions and between the *Gizmo* and *Device* interactions.

We also found significant simple main effects for the AR interaction techniques *Plane* ($p = 0.005$) and *Gizmo* ($p < 0.008$) in reaching the threshold time between tasks in the first evaluated trial. When using the *Plane* interaction, significant differences were observed between the tasks *Order* and *Location*, *Orientation* and *Way-To*, and *Way-To* and *Location*. For the *Gizmo* interaction, significant differences were found between the tasks *Order* and *Way-To*, *Orientation* and *Way-To*, and *Way-To* and *Location*. In the second evaluated trial, the same simple main effects were observed as in the first evaluated trial.

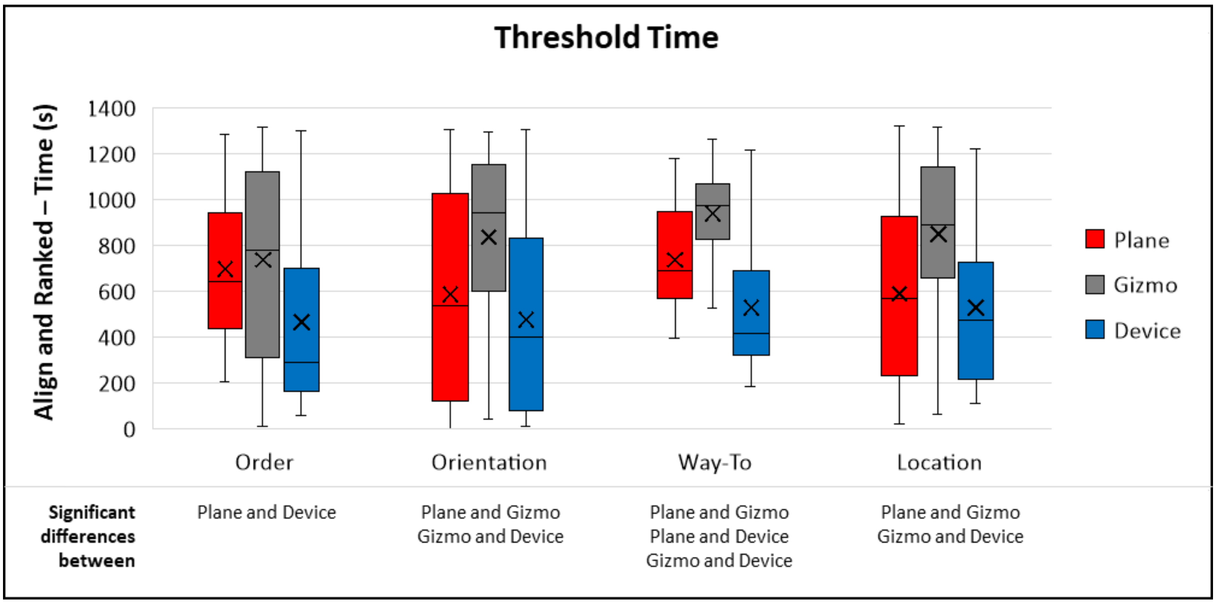

Figure 13. Estimated marginal means of the threshold time

Distance error: Figure 14 shows the estimated marginal means of the distance error for the three interaction techniques across the three tasks between the first and second evaluated trials. We found a significant main effect for the variables *Interaction* and *Time*. Additionally, there was a significant three-way interaction for *Task x Interaction x Time* (F(4,216) = 12.21, p < 0.001). Significant two-way interactions were identified for *Interaction x Time* in the *Order* task (F(2,108) = 6.78, p = 0.005), the *Orientation* task (F(2,108) = 14.05, p < 0.001), and the *Location* task (F(2,108) = 10.16, p < 0.001).

In the *Order* task, a significant simple main effect was found for the distance error across all AR interaction techniques between the first and second evaluated trials (*Plane* p < 0.001, *Gizmo* p = 0.048, *Device* p = 0.003). In the *Orientation* task, significant simple main effects were observed for the distance error with the *Plane* (p < 0.001) and *Gizmo* (p < 0.001) interactions between the first and second evaluated trials. In the *Location* task, significant simple main effects were also found for the distance error with the *Plane* (p = 0.014) and *Gizmo* (p = 0.005) interactions between the first and second evaluated trials.

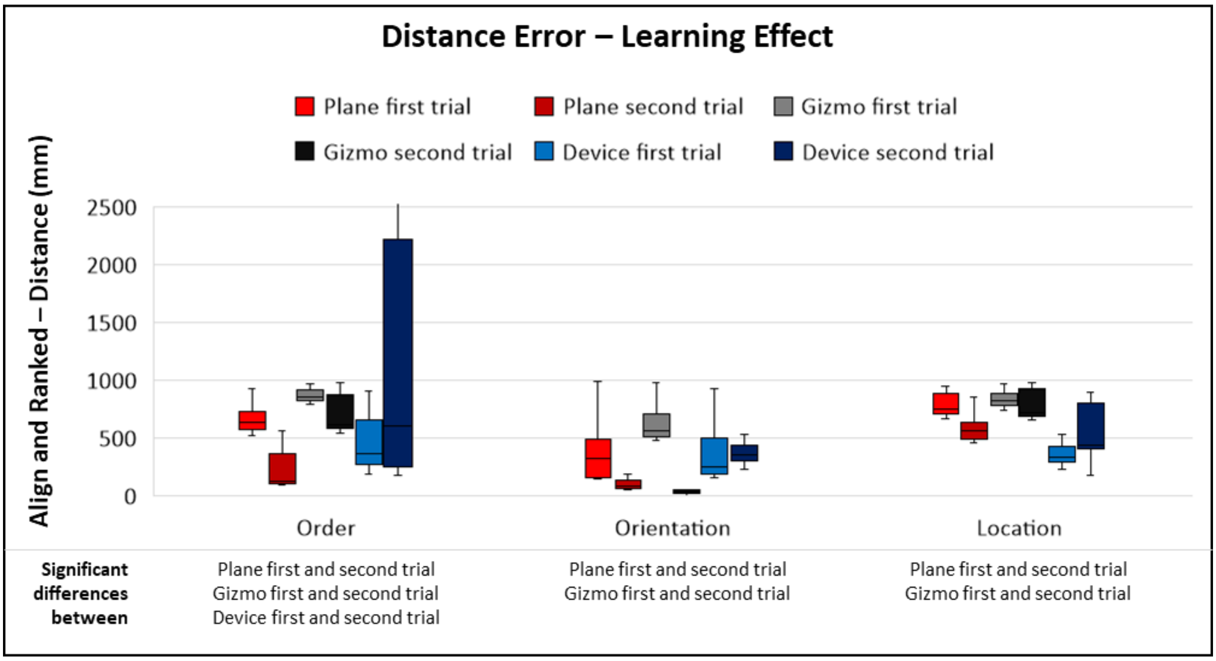

Figure 14. Estimated marginal means of distance error between first and second trail

Figure 15 shows the estimated marginal means of the distance error for the three interaction techniques across the three tasks during the first evaluated trial. We identified significant two-way interactions for *Task x Interaction* in both the first evaluated trial ($F(4,216) = 8.69$, $p < 0.001$) and the second evaluated trial ($F(4,216) = 2.87$, $p = 0.038$). In the first evaluated trial, there was a significant simple main effect for all tasks regarding distance error between the AR interaction techniques ($p < 0.001$). In the *Order* task, significant differences were found between the *Plane* and *Gizmo* interactions and between the *Device* and *Gizmo* interactions. The same significant differences were observed in the *Orientation* task. Significant differences were identified between all AR interaction techniques in the *Location* task.

Additionally, we found a significant simple main effect for the *Plane* ($p = 0.001$) and *Gizmo* ($p < 0.001$) interaction techniques regarding distance error across tasks in the first evaluated trial. Significant differences were observed between all tasks when using the Plane or Gizmo interactions.

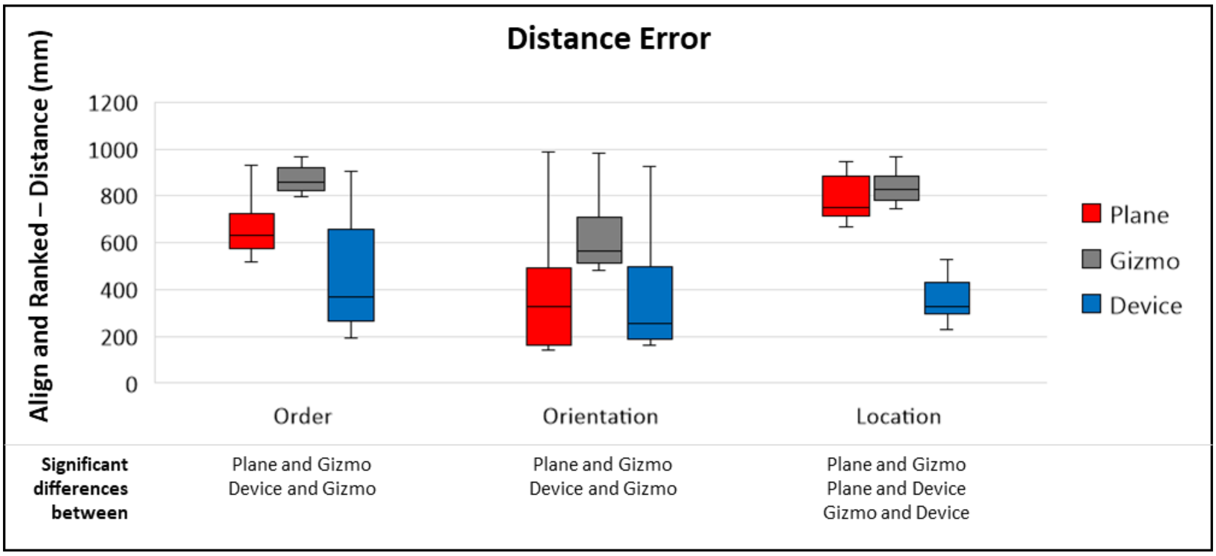

Figure 15. Estimated marginal means of the distance error

Rotation error: Figure 16 shows the estimated marginal means of the rotation error for the three interaction techniques across the three tasks between the first and second evaluated trials. We found a significant main effect for the variables *Task* and *Time*. Additionally, we observed a significant three-way interaction for *Task x Interaction x Time* ($F(4,216) = 7.23$, $p < 0.001$). Significant two-way interactions were identified for *Interaction x Time* in the *Orientation* task ($F(2,108) = 6.97$, $p = 0.006$) and the *Location* task ($F(2,108) = 4.74$, $p = 0.025$).

In the *Orientation* task, we found a significant simple main effect for rotation error with the *Gizmo* ($p = 0.002$) and *Device* ($p = 0.028$) interactions between the first and second evaluated trials. In the *Location* task, a significant simple main effect was observed for the rotation error with the *Device* interaction ($p < 0.001$) between the first and second evaluated trials.

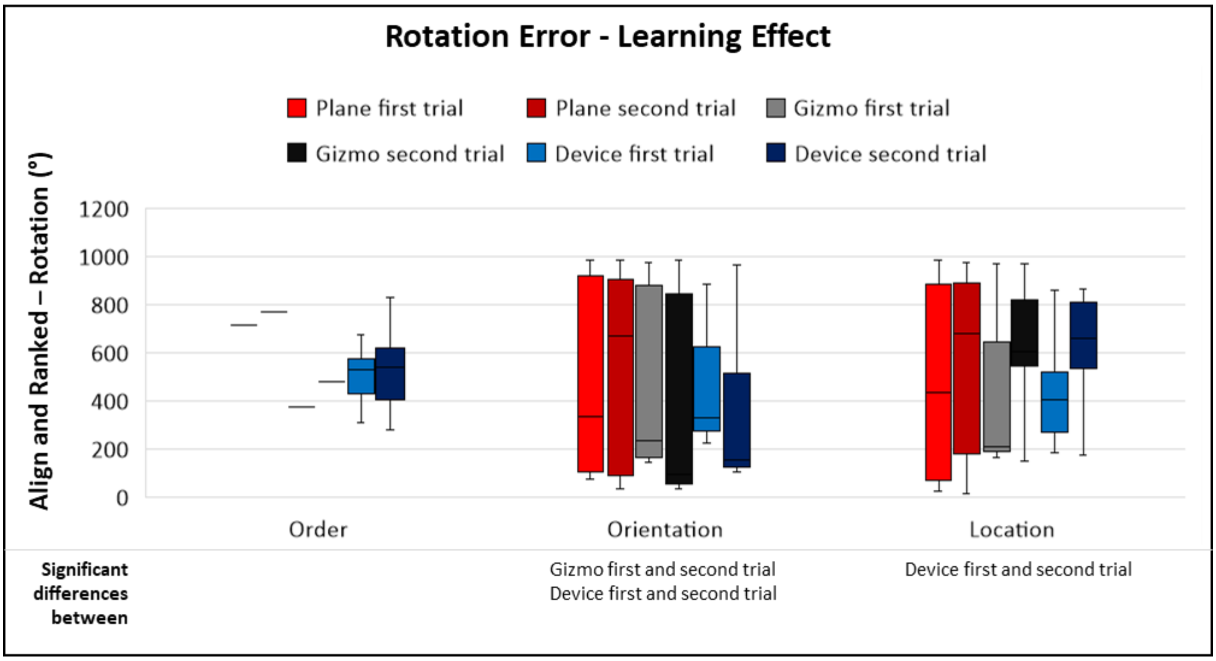

Figure 16. Estimated marginal means of rotation error between first and second trail

Figure 17 shows the estimated marginal means of the rotation error for the three interaction techniques across the three tasks. We identified significant two-way interactions for *Task x Interaction* in both the first evaluated trial (F(4,216) = 8.23, p < 0.001) and the second evaluated trial (F(4,216) = 3.78, p = 0.018). In the first evaluated trial, we found a significant simple main effect for the *Order* (p < 0.001) and *Orientation* (p = 0.037) tasks regarding rotation error between the AR interaction techniques. In the *Order* task, significant differences were observed between the *Plane* and *Gizmo* interactions and between the *Device* and *Gizmo* interactions. The same significant differences were found in the *Orientation* task.

Additionally, we found a significant simple main effect for the *Plane* (p = 0.001) and *Gizmo* (p = 0.016) interaction techniques regarding rotation error across tasks in the first evaluated trial. When using the *Plane* interaction, significant differences were observed between the *Order* and *Orientation* tasks and between the *Order* and *Location* tasks. Similar significant differences were found when using the *Gizmo* interaction.

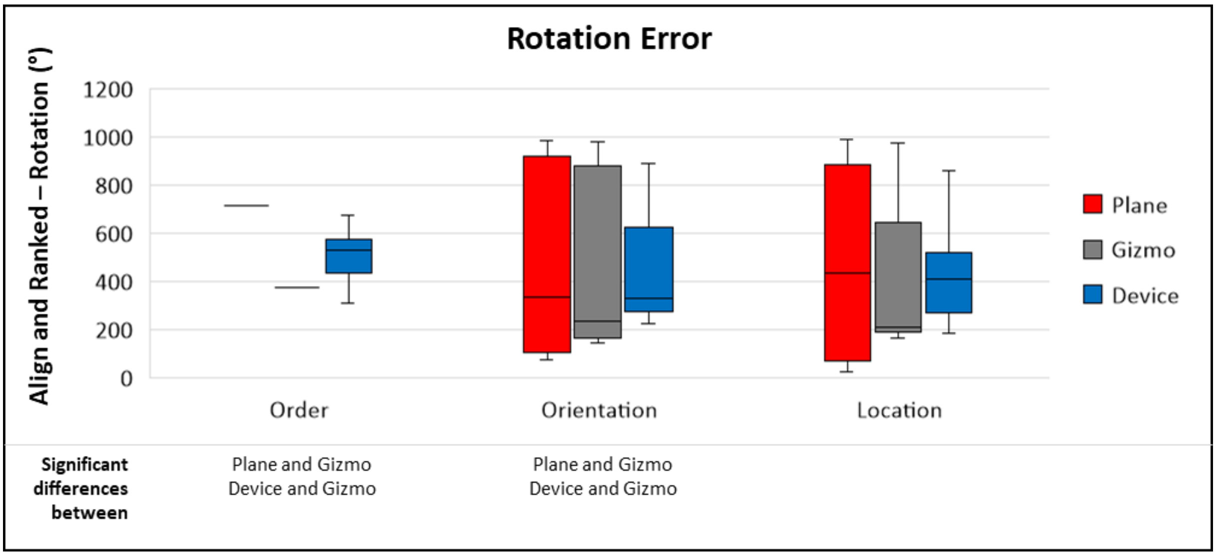

Figure 17. Estimated marginal means of the rotation error

Path error: Since path error was only measured in one task (Way-To), we conducted a two-way repeated measures ANOVA after aligning and ranking the data. We then applied Bonferroni post-hoc tests for pairwise comparisons to identify significant differences between the AR interaction techniques. Figure 18 shows the mean values of the path error for the three interaction techniques in the Way-To task. We found a significant main effect of Time ($F(1,54) = 13.91$, $p < 0.001$) on path error. The post-hoc analyzis revealed a significant difference in path error between the first and second evaluated trials, as well as a significant difference between the *Gizmo* and *Device* interactions.

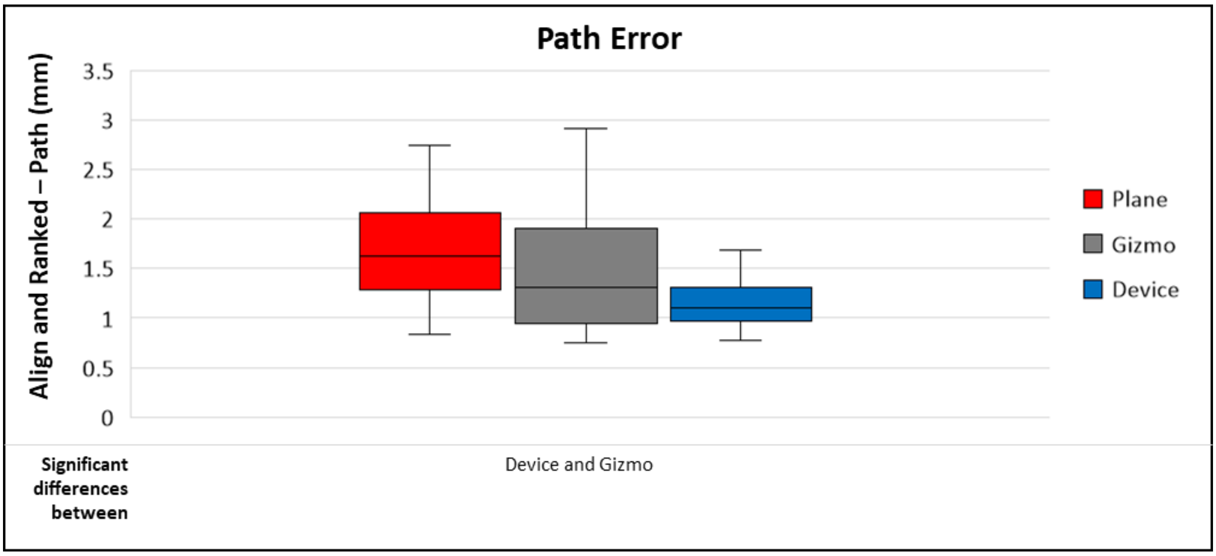

Figure 18. Mean values of the path error

4.4.2 Workload and Satisfaction

Based on the participants' workload and satisfaction ratings when using the different AR interaction techniques, measured on a seven-point Likert scale for satisfaction and a ten-point survey scale for workload, we conducted an ANOVA to compare the main effects of the AR interaction techniques. We then applied Bonferroni post-hoc tests for pairwise comparisons to identify significant differences between the AR interaction techniques.

Workload: Figure 19 shows the mean perceived workload of the three AR interaction techniques. We found a significant main effect of the AR interaction techniques on mental demand ($F(2,162) = 10.19$, $p < 0.001$), effort ($F(2,162) = 11.32$, $p < 0.001$), and frustration ($F(2,162) = 8.68$, $p < 0.001$). The post hoc analyzis revealed that the mental demand of using the *Plane* interaction technique was significantly lower than that of *Gizmo* ($t(162) = -1.56$, $p = 0.001$) and *Device* ($t(162) = -1.82$, $p = 0.001$). It also showed that the effort required for using *Plane* was significantly higher than for *Gizmo* ($t(162) = 1.36$, $p = 0.001$) and *Device* ($t(162) = 1.67$, $p < 0.001$). Additionally, the frustration associated with using *Plane* was significantly lower than that of *Gizmo* ($t(162) = -1.40$, $p = 0.009$) and *Device* ($t(162) = -1.86$, $p < 0.001$). No significant differences were identified between the *Gizmo* and *Device* interaction techniques.

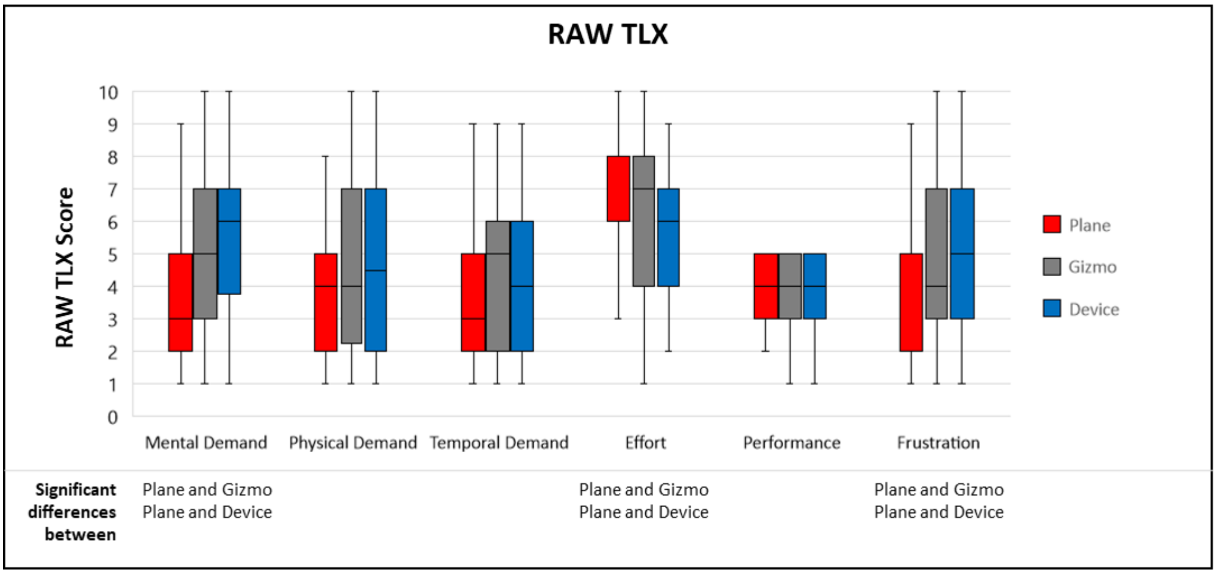

Figure 19. Workload grouped by the AR interaction techniques

Satisfaction: Figure 20 shows the mean perceived satisfaction with the three AR interaction techniques. We found a significant main effect of the AR interaction techniques on satisfaction ($F(2,162) = 14.75$, $p < 0.001$). The post hoc analyzis revealed that the *Plane* interaction technique resulted in significantly higher user satisfaction compared to both *Gizmo* ($t(162) = 0.96$, $p < 0.001$) and *Device* ($t(162) = 1.33$, $p < 0.001$).

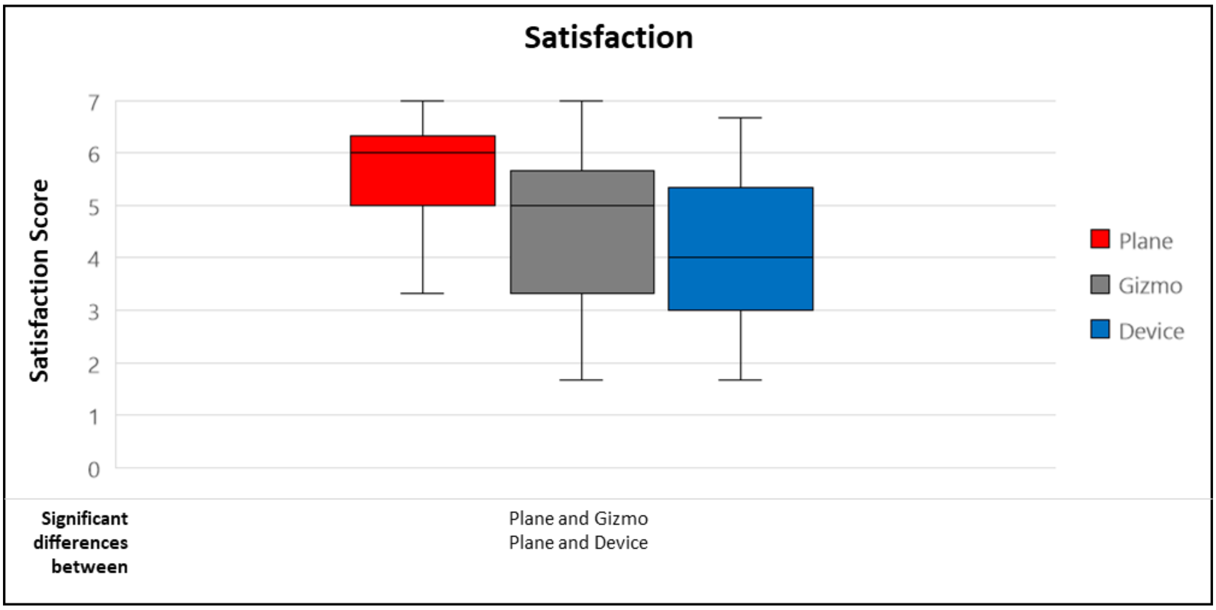

Figure 20. Satisfaction grouped by the AR interaction techniques

4.4.3 Qualitative Results

The objective of the semi-structured interviews was to evaluate the utility of different AR interaction techniques for the task types used to translate technical documentation into AR instructions. We employed a deductive approach to analyze the rich interview data (Sarker et al. 2013). Participants' opinions on the various AR interaction techniques were coded using open coding, with short descriptive statements summarizing the core idea of each text passage (Wiesche et al. 2017). We then analyzed the codes using the framework of SWOT analyzis. SWOT analyzis is a widely recognized method for systematic thinking and thorough assessment of factors related to new products, technologies, management, or planning (Weihrich 1982). The following SWOT analyzes summarize the most frequently mentioned strengths, weaknesses, opportunities, and threats of the different AR interaction techniques. The *Plane* interaction technique was found to be the most familiar to users, though it presented the greatest challenge when initiating 3D rotation. Table 7 provides a summary of the SWOT analyzis for the *Plane* AR interaction technique.

Plane				
Helpful		Harmful		
Familiar Interaction	*"[...] with the touch control it is reasonably intuitive [...] especially the control with one or two fingers is very familiar [...]"*	Difficulties with the rotation of the AR objects	*"The rotation has caused me problems. I haven't quite figured out which gestures to use to initiate which axis rotation. [...]"*	**Internal origins**
Fast translation of the AR Objects	*„I found it very good for the translation and also much faster. You only had to position the object*	Inaccuracy of the rotation of AR objects	*"The rotation has caused me problems. I have not found out with which gestures I initiate which rotation, [...]. "*	

	below the position and then move it up [...]"			
Suitable for occluded interactions	*"I found it worked well in the last task because the shadow (plane) was displayed below the object, and I, therefore, knew whether the position was roughly correct."*	Unsuitable for small AR objects	*"[...] If you click on the object to move it, you can no longer see the object, and then it feels more like a matter of luck whether it does what it is supposed to do."*	**External origins**
Suitable for placing AR objects on a flat surface (4 DOF)	*"[...] to create a navigation in 2D. So a path can be created for the technicians to show where the container door is so they can position themselves correctly."*	Initiating a rotation requires two fingers, which increases fatigue	*"There is a risk of fatigue and thus the risk of dropping the tablet, as you can only hold it in one hand, as the interaction requires two fingers."*	

Table 7. Summary of the SWOT Analyzis Regarding the Plane Interaction

The *Gizmo* interaction technique was found to be the least intuitive, but after a brief adjustment period, it led to the greatest learning effect among the participants. Table 8 provides a summary of the SWOT analyzis for the *Gizmo* AR interaction technique.

Gizmo				
Helpful		**Harmful**		
Precise placement of the AR objects	*"[...] I found it very good that the translation and the rotation are separated from each other, so I can customize exactly the axes I need."*	Difficult interaction due to limited space on mobile devices	*"I found the arrows too small. They were very difficult to grasp. You always had to turn the tablet in the right direction so that you could only see the arrow that you wanted to select [...]."*	**Internal origins**
		Time-consuming	*"Since you have to adjust each axle individually, it takes a very long time."*	
Suitable for technical constructions due to high precision and reliability	*"Rather in the area of construction to represent the position between objects. The focus here is not on movement but rather on the final position, so I would say construction rather than maintenance or assembly [...]"*	Unsuitable for creating animations	*"[...] because it is less about the movement, such as when you install or remove a part, and more about the final positioning."*	**External origins**
Suitable for occluded interactions since the gizmos are a great visual aid.	*"With the arrows, you can imagine exactly in which direction the object can be moved."*			

Table 8. Summary of the SWOT Analyzis Regarding the Gizmo Interaction

The *Device* AR interaction technique offers the most natural interaction, as AR elements can be positioned through the user's physical movement. However, this also presents the greatest challenge in achieving precise placement. Table 9 provides a summary of the SWOT analyzis for the *Device* AR interaction technique.

<table>
<tr><th colspan="5">Device</th></tr>
<tr><th colspan="2">Helpful</th><th colspan="2">Harmful</th><th></th></tr>
<tr><td>Intuitive and natural interaction</td><td>"[...] the strength is that I have control over it, that it does exactly what I want it to do because I can move it in a 3D environment, and I'm not locked into the screen [...]"</td><td rowspan="2">Difficulties with the precise positioning of the AR objects</td><td rowspan="2">“Only all axes can be manipulated at the same time. If I want to move the object just a little bit to the left, then I move all axes, and then there is a chance that it will be positioned worse than before.”</td><td rowspan="2">Internal origins</td></tr>
<tr><td>Fast positioning of the AR objects</td><td>"[...] due to the fact that I could do both the translation and the rotation at the same time through this interaction, this interaction was much faster [...]."</td></tr>
<tr><td>Suitable for creating Animations</td><td>“[...] especially for the task of moving the object along the blue line, the interaction seems very suitable.”</td><td>Unsuitable for occluded interactions</td><td>"[...] if the elements are placed in another object [...] then there is no visual display that indicates whether the object is currently aligned."</td><td rowspan="3">External origins</td></tr>
<tr><td rowspan="2">Suitable to move the AR objects over large areas</td><td rowspan="2">“You could use this in a large room if you want to move large components [...] this is much easier.”</td><td>Unsuitable for positioning 2D elements</td><td>“The positioning of 2D objects did not work well. I found it difficult to position the 2D objects on the same layer as indicated.”</td></tr>
<tr><td>The interaction takes up a lot of space, and people can get hurt</td><td>“You only look at the tablet and concentrate on the exact positioning, which means I don't really notice the surroundings, and there's a risk of bumping my head or similar.”</td></tr>
</table>

Table 9. Summary of the SWOT Analyzis Regarding the Device Interaction

4.5 Design Guidelines

Our experiment demonstrated the performance, workload, and satisfaction trade-offs across a series of tasks involved in creating AR instructions. In subsequent interviews, we identified the strengths, weaknesses, opportunities, and risks associated with different AR interaction techniques. Below, we consolidate our quantitative and qualitative findings into design guidelines to support the development of future AR instructions and AR authoring tools.

- **When focusing on time when creating the AR application, implement a device-based interaction.** By using device-based interaction, the AR objects can be positioned significantly faster in almost any task without a significant loss in positional accuracy in the physical environment.

- **When focusing on precision when creating the AR application, implement a gizmo-based interaction.** By using a gizmo-based interaction, AR objects can be positioned with the smallest rotation error in the physical environment by taking more time, as users can adjust each translation and rotation axis individually without affecting the other axes.
- **When creating an AR application with only 3DOF manipulation (i.e., 2 DOF translation and 1DOF rotation), implement a plane-based interaction.** The use of plane-based interaction provides a familiar interaction with the least effort and the highest satisfaction. Implementing full 3D manipulation (6DOF) causes the AR elements to be placed with a significantly larger rotation error due to an illusion of control.
- **When creating an AR application with many occluded objects, implement a gizmo-based interaction.** By using the gizmo-based interaction, the gizmos, which are always visible, provide a visual aid that indicates the orientation of the AR objects to the users.
- **When creating an AR application over a large area, implement a device-based interaction.** By using device-based interaction, users can manipulate all translation and rotation axes simultaneously, making moving AR objects over long distances easier and faster.
- **When creating an AR application with many animations, implement a device-based interaction.** By using device-based interaction, users can manipulate all translation and rotation axes simultaneously, allowing them to create animations faster and more naturally.
- **Avoid using 2D objects anchored to the physical environment in AR instructions.** The 2D objects are manipulated using a 3D interaction technique, which resulted in the 2D objects behaving differently than users expected.
- **Avoid using occluded interactions in AR instructions.** The orientation and exact position of the AR objects to be manipulated are no longer visible to the user. Users are dependent on visual cues, as with gizmo-based interaction.

4.6 Discussion

Our findings can potentially enhance AR utilization in the industry by revealing previously unexplored aspects of AR authoring tools. We evaluated the performance of three AR interaction techniques relevant to practical applications. We highlighted the importance of assessing these techniques within AR authoring tools that belong to the second cluster, specifically tailored to the intended application domain. In our case, this domain is the manufacturing industry in the service sector, particularly for creating AR instructions. Our study produced performance results that differ somewhat from those in the existing literature, which often assessed AR interaction techniques without considering specific application domains. These findings have theoretical and practical implications for companies as they adopt or design future AR authoring tools, whether for creating AR instructions or or beyond this application domain.

4.6.1 Theoretical Implications

First, we contribute to understanding users' performance, perceived workload, and satisfaction when using different AR interactions for industrial applications, specifically in positioning AR elements within the physical environment. Recent studies indicate that time is one of the most critical factors in the adoption of new technology in the service sector (Allmendinger and Lombreglia 2005; Kundu and Ramdas 2022). In this regard, the *device-based* technique appears to be the most suitable for creating AR instructions, our chosen application domain, since it enables participants to position AR elements significantly faster across almost any task.

Second, the performance of AR interaction techniques has traditionally been evaluated using general threshold tasks (Bergström et al. 2021). However, an analyzis of 60 AR authoring tools from both practice and research shows that tools in the second cluster, those that enable the creation of AR applications without programming knowledge, are typically designed for a specific application domain. Therefore, we propose evaluating the AR interaction techniques used in these second-cluster AR authoring tools with respect to their intended application domain. Our study provides initial evidence supporting this proposal, as we found performance results that differ from existing studies that did not consider the application domain. Consistent with the literature, our results show that across all tasks, participants were the fastest at placing AR elements using the *device-based* technique (Grandi et al. 2018; Marzo et al. 2014; Mossel et al. 2013). However, contrary to previous studies, our findings do not indicate that AR elements placed with touch-based interactions (*Plane* and *Gizmo*) are significantly more precise (in terms of distance error and rotation error) than those placed with the device-based interaction (Grandi et al. 2018; Marzo et al. 2014; Mossel et al. 2013). Additionally, while traditional threshold tasks only compare the final positions of AR elements, AR instructions often involve dynamic AR elements, such as animations (Gattullo et al. 2020; Hoffmann et al. 2021). Our results demonstrated that the *device-based* technique also achieved the lowest path deviation in such tasks.

4.6.2 Practical Implications

Third, it is notable that the *Orientation* task appeared to be the easiest for participants, who demonstrated the greatest accuracy in positioning AR elements (in terms of distance and rotation error) using most of the AR interaction techniques. These findings have important implications for the future design of AR instructions. For example, the results indicate that positioning 2D elements (*Order* task) using various AR interaction techniques was more challenging for participants than positioning 3D elements (*Orientation* task). As a result, we recommend that future AR instructions use 3D texts to visualize the assembly sequence (*Order* task) and, if possible, avoid occluded interactions (*Location* task). Additionally, our results show that the workload for touch-based interactions is lower than for device-based interactions, and touch-based interactions generate higher satisfaction levels among participants. This effect is likely due to participants' familiarity with touch-based interactions, whereas device-based interaction represents a new form of interaction for them (Beer and Mulder 2020). Therefore, when incorporating device-based interactions into AR authoring tools, we suggest implementing a short tutorial to ease users' initial experience with this new form of interaction.

Finally, our results contribute to overcoming the barriers to adopting and using AR authoring tools in the industry. Our study provides concrete design guidelines for future AR authoring tools, particularly for creating AR instructions. Moreover, the qualitative results extend beyond this specific application domain, addressing one of the most challenging aspects of designing AR applications: the physical design of immersive experiences (Ashtari et al. 2020). Additionally, our research helps dispel misconceptions about AR hardware, particularly the tendency to overestimate hardware and software performance while overlooking hardware-specific limitations (Krauß et al. 2021). For instance, several participants expected to be able to place AR content in the physical environment with millimeter precision and persistence without additional hardware. Others assumed that complete 3D translation and rotation on a 2D display would be intuitive, given their daily use of mobile devices (Langer 1975). However, this is not the case, as such interactions represent a new skill that most users must learn.

4.6.3 Limitations and Future Research

Although our lab experiment adhered to established guidelines, some potential limitations warrant further research. First, a virtual 3D model was used as the basis for the tasks in the lab experiment, replacing the physical model on which AR instructions would typically be created.

The use of a physical model may impact task processing, potentially leading to different results. Second, the selected tasks in the lab experiment, reflecting the four information types proposed by Gattullo et al. (2020), may differ from the real tasks encountered in developing AR instructions. However, we believe the chosen tasks have significant practical relevance and can be generalized to various industrial operations. Third, participants used the AR interaction techniques for only a limited period. Over several hours, the prolonged use of AR interaction techniques in everyday work could yield different results, as factors such as fatigue might significantly influence performance. A long-term study conducted in a manufacturing company could provide valuable new insights. Finally, we administered the cognitive workload and satisfaction survey after the short interviews, which may have affected the accuracy of the measurements.

Although our study has shown that device-based interaction is well suited to convey traditional technical documentation into AR instructions, some open questions allow different research directions. First, our results are based on the largest handheld device known to us, a tablet. It remains unclear how display size might affect the performance of different 3D object manipulation techniques and tasks. Additionally, as the development of wearable devices such as HMDs becomes increasingly important, the question of which 3D object manipulation techniques are best suited for this hardware is raised. In evaluating the different manipulation techniques, we used a threshold-based approach where the final position of the 3D object was visually displayed to the user. In the actual development of AR instructions, novice users independently decide where to anchor the 3D objects in the real environment, making their own decisions about translations and rotations. Assessing novice users during the development of an AR technical guide could provide valuable insights into how they prefer to interact with the authoring tool.

4.7 Conclusion

In this paper, we compare three AR interaction techniques across four tasks relevant to AR instruction development, demonstrating the performance, workload, and satisfaction trade-offs associated with using these techniques to position AR elements in the physical environment. The tasks in our study design were derived from AR instruction literature, and the three AR interaction techniques represent those frequently mentioned and used in both science and practice. Our results show that participants were able to place AR elements the fastest across all tasks using the *device-based* interaction technique, which is particularly relevant for our chosen application domain, the service sector. Additionally, our findings indicate that participants experienced the lowest workload and highest satisfaction with the touch-based Plane interaction technique when placing 3D elements in specified positions in the physical environment, likely due to familiarity with this interaction technique. Our results also offer valuable insights for the future design of AR instructions by identifying tasks that participants found particularly challenging, such as occluded interactions in the Location task or positioning 2D objects as in the Order task. Our design guidelines provide direction for researchers and practitioners in designing and implementing AR interaction techniques for their specific application domains and in the future development of AR instructions.

5 Designing an Effective Augmented Reality Interaction Technique to Develop AR Instructions (P2)

Title	Designing an Effective Augmented Reality Interaction Technique to Develop AR Instructions
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Table 10. Fact Sheet Publication P2

Abstract: Augmented Reality (AR) instructions hold significant potential for cost savings in industrial applications. However, the creation of AR instructions presents a challenge, requiring both programming and spatial knowledge. While efforts to simplify AR development focus on reducing the complexity of content creation, a critical aspect often overlooked is the positioning of AR elements in the physical environment, which is facilitated by AR interaction techniques. This study employs a Design Science Research approach to investigate how AR interaction techniques can be designed to enable the creation of AR instructions without necessitating programming or spatial knowledge. Grounded in the Effective Use Theory and existing knowledge of AR interaction techniques, we propose two design principles and instantiated them in a software artifact. Our findings from a laboratory experiment with 55 participants demonstrate that using a device-based interaction technique enhances transparent interaction and representational fidelity, thereby facilitating the effective creation of AR instructions.

5.1 Introduction

Augmented Reality (AR) technology has gained significant traction in various industries due to its flexibility and potential to enhance operational efficiency (Bottani and Vignali 2019). One of the most prominent applications of AR is in the form of AR instructions (Klinker et al. 2018; Kortekamp et al. 2019), which serve as process guidance systems, providing relevant information at the right time and place within the physical environment, assisting users in performing tasks in a process-compliant manner (Morana et al. 2019). In an industrial context, organizations are increasingly adopting AR instructions, driven by their potential to reduce error rates, speed up task completion, and improve work conditions. For instance, a study by Serván et al. (2011)demonstrated that implementing AR instructions reduced preparation time by 90% in the context of wiring harness installation. The tool-assisted service operators by displaying the required work steps and critical operating parameters directly within their physical workspace (Serván et al. 2011). This is just one example among numerous studies highlighting the potential of AR instructions (Cohen et al. 2018).

Despite the growing adoption of AR, challenges persist, particularly for small and medium-sized enterprises (SMEs). The complexity involved in developing AR applications remains a significant barrier (Ashtari et al. 2020; Azuma 2016; Konopka et al. 2024). While efforts are underway to simplify AR development processes, reducing the need for extensive programming knowledge, similar to advancements in traditional software development (Matook et al. 2023) or AI-based system development (Elshan et al. 2023). Recent research indicates that AR development is still predominantly carried out by experienced software developers (Ashtari et al. 2020; Krauß et al. 2021; Nebeling and Speicher 2018).

To date, much of the research has focused on the creation of AR content (Damarowsky and Kühnel 2022; Gattullo et al. 2020), while a unique challenge remains underexplored: the precise positioning and anchoring of AR content in the physical environment (Bräker et al. 2023a). This challenge necessitates effective human-technology interaction to support the 3D manipulation of AR content, referred to as AR interaction techniques. The selection of appropriate AR interaction techniques is vital, as it directly influences the efficiency and accuracy of AR content placement, an essential factor in the development of robust AR applications (Bräker et al. 2023a).

Although the performance of AR interaction techniques has been extensively studied in Human-Computer Interaction (HCI) literature (Marzo et al. 2014; Mossel et al. 2013), their effective use remains a critical challenge. According to the Effective-Use Theory (EUT), effective use of technology depends on two key dimensions: transparent interaction and representational fidelity. Transparent interaction ensures seamless user access to information without interface hindrances, while representational fidelity guarantees the accuracy and reliability of the presented information (Burton-Jones and Grange 2013). In AR, the inability to position and anchor AR content transparently and accurately significantly reduces the likelihood of precise placement. For example, studies have shown that even small misalignments of AR content in AR instructions during assembly tasks can lead to longer completion times and higher error rates (Khuong et al. 2014). To address these challenges, this research focuses on the following research question: How can an AR interaction technique be designed to improve transparent interaction and representational fidelity when placing AR content?

To answer these questions, we adopt a Design Science Research (DSR) approach (Hevner et al. 2004; Kuechler and Vaishnavi 2008). Drawing on EUT (Burton-Jones and Grange 2013) and existing research on AR instructions (Gattullo et al. 2020) and AR interaction techniques (Goh et al. 2019), we propose two meta-requirements (MRs) and two corresponding Design Principles (DPs) aimed at improving the effective use of AR interaction techniques for the creation of AR instructions. These DPs have been instantiated in a software artifact, which was evaluated for validity through a laboratory experiment involving 55 participants. This evaluation assessed the effectiveness of the proposed DPs and the benefits of the developed software artifact.

5.2 Theoretical Background

5.2.1 AR Development Tools

AR development tools provide an environment for designing, developing, and managing AR applications and experiences by integrating virtual objects into the physical environment (Nebeling and Speicher 2018). In recent years, design research has focused on simplifying such tools, for example by proposing design principles for no-code solutions that enable users without programming experience to create AR content (Hönemann et al. 2023b). Other design work has focused on software artifacts primarily, making it more difficult to generalize design decisions to future systems (Kammler et al. 2019). In addition, recent design studies present a set of design principles to assist researchers and practitioners in designing future AR development tools (Bräker et al. 2023a; Damarowsky et al. 2023). While these studies primarily address AR content, AR interactions are only mentioned in passing, for example through phrases such as "providing comprehensive user interaction" or "consider traditional interaction design", without acknowledging that there is currently no de facto standard for AR interaction techniques for handheld devices (Goh et al. 2019).

Furthermore, AR development tools can generally be divided into two clusters (Hönemann et al. 2025a). The first cluster consists of complex tools that require programming and scripting skills. These tools enable the development of highly customized AR applications that can meet a wide range of requirements. The second cluster includes less complex tools that require little to no programming skills. However, these tools are limited in functionality and scope, often targeting a specific application domain (Hönemann et al. 2025a). As a result, tools in this second cluster need to tailor their AR interaction techniques to the requirements of the intended application domain. To address this, Gattullo et al. (2020) proposed six information types that translate traditional technical documentation into AR instructions. This framework aims to streamline the creation of AR instructions and identify essential AR content. Table 11 presents an overview of these six information types along with their respective characteristics.

Information Type	Description	System Models	Spatial Models	Example
Identity	To display the identity of an object	Static	2D	An image of the object
Location	To determine or highlight the location of an object in the user's physical environment	Static	3D	An arrow pointing at the object
Way-To	To visualize the operation to be carried out	Dynamic	3D	An animation showing how to move the object
Notification	To display additional information which are necessary for an assembly step but also for different conditions or other quality indications	Static	2D	A text that displays a hint
Order	To visualize the assembly sequence	Static	2D	A number that indicates the assembly sequence
Orientation	To visualize the alignment of an object	Static	3D	A 3D model of the object

Table 11. Information types in AR instructions proposed by Gattullo et al. (2020)

5.2.2 Augmented Reality Interaction Techniques

Our study focuses on handheld devices for AR, as they are particularly relevant for SMEs due to their widespread availability and low acquisition costs. Furthermore, recent research has demonstrated that these devices are well-suited for industrial applications, where the creation of AR instructions does not necessarily require hands-free operation (Hönemann et al. 2024). At the core of AR is the concept of 3D interaction, which has been integral to its definition from the outset (Azuma 1997). This interaction necessitates the control of six degrees of freedom (6DOF), where 3DOF pertains to object translation and the remaining 3DOF to object rotation.

In handheld mobile AR, virtual object manipulation techniques are categorized into two main categories widely recognized in both research and practice: (1) *touch-based interaction* and (2) *device-based interaction* techniques. The following sections provide a detailed description of these AR interaction techniques.

Touch-based interaction: Touch-based interaction involves the use of on-screen touch inputs via fingertips to manipulate AR content (Goh et al. 2019). A primary challenge in this method is mapping 2D touch points on a screen to 3D attributes, enabling full 6DOF object manipulation (Martinet et al. 2010). To address this, three approaches have been proposed. The first approach is to provide additional hardware. Wilson et al. (2008) proposed using a depth-sensing camera that provides depth information for each pixel. This depth data can be utilized to create a comprehensive 3D model of the hand, thereby expanding interaction possibilities. However, the requirement for additional hardware often introduces extra costs. The second approach to enable complete 3D manipulation of AR content is a touch-based interaction using two fingers. Liu et al. (2012) introduced an interaction concept that enables 6DOF manipulation through multi-touch inputs. Specifically, simultaneous movement of two fingers enables 3DOF translation and 1DOF rotation, while an additional gesture, where one finger remains stationary while the other moves, allows for an extra 2DOF rotation (Liu et al. 2012). The third approach involves using on-screen gizmos to facilitate 6DOF manipulation with a single finger (Drey et al. 2023). This technique provides an intuitive way to control object positioning and orientation.

Device-based interaction: Device-based interaction techniques leverage the physical attributes of handheld mobile devices to manipulate AR content. Users can manipulate virtual objects by rotating, tilting, skewing, or moving the device itself (Goh et al. 2019). This approach offers several advantages, such as eliminating occlusion (Tanikawa et al. 2015) and typically allowing for faster manipulation compared to touch-based interactions (Marzo et al. 2014; Mossel et al. 2013). Despite its benefits, device-based interaction also presents several challenges. For example, large rotations (beyond 90°) are difficult to achieve. To address this issue, Samini and Palmerius (2016) introduced an interaction method with a "hold" function, allowing users to fix objects at different positions to facilitate larger rotations (Samini and Palmerius 2016). Another major drawback of device-based interactions is the inherent coupling of translation and rotation, meaning that simultaneously moving the device results in translational and rotational changes. To overcome this limitation, Polvi et al. (2016) employed ray casting combined with epipolar geometry. This method utilizes the device's positioning capabilities by aligning the built-in camera with the 3D object, effectively tracking movement. However, as this method does not support rotation, it was complemented with touch-based interaction techniques to enable full 6DOF manipulation.

5.2.3 Effective Use Theory

Effective Use Theory (EUT) provides a foundational framework for understanding how users interact with and derive value from information systems. According to Burton-Jones and Grange (2013) effective use is defined as "*using a system in a way that helps attain the goals for using the system*." This concept is structured around three hierarchical dimensions derived from representation theory: transparent interaction, representational fidelity, and informed action (Burton-Jones and Straub 2006; Wand and Weber 1990). Each dimension builds upon the previous one, with transparent interaction forming the base, followed by representational fidelity, and culminating in informed action.

For example, in the context of the creation of AR instructions, these dimensions play a crucial role in enhancing user experience and system effectiveness. Transparent interaction ensures that users can engage with AR content effortlessly without being hindered by interface complexities. Representational fidelity is essential for accurately depicting real-world elements within the AR environment, ensuring that the virtual content aligns with the physical world. Ultimately, informed action enables users to leverage the information provided by the AR development tool to perform tasks more effectively, such as service technicians using AR instructions to complete maintenance tasks efficiently. In this study, we focus on the first two dimensions of EUT, transparent interaction and representational fidelity, as they can be evaluated using validated questions. In contrast, assessing the outcome of an informed action is highly subjective and additionally depends on the preceding two dimensions.

Beyond AR, the EUT has been successfully applied in the Information Systems (IS) field to improve system design and to understand human-technology usage. For instance, IS researchers have utilized EUT to develop dashboards that present information efficiently and effectively, aiding users in making optimal decisions during crisis situations (Ruoff et al. 2023). Furthermore, EUT has been employed to study seniors' effective use of wearable device technology, highlighting its potential to enhance health outcomes (Abouzahra and Ghasemaghaei 2022).

5.3 Designing an Augmented Reality Interaction Technique

5.3.1 Design Process

We adopted a comprehensive Design Science Research (DSR) approach to design IT artifacts to solve real-world problems (Gregor and Hevner 2013). Specifically, our research addresses the lack of design knowledge regarding the suitability of AR interaction techniques for AR instructions, aiming to enhance the accessibility of AR technologies for SMEs. Our study follows the DSR methodology outlined by Kuechler and Vaishnavi (2008).

The research process begins with the *problem awareness* phase, which motivates our study by identifying real-world problems based on an extensive review of the literature on AR instructions and interaction techniques. Based on this, in the *suggestions phase*, we suggest a definition of an effective AR interaction technique from which we derive a set of meta-requirements (MRs). In the *development phase*, we follow a theory-driven approach to develop our software artifact. We begin with the EUT, which serves as a kernel theory to explain the effective use of AR interaction techniques to create AR instructions. Based on our kernel theory, we derive design principles (DPs) that promote effective use by comparing them with solution knowledge derived from related literature. We instantiated our DPs through a software artifact, which serves as a medium to communicate and evaluate our proposed principles (Jones and Gregor 2007). With the developed software artifact, users are able to create complete AR instructions independently. In the *evaluation phase*, we conducted a laboratory experiment to validate our DPs. We chose this evaluation method since laboratory experiments are well-suited for testing different DPs implemented in various design alternatives (Niehaves and Ortbach 2016). Additionally, experiments provide a controlled and formative evaluation environment that enables us to assess, at an early stage, whether our proposed DPs enhance transparent interaction (Venable et al. 2016). In the *conclusion phase*, we conclude our design process by discussing the implications of our design for research and practice.

To ensure the validity of our DPs, we applied the framework proposed by Niehaves and Ortbach (2016) to address a common shortcoming of current DSR approaches: overcoming the conceptual gap between the design of an artifact and its intended design goals. By employing this approach, which includes both a design model representing cause-related aspects of the artifact and a measurement model representing effect-related aspects, we not only explain how theoretical foundations guided our design but also demonstrate that our design works as intended (Lipusch et al. 2020; Niehaves and Ortbach 2016).

5.3.2 Awareness of the Problem and Suggestion

In the following section, the findings from the problem awareness phase are presented through the lens of two dimensions of the EUT: *transparent interaction* and representational fidelity. A total of six major issues **(I)** regarding AR interaction techniques used to create AR instructions are identified and highlighted.

Transparent interaction: The development of multi-modal AR interfaces has shown that manipulating visualized AR content is more effective when integrating natural interactions, such as voice input (Nguyen et al. 2017). Intuitiveness and naturalness are crucial aspects of developing AR interactions (Zhou et al. 2008). However, achieving such natural interactions for manipulating AR content on a 2D screen without additional hardware, such as sensor gloves or computer recognition cameras, remains unclear (Goh et al. 2019). **I1:** Therefore, users face difficulties with existing AR interaction techniques due to their unintuitive nature, requiring a high level of spatial knowledge (Nebeling and Speicher 2018). Spatial knowledge refers to the cognitive ability to perceive, organize, and navigate the physical environment.

Another challenge arises from the need for single-handed interaction, as users must hold the tablet with one hand. In this industrial context, using a tablet is more suitable than smartphones for creating AR content, as the larger screen aids in precise positioning (Hönemann et al. 2021). Recent studies emphasize the ergonomics of using AR interaction techniques on tablets in the service sector, suggesting that users should avoid holding the tablet with one hand for extended periods (Bräker et al. 2023a). **I2:** The necessity for AR interactions to allow users to hold the tablet with both hands while performing 6DOF interactions.

Additionally, users creating AR instructions are often domain experts in their field but may have limited experience with AR technology (Bhattacharya and Winer 2019). **I3:** The importance of sufficiently supporting these domain experts in learning new interactions, providing contextual information, and building their knowledge of this new technology (Bräker et al. 2023a).

Another important issue in the interaction of AR content in the physical environment is the consistency of the interaction (Azuma et al. 2001). If the position and rotation of the AR content in the physical environment change, the axis orientations along the AR content also change. As a result, the AR content has a different axis orientation depending on their position in the physical environment. The users have to move the AR content differently each time. **I4:** The position and rotation of AR content in the physical environment affect the axis orientations, requiring users to adjust their interactions each time, which can be unclear and inconsistent.

Representational Fidelity: Placing AR content requires spatial knowledge, particularly for identifying where AR content is located in the users' physical environment (Nebeling and Speicher 2018). **I5:** It is unclear how AR content can be displayed in the physical environment to help users track the position of AR content regardless of viewing angle and distance.

For users to create AR instructions that support maintenance tasks in a process-compliant manner, the interaction must enable both static and dynamic AR content, such as animations showing the direction of component rotation (Gattullo et al. 2020). **I6:** It is unclear which AR interaction techniques allow users to create both dynamic and static content.

To address these issues, we propose two meta-requirements **(MRs)** based on the dimensions of EUT: **MR1:** An AR interaction technique should have a high level of transparent interaction; **MR2:** An AR interaction technique should have high representational fidelity. We argue that an effective AR interaction technique provides unhindered access to the AR development tool (*transparent interaction*) and enables users to obtain accurate representations of the AR content (*representational fidelity*), thereby supporting users in creating AR instructions (*informed action*).

To support transparent interaction (MR1) and address issues I1, I2, I3, and I4, we propose using device-based interaction for creating AR instructions. This approach, along with mid-air gesture-based interaction, is perceived as natural by users, as AR content can be moved and rotated through user movements (Goh et al. 2019). Device-based interactions are based on single-handed use, allowing the tablet to be held with both hands. Users can tap and hold a button to grab AR content, ensuring consistent displacement and rotation regardless of the content's position in the physical environment (Marzo et al. 2014; Mossel et al. 2013). To enhance transparent interaction, users should have the opportunity to familiarize themselves with the AR interaction interface independently, with support available when needed (Ruoff et al. 2023). It is important to provide users with the freedom to explore the AR interaction independently and to offer them the possibility of support, as users have great difficulties without support (Bräker et al. 2023a). In this case, tooltips can assist users in learning the system and reducing cognitive load (Blooma et al. 2023), which is crucial as cog-nitive load is a significant barrier in the learning process (Sweller 1988). Based on MR1, we formulate our first DP following the framework proposed by Gregor et al. (2020).

DP1: To enable service technicians (*users*) to independently create AR instructions (*aim*), a natural, consistent, and single-handed AR interaction should be provided with additional guidance to help them gain new capabilities (*rationale*).

To support representational fidelity (MR2) and issues I5 and I6, the EUT suggests adapting the system's representation to enable tasks such as creating AR instructions. To increase representational fidelity for positioning AR content in the physical environment, the HCI literature recommends displaying a drop shadow beneath the AR content, indicating its position (Mohr et al. 2015). Device-based interaction allows users to perform both displacement and rotation of AR content simultaneously, enabling the creation of both static and dynamic AR content (Marzo et al. 2014; Mossel et al. 2013), which is essential for AR instructions (Gattullo et al. 2020). Based on MR2, we formulate our second DP:

DP2: To enable service technicians (*users*) to independently create AR instructions (*aim*), the AR interaction should allow them to create dynamic and static AR content while supporting them in identifying the location of the AR content in the physical environment (*rationale*).

5.3.3 Artifact Description

First, we have developed an AR interaction technique without taking our proposed DPs into consideration, enabling users to create AR instructions independently. As shown in Figure 21a) and Figure 21b), this AR interaction technique employs gizmos for manipulating AR content, allowing users to displace and rotate them through touch interactions. Given the limited screen space and the desire to simplify user interaction, we separated displacement and rotation functions, enabling users to switch between modes via a button. This implementation omits a tutorial and a drop shadow for AR content, reflecting a basic interaction without the EUT applied. In addition, how the AR content can be moved or rotated varies depending on the orientation of the AR content, so the interaction is not consistent. We selected this technique as it aligns with state-of-the-art AR development in practice and is frequently used in scientific tools (Krings et al. 2022). This software artifact represents the AR interaction technique.

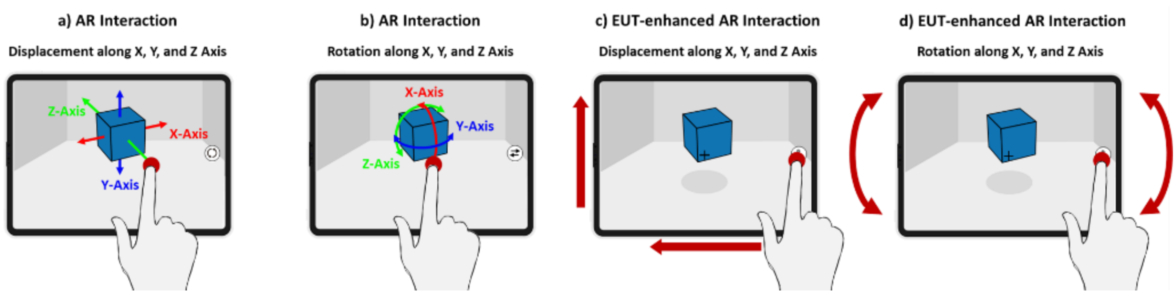

Figure 21. Software artifacts with and without effective use theory applied

In addition to the AR interaction in which our proposed DPs were not considered, we implemented our DPs in another AR interaction technique in a second software artifact. In this technique, the device serves as a controller for interaction. As illustrated in Figure 21c) and Figure 21d), users can displace or rotate AR content by pointing a crosshair at the center of the display to the desired content. Interaction begins when the button is pressed and ends when the button is released. For displacement, users move the device along the desired axis (e.g., moving forward or backward to adjust the Z-axis). For rotation, users physically rotate the device along the axis (e.g., imitating a steering wheel movement to rotate around the Z-axis). However, ergonomic constraints limit single-movement rotations to 90°, requiring multiple interactions for larger rotations (e.g., 180°). A tutorial in the top right corner is available to facilitate learning, explaining the interaction (DP1). This technique allows 6DOF manipulation, enabling users to create both static AR content by anchoring it in specific positions and dynamic elements that can be freely moved by tablet movements (DP2). To enhance representational fidelity, a drop shadow indicates the AR content's position in the physical environment (DP2). This software artifact represents the EUT-enhanced AR interaction technique.

5.4 Evaluation

We conducted a laboratory experiment to evaluate if our DPs can improve the effective use of AR interaction techniques to create AR instructions. To do so, we have developed two versions of our software artifact. One prototype in which the interaction design is based on the EUT and one prototype without applying the EUT. To test our DPs, we conducted a within-subject design in which each participant had to use both AR interaction techniques in a random order. We opted for a within-subject design so that the individual differences do not distort the results (Charness et al. 2012) and thus represent the state of the art in the evaluation of AR interaction techniques (Bergström et al. 2021).

Participants. A student sample was selected for this study, comprising 55 participants, primarily business economics and engineering students, who represent both users without AR development knowledge and future domain experts in the industry. One participant was excluded due to incomplete performance data, resulting in a final sample of 54 participants. Of these, 24 were female, 28 were male, and two chose not to disclose their gender, with an average age of 28.76 years (SD = 9.87). When asked about their experience with AR, participants reported varying levels of experience with AR, while seven indicated no prior experience. When asked about their 3D modeling experience, we obtained a similar distribution. 41 participants had some experience with 3D modeling, and 13 reported no experience.

Procedure and Stimuli. The laboratory experiment was conducted in multiple parts, each lasting approximately 60 minutes. Participants received 15 Euros for their involvement, with the top three performers receiving an additional 20 Euros to motivate optimal performance. At the beginning, participants were briefed on the research objective, which involved evaluating two AR interaction techniques across a set of information types to convey technical documentation into AR instructions and the experimental procedure.

In the second part of the experiment, the moderator initiated one of the two AR interaction techniques and placed a 3D model (an Engine) on the table, serving as the task basis. Participants were instructed to start the experiment from the same position to avoid the effects of distance and angle (Bergström et al. 2021). They independently completed four tasks, each repeated three times. The first trial of each task was a practice trial, allowing participants to familiarize themselves with the manipulation technique and task. Subsequent trials were evaluated. Bergström et al. (2021) recommend using thresholds to evaluate an AR interaction technique. In our case, the threshold is determined by the participants themselves. They place the object at a given position and confirm with a button that they are satisfied with the positioning. Bergström et al. (2021) recommend using a transparent version of the AR content to visualize the colocation.

Tasks were based on four of the six information types proposed by Gattullo et al. (2020) for conveying technical documentation into AR instructions. They were selected to reflect a realistic industrial context, specifically an engine assembly (i.e., to mount a piston on the connecting rod). The two information types, Identity, and Notification, were excluded as they involve 2D objects without a need for a physical world reference.

After the participants completed all four tasks with the one AR interaction technique, they answered a questionnaire to measure the construct's transparent interaction and representational fidelity. Lastly, after the participants had completed all task questionnaires with both AR interaction techniques, they had to fill out a final questionnaire regarding their demographic data, AR experience, and 3D modeling experience.

Measures. We collected three performance measures for each evaluated trial: (1) Task time (i.e., the time from starting the first interaction to reaching the threshold accuracy). (2) Distance error (i.e., the deviation in X, Y, and Z in mm). (3) Rotation error (i.e., the deviation in X, Y, and Z in °) and for the task of creating an animation (way-to), the path deviation (i.e., the deviation in X, Y, and Z in mm) was measured additionally. Transparent interaction and representational fidelity were assessed using items adapted from Eden et al. (2019).

5.5 Results

To evaluate the validity of our proposed DPs, we examined the differences in the mean values of *transparent interaction* and *representational fidelity* between two AR interactions: one with the EUT applied and one without. To achieve this, we conducted a t-test to compare the results of both AR interactions. Table 12 provides a summary of the findings from the AR interaction comparison.

	EUT-enhanced AR Interaction		AR Interaction		
Dependent Variable	**M**	**SD**	**M**	**SD**	**t-test**
Transparent Interaction	4.068	1.740	5.265	1.535	-4.414*
Representational Fidelity Input	4.494	1.664	5.179	1.499	-2,567*
Representational Fidelity Output	4.907	1.739	5.568	1.295	-2,572*
Representational Fidelity	4.701	1.714	5.374	1.414	-2,801*
*p<0.05					
M = Mean; SD = Standard Derivation					

Table 12. Effective use results of the t-test

The effective use results of the comparison of the two AR interactions showed that the users in the EUT-enhanced AR interaction achieved a significantly higher level of transparent interaction than those without the EUT. Moreover, users experience a significantly higher level of representational fidelity input as well as representational fidelity output when interacting with the EUT-enhanced AR interaction than users when interacting with the AR interaction without the EUT. This results in users achieving a significantly higher level of representational fidelity in EUT-enhanced AR interaction than users in the AR interaction without the EUT.

In addition to assessing transparent interaction and representational fidelity, we examined task performance differences between the two AR interactions by comparing their task performance results using a t-test. Table 13 summarizes these findings, including data from all tasks in the comparison.

		EUT-enhanced AR Interaction		AR Interaction		
Task	**Measure**	**M**	**SD**	**M**	**SD**	**t-test**
ORDER	Task Time	55,074	38,151	25,644	23,423	4,786*
	Distance Error	4,029	8,709	1,825	0,504	1,840*
	Rotation Error	1,877	11,412	7,752	3,849	-2,9464*
ORIENTATION	Task Time	58,963	31,251	37,530	29,144	3,652*
	Distance Error	5,164	12,297	1,767	2,866	1,959*
	Rotation Error	11,238	12,597	9,414	11,408	0,781
WAY-TO	Task Time	20,014	12,130	15,566	14,803	1,692*
	Path Deviation	1,694	0,929	1,178	0,299	3,850*
LOCATION	Task Time	56,797	30,114	27,820	20,386	5,801*
	Distance Error	5,976	6,313	1,776	2,873	4,408*
	Rotation Error	7,097	8,924	6,230	6,985	0,556

Table 13. Performance results of the t-test

The task performance comparison revealed that users could anchor AR content significantly faster (in terms of task time) and with greater precision (in terms of distance error) in the physical environment when using the EUT-enhanced AR interaction technique compared to the one without EUT. Similarly, the EUT-enhanced interaction technique enabled users to create animations with reduced path deviation.

Interestingly, and contrary to our expectations, the task performance comparison showed no significant difference in the orientation accuracy (rotation error) of the AR content placed across most tasks. Moreover, users demonstrated significantly greater accuracy in orienting AR content when using the interaction without EUT compared to the EUT-enhanced AR interaction technique.

5.6 Discussion

Efforts to simplify AR development processes through low/no-code tools have gained momentum, reducing the need for extensive programming knowledge (Elshan et al. 2023; Matook et al. 2023). Despite these advancements, recent research indicates that AR development remains predominantly the domain of experienced software developers (Ashtari et al. 2020; Krauß et al. 2021; Nebeling and Speicher 2018). Our study contributes to bridging this gap by proposing a use-case-dependent and theory-driven AR interaction technique designed to support users in creating AR instructions. Our results demonstrate that implementing our DPs, focusing on transparent interaction and representational fidelity, can enhance the two bottom dimensions of the EUT.

Furthermore, our research contributes to the request of Hibbeln et al. (2017), as the AR interaction technique we propose operates within a 3D environment, generating more sophisticated data than mouse-cursor tracking. Movement data from this AR interaction technique could be used to gain deeper insights into user behavior and information processing. This presents a broad range of potential applications for industrial enterprises. For example, the movement data from AR interactions could help to detect cognitive load or stress in employees, offering real-time metrics to assess task complexity and employee well-being (Koldijk et al. 2018) or such insights could facilitate the development of adaptive work environments that dynamically respond to employees' needs (Michalos et al. 2018).

With regard to analyzing this movement data, our AR interaction technology offers a novel contribution to the DSR community by providing a non-invasive method for assessing and analyzing emotions in immersive systems (Hevner et al. 2004; Hibbeln et al. 2017). Traditional methods, such as questionnaires or psychophysiological devices, often compromise the ecological validity of real-time interactions. In contrast, by monitoring human motor control data, our approach enables researchers to infer behavioral changes with high temporal precision while preserving the user experience. This directly addresses Peffers et al. (2012) call for real-world evaluations, facilitating artifact assessments in naturalistic environments. Thus, our research contributes to unlocking the potential of AR instructions while setting new standards for design science research and practice in HCI and IS.

While our study adheres to established guidelines for DSR projects and evaluations, several limitations warrant attention and suggest avenues for future research. First, the tasks selected for the lab experiment reflect the four information types proposed by Gattullo et al. (2020), may not fully capture the complexity of real-world tasks encountered in creating AR instructions. We argue that the chosen tasks hold significant practical relevance and can be generalized to various industrial operations. Second, using a virtual 3D model instead of a physical model for the laboratory experiment may have influenced task processing, potentially leading to different outcomes. Future studies could explore whether the use of physical models yields distinct results.

Despite these limitations, our study demonstrates the efficacy of our proposed AR interaction technique in facilitating the creation of AR instructions. However, several open questions remain, suggesting promising directions for future research. Our findings are based on experiments conducted using the largest handheld device available, a tablet. How display size might influence AR content manipulation techniques and task performance remains unclear. Additionally, as head-mounted displays become increasingly prevalent, there is a growing need to investigate which AR content manipulation techniques are best suited for this hardware.

6 Designing a User-Metaverse Interface for the Industrial-Metaverse (P3)

Title	Designing a User-Metaverse Interface for the Industrial-Metaverse
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Status	Published
Contribution of first author	The first author was responsible for Methodology, Investigation, Formal analyzis, Conceptualization, problem definition, research design, data collection and analyzis, interpretation, and conceptual development and reporting. He further significantly contributed to the creation of the manuscript.
Citation	Hönemann, K., Konopka, B., Thatcher, J. B., and Wiesche, M., (2023) "Designing a User-Metaverse Interface for the Industrial-Metaverse". International Conference on Information Systems (ICIS 2023). 14. https://aisel.aisnet.org/icis2023/user_behav/user_behav/14 .

Table 14. Fact Sheet Publication P3

Abstract: The Industrial-Metaverse will create interactions between the physical and virtual worlds to extend operations in the physical industry. This particularity and the demand for increasing immersion in the Metaverse require using XR technologies called User-Metaverse interfaces (UMI). How such a UMI must be designed for the Industrial-Metaverse is unknown. This study adopts a design science approach to design a UMI based on social-cognitive theory (SCT). According to SCT, creating user-generated Metaverse content is crucial to the UMI design. It empowers users to generate content through their efforts, leading to higher self-efficacy and user engagement. We formulate two theoretically based design principles and instantiate a software artifact, which we evaluate in a laboratory experiment with 57 participants. Our study shows the importance of belief in success in the design of future UMI. Furthermore, our design principles show significant positive outcome expectations of users in their interaction with the software artifact.

6.1 Introduction

The Industrial-Metaverse means the convergence of virtual and augmented realities with the physical environment in industrial production and maintenance. This convergence will change how users work and interact, enabling real-time interaction with other humans and machines (MIT Technology Review Insights 2023). The revolutionary aspect of the Industrial-Metaverse is that, on the one hand, users can innovate without fear of risk or additional costs; on the other hand, it recognizes and solves certain clearly spatial problems. The interaction of digital and physical realities is enabled by extended Reality (XR) technologies which is an umbrella term for immersive technologies such as Augmented Reality (AR), Mixed Reality (MR), and Virtual Reality (VR) that are used to digitally and physically intertwine human-machine interaction in the Industrial-Metaverse (Rauschnabel et al. 2022) . An example of such interaction is Burghardt et al. (2020) pairing of a digital twin and XR to control a physical robot. A digital twin of the robot's environment is displayed in XR. The XR system records the reproduces the operator's movements in the physical robot. This new way of controlling robots is especially useful for performing complicated tasks, and successful task performance depends on the experience of the operator (Burghardt et al. 2020). In order for the Industrial-Metaverse to realize its full potential, users must be able to interact with the Metaverse content, such as the digital twins, as well as create new content. To achieve this goal we need a complete understanding of the conditions under which XR interfaces are more or less effective in enabling human-machine interaction, and what types of hardware are best suited to support Metaverse applications (Dwivedi et al. 2022).

Practice-based and academic research have proposed different perspectives on how to best interact in the Metaverse. While Siyaev and Jo (2021) propose a mixed-reality interface to combine the virtual and physical worlds, using the virtual to augment the physical experience, other researchers propose a fully immersive environment where avatars act on behalf of users in the physical environment (Duan et al. 2021), drawing attention to the purely virtual experience. Other authors suggest that the Metaverse can be accessed through screen-based interfaces (Schultze and Orlikowski 2010). This inconsistency in the Metaverse interface literature has delayed the emergence of a de facto standard for designing interfaces for the Metaverse, which could be one of the reasons that have led to slower adoption of the Metaverse by users and causing some companies, such as Microsoft, to abandon the Metaverse altogether (Bonifacic 2022).

While most of the IS Metaverse research since the release of Second Life has focused on the screen-based interface (Chaturvedi et al. 2011; Davis et al. 2009; Schultze and Orlikowski 2010), the Metaverse has continued to evolve, which leads to new possibilities. An important evolution of the Metaverse is the increasing immersion that can only be achieved through XR interfaces. Therefore the term "User-Metaverse-Interface (UMI)" has been coined in the current IS Literature (Dwivedi et al. 2022) but how to design such a UMI has not yet been investigated in the IS literature.

To bring coherence to Metaverse interface design, this research uses a design science research approach to articulate a set of design principles for a UMI. We propose design principles for a UMI based on social cognitive theory (SCT) (Bandura 1986) and research on existing Metaverse interfaces (Biocca et al. 2007; Davis et al. 2009; Peukert et al. 2019). In doing so, we rely on an important aspect that, to our knowledge, has not yet been addressed in research, the creation of user-generated Metaverse content. The creation of user-generated Metaverse content is a key possibility suggested by SCT, as users create content through their own efforts and actions, leading to self-efficacy (Bandura 1997). We enable novice users in the Industrial-Metaverse to create user-generated Metaverse content (i.e., digital twins). The term novice user in this context describes technicians with great process knowledge but not necessarily deep spatial knowledge or any programming experiences. By empowering novice users, organizations can develop Metaverse applications on their own without the help of external IT service providers. On the one hand, this avoids expensive individual developments; on the other hand, organizations can adapt their Metaverse processes more quickly. In doing so, we investigate: *How can an User-Metaverse interface be designed to enable novice users to create user-generated Metaverse content for the Industrial-Metaverse?*

To answer this question, we conducted a comprehensive Design Science Research (DSR) project focused on eliciting design principles for XR interfaces in the Industrial-Metaverse (Gregor and Hevner 2013). Our DSR approach (Hevner et al. 2004) suggested three theoretically grounded principles that provide prescriptive knowledge about the design of XR interfaces in the Industrial-Metaverse. We evaluate the two design principles in a UMI designed to enable novice users to create user-generated Metaverse content in the Industrial-Metaverse (Yang et al. 2022; Zheng et al. 2022). We evaluate the proposed design in a large-scale laboratory experiment. More specifically, we aim to identify the major sources of self-efficacy in designing UMIs to analyze novice users' motivation to contribute content to the Industrial-Metaverse. As a result, we contribute theoretically by providing design knowledge of a UMI to create user-generated content in the Industrial-Metaverse. We also contribute practically with our two theoretically grounded design principles that support the implementation of interfaces in the Industrial-Metaverse. Finally, we show that access to a library of 3D elements and the ability to create own media and anchor them in the physical environment has a significant positive impact on the task performance and the performance-related outcome expectations of the users.

The paper is organized as follows. The basic concepts and related work are presented in the following section. The research methodology is described in the third section. In the fourth section, the meta-requirements, the design principles, and the instantiated software artifact are explained. The evaluation and results are presented in the fifth section. The final section discusses the evaluation results, limitations, and future research.

6.2 Conceptual Foundations

6.2.1 Metaverse Realms

Stephenson (1992) coined the term "Metaverse" in his novel "Snow Crash". According to Stephenson, the Metaverse is a computer-generated universe drawing onto goggles and pumping into earphones. Perhaps because of its fictional roots, competing technical views of the Metaverse interfaces have emerged.

These competing technical views of the Metaverse make it difficult to make design decisions because the technologies have different requirements. Therefore, we consider the existing research on the Metaverse from a sectoral perspective. The variety of Metaverse applications shows that researchers are trying to understand and describe the usefulness of this sociotechnical phenomenon (Dwivedi et al. 2022). Therefore, we consider it important to understand this phenomenon from the capability perspective of users in different sectors.

Table 15 distinguishes the different Metaverse realms using defining characteristics (i.e., the environment, the interaction, and the interface) (Park and Kim 2022), experienced immersion, and examples of application domains. While IS research has focused on Consumer- and Enterprise-Metaverse applications (Davis et al. 2009; Peukert et al. 2019; Schultze and Orlikowski 2010), it has left the Industrial realm relatively unexamined.

	Metaverse Realms		
	Consumer	**Enterprise**	**Industrial**
Definition	Create immersive experiences for entertainment and gaming purposes.	Create immersive communication and collaboration in the workplace and immersive business environments for company interactions with customers and other businesses.	Create interactions between the physical world and the virtual world to broaden the operations in the physical industry.

Environment	Predominantly an unrealistic environment	Predominantly a realistic environment	Predominantly a fused environment
Level of immersion	High	Low and High	Medium
Interaction	Controllers, gestures, speech	Keyboard, mouse, controllers, gestures, speech	Touch, gestures, speech
Interface	3D and immersive methods	Immersive and physical methods	Physical methods
Application Domain	Games, Social	Office, Marketing, Education, Health Care, Tourism	Simulation, Digital Twin, Augmented Work instructions

Table 15. Summary of the Metaverse realms and their different characteristics

The Consumer-Metaverse aims to create immersive experiences for users for social (Duan et al. 2021), or for gaming and entertainment purposes (Nickerson et al. 2022a). Often it is a highly immersive three-dimensional virtual world in which people interact as avatars with other people and non-player characters in an environment that deceives the user's senses and removes the barriers between space and time (Dwivedi et al. 2022). These unrealistic environments are not related to the degree of immersion but rather to how similar the physical world and the virtual world are. In unrealistic environments, for example, physical constraints such as gravity do not matter and users can experience unrealistic scenarios such as a journey to Mars (Dwivedi et al. 2022). To enter the Consumer-Metaverse, highly immersive methods are used, allowing users to be fully immersed in a virtual environment implemented through the use of VR (Xi et al. 2023).

In contrast, the Enterprise-Metaverse aims to create immersive communication and collaboration between people in a work environment on the one hand (Purdy 2022), as well as immersive environments in which companies can conduct business and interact with customers and other companies on the other (Liu et al. 2019). These environments often mirror the physical and geographic elements of the physical environment (Dwivedi et al. 2022). These realistic environments are not related to the degree of immersion but rather to how similar the physical and virtual worlds are. For example, in realistic environments, avatars cannot exist in different worlds or defeat gravity (Dwivedi et al. 2022). Research has examined two ways of entering the enterprise metaverse: 3D interfaces shown on a display, often in screen-based applications (Dwivedi et al. 2022), and highly immersive methods analogous to the consumer metaverse (Winkler 2018).

The Industrial-Metaverse aims to increase the efficiency and productivity of manufacturing companies (Siyaev and Jo 2021). It focuses on physical human-machine interaction, industrial process simulation, and knowledge assessment (Zheng et al. 2022). An important aspect of the

Industrial-Metaverse is the fused environments where virtual elements are fused with the user's physical environment according to the laws of reality (Siyaev and Jo 2021). AR or MR technologies are required to create these fused environments and thus enter the Industrial-Metaverse (Laviola et al. 2022). The predominant use of physical human-machine interactions in the Industrial-Metaverse to semantically intertwine people, spaces, and machines, both digitally and physically, determines how users create and interact with content for the Industrial-Metaverse.

One example of an Industrial-Metaverse application based on AR/MR technologies is that of Laviola et al. (2022). With their XR application *minimal AR*, users from the Industrial-Metaverse are guided in assembling technical assets. They are provided directly at the machine with the technical instructions to conduct the desired assembly process. The efficiency of the assembly process and the field service can be increased through the convergence of augmented reality and physical reality in the form of XR-based work instructions. Instead of sending a service technician to the customer's site, industrial manufacturers could provide the XR-based work instructions to their customers so that they can perform the repair/maintenance on their own. This will create new sustainable business models for industrial organizations, which are of fundamental importance for the fifth industrial revolution (*Industry 5.0*) (Xi et al. 2023).

In all Metaverse realms, the immersion and the possibility for the user to actively participate in the Metaverse (e.g., through user-generated Metaverse content) are central key characteristics. The particularity of the Industrial-Metaverse lies in the real-time human-machine interaction and the associated fused environments (Laviola et al. 2022; Siyaev and Jo 2021). Two development directions essentially drive the Industrial-Metaverse. On the one hand, an enormous application pull is driven by changes in the business environment and a significant need for change. These are, for example, to optimize processes and increase production efficiency or to enable technical experts to virtually explore complex systems, identify problems, and test solutions without actually being physically present (MIT Technology Review Insights 2023). On the other hand, a huge technology push can impact users' daily work. The technologies relevant to the Industrial-Mmetaverse are the following: XR Interfaces, Digital Twins, Artificial intelligence, blockchain, IoT, 5G/6G (MIT Technology Review Insights 2023).

6.2.2 User Metaverse Interface

To advance the use of the Industrial-Metaverse, we need a better understanding of how to design Metaverse interfaces. IS researchers have identified a wide variety of effects of interface design, ranging from the consistency of interfaces across applications (Satzinger and Olfman 1998) to the effects of interface design on decision-making capabilities (Speier and Morris 2003) and many more (Vance et al. 2015). We briefly examine three different interfaces that have been explored in the IS literature and relevant designing interfaces for the Metaverse. Table 16 briefly compares the three different Metaverse interfaces discussed in the IS literature.

		XR	
Definition	**Screen-based**	**VR**	**AR/MR**
Definition	Through avatars, users can interact with each other and non-player characters in a non-immersive environment.	Through avatars, users can interact with each other and non-player characters in a high-immersive immersive environment.	The physical environment of the users is enhanced with digital content.
Level of immersion	Low	High	Mid-High
Interaction	Keyboard and mouse	Controllers, gestures, speech	Touch, gestures, speech
Accessibility	High	Mid	Low-Mid
Use-Cases	Second Life, Roblox, Decentraland, Sandbox	Horizon Worlds and Workrooms, VRChat	Pokémon Go, Loreal ModiFace, IKEA Place

Table 16. Summary of Metaverse interfaces in the IS literature

The first and one of the most commonly associated interfaces with the Metaverse is the screen-based interface. Users can access the Metaverse using a laptop/computer and interact with it using a mouse and keyboard. Through avatars, users can interact with each other and non-player characters in an environment that resembles the physical world without facing physical limitations (Davis et al. 2009).

The second interface, and the one most commonly associated with current views of the Metaverse, is a VR interface. Users can access the Metaverse through VR interfaces such as a head-mounted display (HMD) and interact with it using controllers, gestures, or speech. Users also interact with other users and non-player characters in a virtual environment as avatars (Peukert et al. 2019). The difference lies in the degree of immersion, which includes the degree of isolation from reality.

The third interface, and the most commonly associated interface with the Industrial-Metaverse, is an AR/MR interface. Here, users can access the Metaverse via AR/MR interfaces such as smartphones or HMDs and interact through touch, gesture, or speech. The difference between the other two interfaces (screen-based or VR interfaces) is that no virtual environment is created. Rather, the user's physical environments are augmented with digital content (Azuma 1997). An example from the IS literature is the research of the authors Biocca et al. (2007) on the impact of an AR interface technique, "the omnidirectional attention funnel," compared to standard cueing techniques such as visual highlighting and audio cueing.

The IS literature has extensively explored the screen-based Metaverse interface. Work such as that by the authors Chaturvedi et al. (2011) developed design principles for early virtual worlds. Davis et al. (2009) laid the groundwork to define an initial understanding of virtual collaboration that has informed ongoing Metaverse research. One reason the screen-based Metaverse interface has been explored for so long is the game SecondLife, released in 2003 and associated with the Metaverse concept (Davis et al. 2009). Another reason is that this interface is very accessible and familiar to users.

6.2.3 Social Cognitive Theory and XR

Design and action theory, also known as design theory, is intended to help designers create new IT artifacts more efficiently (Gregor 2006). In DSR projects, these artifacts are developed by eliciting requirements from the theories and application domains and applying them to the corresponding instantiation for rigorous evaluation (Briggs 2006). Furthermore, design theories are distinctly prescriptive and aim to guide designers in developing novel IT artifacts more efficiently. Therefore, a solid theoretical foundation is necessary to underpin design theories and justify their effectiveness in achieving specific objectives. Furthermore, this foundation should explain why these theories work and how they can achieve their intended outcomes. For this reason, Walls et al. (1992) suggested that design theories should draw upon kernel theories.

We draw on a social cognitive theory (SCT) (Bandura 1986) as a kernel theory to conceptualize and represent our contributions to design knowledge and to develop our design principles. SCT postulates that the continuous reciprocal interaction between behavioral, cognitive, and environmental factors determines human behavior. Specifically, SCT is concerned with how environmental and cognitive factors influence human behavior in a given context (Bandura 1986). Self-efficacy represents the core of the cognitive factors of SCT, which is a form of self-assessment that influences decisions about what behaviors to engage in, and the amount of effort and persistence to exert when faced with obstacles. Individuals with high self-efficacy are more likely to exhibit certain behaviors than those with low self-efficacy. Bandura (1997) proposed that self-efficacy is mainly driven by four different sources: the enactive mastery experience, the vicarious experience, the verbal persuasion, and the physiological and affective states. The enactive mastery experience is the strongest source of self-efficacy and is driven by the repetitive successful completion of tasks (Bandura 1997). Vicarious experiences are created when individuals observe someone with similar abilities performing a task successfully. Verbal persuasion or the belief in success is the thought and reinforcement of a person's belief that they have the ability to complete the task. A person's emotional and physiological state induced by task performance is the final source of self-efficacy (Bandura 1997).

Many IS researchers have used self-efficacy to study a wide variety of effects. For example Compeau and Higgins (1995) extended SCT to include computer self-efficacy in the context of computer use. In another example, authors Hsu and Chiu (2004) extended SCT to include Internet self-efficacy to explore user acceptance of the internet. Self-efficacy also carries a crucial role in virtual environments, with implications for a wide range of domains. A large area of research is related to understanding knowledge sharing and knowledge acquisition in virtual teams (Chiu et al. 2006; Kim et al. 2011). The findings also show that self-efficacy, directly and indirectly, influences knowledge sharing in virtual teams (Hsu et al. 2007).

SCT has been applied to study the design of virtual settings. For example, the authors Koulouris et al. (2020) found that user-defined avatars lead to people being able to identify with them, leading to more learning and imitation of the avatar's behaviors. Self-efficacy also significantly impacts whether users want to participate in virtual environments such as the Metaverse. Individuals with high self-efficacy are more willing to explore and try new experiences within virtual environments, as they believe in their ability to learn and adapt to new tasks and challenges (Pellas 2014). Most (all) of these studies focus on the exploration of SCT in virtual teams in the context of screen-based interfaces. But little is known about the effect of SCT on the utilization of XR interfaces.

6.3 Design Science Research Project

We conducted a comprehensive Design Science Research (DSR) approach (Hevner et al. 2004), focusing on the design of innovative artifacts for the Industrial-Metaverse. In doing so, we propose an innovative solution to a real-world problem (Gregor and Hevner 2013). We address the lack of design knowledge about how to design a UMI to create user-generated Metaverse content (digital twins) for the Industrial-Metaverse. In this way, we hope to improve access to the Industrial-Metaverse for the specific target group (e.g., service technicians). We divided the DSR project into two successive design cycles (Kuechler and Vaishnavi 2008). This paper focuses on the quantitative evaluation results from the second design cycle. The following section briefly describes the overall DSR project to provide additional information and highlight the overall research goal.

In the **first design cycle**, we examined how XR applications can be integrated into these application domains in two organizations (i.e., a manufacturing company and a logistics company). For this purpose, we conducted a focus group and a think-aloud study in each organization to identify the requirements for XR applications in the respective contexts. Despite the different application domains, the case studies revealed that users have problems carrying out and documenting their physical tasks in a process-compliant manner. For example, a user from the logistics company that performs depth measurements in a harbor mentioned the following: "*I probably look at the monitor 80% of the time and only about 20% out of the window*." Another example from the manufacturing company from a user who is responsible for the final assembly of technical energy assets said: "*If I am thrown off track during the assembly by a colleague or something similar, it happens more often that I don't remember which step I was actually at*." These two examples show the need for process guidance during task completion (Morana et al. 2017). We then used the results of the literature review and focus groups to formulate an initial set of design principles.

We instantiated these initial design principles into two different software prototypes. The prototype in the manufacturing sector is an XR guidance tool that guides users step-by-step through the assembly process of an industrial asset. With XR instructions, only the required information is displayed in the right place in the physical environment at the right time. The prototype from the logistics sector represents another XR guidance tool in which users are displayed a bearing line representing the measurement route in their field of view. Followed by evaluating the software prototypes in a case-study (logistics sector) and a think-aloud study (manufacturing sector). The detailed approach and the results of the case study from the logistics sector can be found in our previous publication (Bräker et al. 2023b). In line with the literature, our results have shown that using XR-based process guidance systems offers great potential for companies (Choi et al. 2022). This is one possible reason why a large part of the XR applications in the industrial sector can be classified as process guidance systems (Kortekamp et al. 2019). In addition, we have found that a major problem in practice is not using XR applications but the complex, time-consuming, and cognitively challenging creation of XR content (Ashtari et al. 2020). Creating XR content requires strong programming skills and deep spatial knowledge, making it difficult for novice users (Nebeling and Speicher 2018).

We began the **second design cycle** with ten interviews with experts in XR content creation to further understand XR content creation (i.e., Metaverse authoring). We also read more on SCT to broaden our theoretical design base. We adapted the design principles based on the SCT because individuals are generally more willing to embrace new technologies due to high self-efficacy. We then instantiated the design principles in an industry-independent prototype. The evaluation of the industry-independent prototype is based on the framework for evaluation design science, which consists of four sequential steps (i.e., outline the objectives of the evaluation, select an evaluation strategy, define the properties to be evaluated, and create the evaluation episodes) (Venable et al. 2016). The objective of the evaluation is to verify the validity of the proposed design principles instantiated in a software artifact (i.e., Metaverse authoring tool) that provides a solution for a real-world problem. To facilitate the creation of metaverse content for novice users so that they can contribute to the industrial metaverse, we followed the evaluation strategy of technical risk & efficacy, which is used to rigorously determine the effectiveness of the software artifact. In applying the technical risk & efficacy strategy, we checked whether a specific technology (i.e., Metaverse authoring tool) had the intended effects, as proposed in the design. Venable et al. (2016) recommend starting the evaluation with a laboratory experiment to clarify the boundaries of the technologies. The focus of the evaluation properties is on the validity of the proposed design principles, the effect of user-generated metaverse content on self-efficacy, and the associated intention of users to participate in the Metaverse. In a laboratory experiment, we evaluated the effects on the cognitive and behavioral factors of the users by using different rich Metaverse authoring tools to create a digital twin (XR-based process guidance system). Using a between-subject design, we examine how the richness of the Metaverse authoring interfaces affects self-efficacy, perceived functionality, perceived usefulness, and task performance.

6.4 Conceptual and Instantiation of the Design

6.4.1 Meta Requirements and Design Principles

Our formulated design principles (DP) are based on the schema proposed by Gregor et al. (2020), which suggests how DP should be formulated in order to be usefully applied in a real-world context. The authors point out the need to involve actors in formulating the DP so that they provide prescriptive knowledge of "how to do something to achieve the goal" (Gregor et al. 2020). The structure of a DP consists of the aim, the implementer, the user, the context, the mechanism, and the rationale (Gregor et al. 2020).

Our first meta requirement for a UMI is that novice users must be able to create their user-generated Metaverse content for the Industrial-Metaverse (**MR1**). Since the enactive mastery experience and the creation of user-generated Metaverse content are closely related, as users can create content through their own efforts and actions, such as writing a blog or creating videos, which results in a resilient sense of self-efficacy. In the process of creating user-generated Metaverse content, users are actively involved in achieving an outcome that promotes the acquisition of generative skills (Bandura 1997). Not only in social media, user-generated content has an enormous impact (Goh et al. 2013) but also in several successful Metaverse applications like SecondLife or Roblox, user-generated content is an important element (Bessière et al. 2009; Rospigliosi 2022). In these applications, users can not only navigate through the virtual environments but also create their own game experiences by creating their own content, such as virtual skins (i.e., a costume for avatars) or entire structures (Bessière et al. 2009; Rospigliosi 2022). Our second meta-requirement relates to the general design approach of the UMI, as the creation of XR content poses special and unique challenges to users. The creation of XR content requires good programming skills as well as deep spatial knowledge (Ashtari et al. 2020; Azuma 2016; Nebeling and Speicher 2018). Nebeling and Speicher (2018) analyzed existing XR authoring tools in their research. As a result, they were able to divide the existing tools into five different groups. Considering the skills and resources required to use applications from these five groups, they can be categorized into two categories. In the first category (consisting of groups 4 and 5), a high level of programming skills and deep spatial knowledge is required to make adaptations. In the second class (consisting of groups 1, 2, and 3), no programming skills and less spatial knowledge are necessary to make adjustments. XR authoring tools in this class are no-code or low-code tools for developing XR content. Tools from this class differ from conventional no-code, low-code tools from software development because they provide an XR interface allowing 3D content to be anchored in the physical environments (Azuma 1997) or to create fully immersive virtual worlds. These aspects make the XR authoring tools unique.

Through the concept of a Metaverse authoring tool (i.e., a no-code tool for creating XR content), novice users are empowered to create XR content without any prior experience or programming knowledge (**MR2**) (Nebeling and Speicher 2018). Since the Metaverse authoring tool is used in the Industrial-Metaverse and applications from this context require fused environments, these tools should be based on AR or MR interfaces (Laviola et al. 2022; Siyaev and Jo 2021).

The two meta requirements aim to create higher self-efficacy and, thus, higher user participation in the Metaverse, which can catalyze psychological empowerment (Leung 2009). As a result, users enactive mastery experience their activities as meaningful and have confidence in their work tasks, which could lead to more proactivity (Zimmerman 1990). The meta requirements are supported by SCT, which argues that the content and type of user interaction in the context of the constructed environment influence user engagement (Bandura 1986). The two meta requirements described above form the foundation for the first design principle we propose:

DP1: *Design of an UMI in the form of a Metaverse authoring tool empowering novice users to contribute to the Industrial-Metaverse with user-generated Metaverse content.*

The third meta requirement refers to providing novice users with a library of abstract 3D elements that can be anchored in the user's physical environment (**MR3**). The use of AR content is necessary to represent the digitally and physically intertwined human-machine interaction, which is the focus in the industrial context (Laviola et al. 2022; Porter and Heppelmann 2017). However, in the literature, it has been found that the use of complex XR elements has a negative impact on user attention, as users can be distracted by complex XR elements, which could affect the error rate (Lavric et al. 2022). In addition, recent research has shown that the best results in this context can be achieved using abstract 3D elements combined with media content (i.e., pictures or videos) (Jasche et al. 2021). Therefore, the fourth meta-requirement refers to the need for novice users to be able to create their own media for the Metaverse application (**MR4**).

The two meta-requirements aim on the one hand to enable novice users to create perceived useful applications for the Industrial-Metaverse in their specific application domain, thereby increasing their outcome expectations. On the other hand, the perceived functionality (i.e., completeness) of the Metaverse authoring tool should increase the belief of success of the users. By increasing outcome expectations and the belief in success, users will be more willing to perform challenging tasks, thereby increasing their intention to use the Metaverse (Bandura 1986; Hsu et al. 2007). These two meta requirements thus form the final design principle that we propose:

DP2: *Provide the UMI with a library of abstract 3D elements and allow novice users to add their own media in order to create complete and perceived useful applications for the Industrial-Metaverse.*

6.4.2 Instantiation of the Design

To instantiate our design principles, we developed a software artifact of a Metaverse authoring tool. The first design principle maps to the basic design of a standalone Metaverse authoring tool that runs on a tablet without the need to install additional software or plug-ins or use additional hardware. Through the use of a no-code development approach, the graphical user interface does not require users to implement their code. Therefore, users can create Metaverse applications (i.e., XR-based process guidance systems) via drag and drop, enrich them with 2D and 3D elements, and anchor them in the physical environment.

The second design principle is the 2D node editor and the 3D authoring environment. The 2D Node Editor is used to define the structure and sequence of commands. Three different node types are available to the user. The first node type is the Info-Node, where only 2D elements (i.e., text) can be added. An Instruction-Node represents one step in an instruction, and an Exploration-Node can only display location-specific content. The display and information elements used to represent the XR-based process guidance systems are defined in the 3D authoring environment. For our application domain, the library of 3D elements is built on the six information types (i.e., identity, location, way-to, notification, order, and orientation) proposed by Gattullo et al. (2020) to fully map XR-based process guidance systems. In addition, we have implemented an attention funnel that supports users in highlighting dangers or obstacles in a visual search or spatial navigation (Biocca et al. 2007). In addition to 3D elements, 2D elements such as media or text can be added to an instructional step.

Apart from creating the XR-based process guidance systems, novice users can also use them to carry out their work in a process-compliant manner. In a Viewer Mode, the XR-based process guidance systems can be displayed. As the name suggests, changing or adapting the AR instructions in the viewer mode is impossible. The designed 2D and 3D content is rendered precisely where the creators placed it. Figure 22 shows the Node Editor on the left and the XR authoring environment on the right.

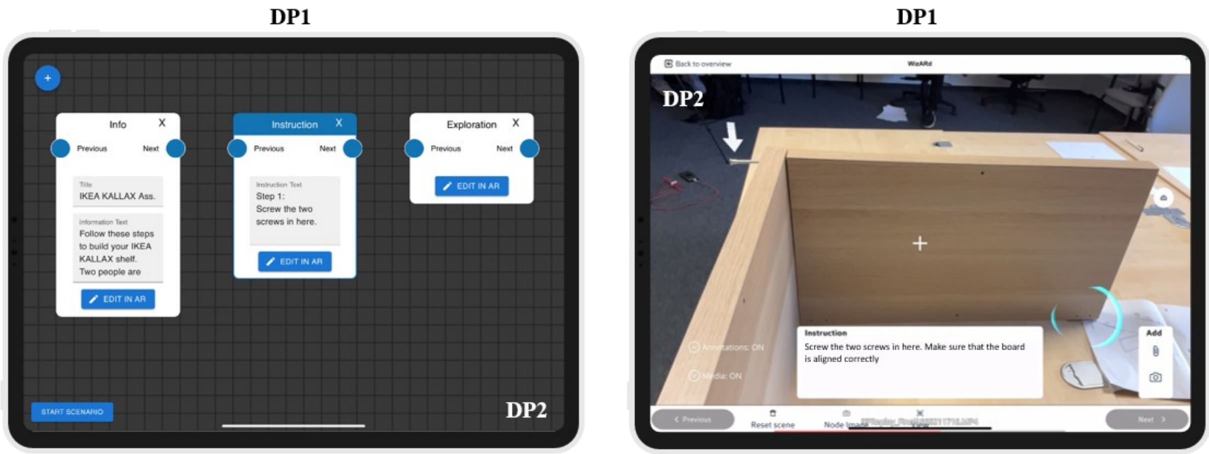

Figure 22. Software artifact: Metaverse authoring tool

6.5 Evaluation

In a laboratory experiment, we evaluated the impact of the proposed DPs and the resulting instantiated artifacts in a controlled laboratory environment. In order to test the functionality of our first DP, we investigate the impact of user-generated Metaverse content on self-efficacy and users' intention to contribute to the Metaverse. To test the functionality of the second DP, we have developed two XR authoring tools of different richness, which can be used to create

Metaverse content of different richness. On the one hand, we want to check the functionality of our second DP. On the other hand, we want to identify the most relevant 3D elements based on the evaluation results and, if necessary, adapt our DPs accordingly. We argue that when novice users feel empowered to create Metaverse content (i.e., they have everything they need to create complete XR-based process guidance systems), belief in success increases, and if they believe that the created content is useful for other users, this, in turn, increases their outcome expectations. The two factors' belief in success represented by perceived functionality as outcome expectations represented by perceived usefulness will increase task performance.

As described in Chapter "Instantiation of the Design" the first prototype (rich XR authoring tool) provides users with seven different 3D elements; additionally, the users can add their own media. On the other hand, in the second prototype (reduced XR authoring tool), only two 3D elements are available to the user (i.e., arrow and point of interest). In addition, users cannot add any media to an instruction step.

6.5.1 Hypotheses Derivation

We formulate hypotheses regarding the proposed effects of the DPs based on existing research to evaluate their validity. Figure 23 shows the conceptualized research model and hypotheses.

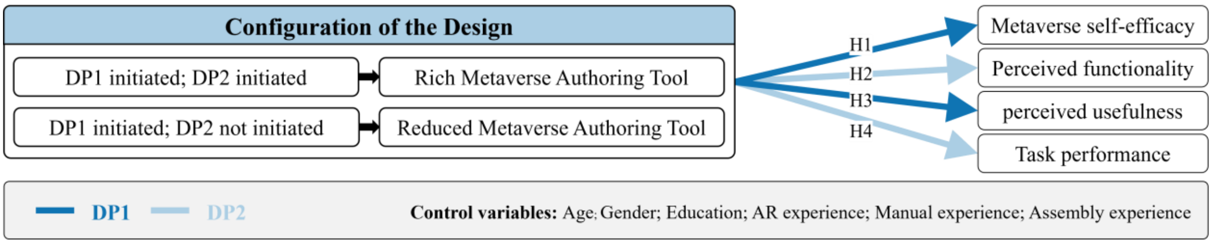

Figure 23. Research model

According to SCT, users who have a strong belief in their ability to successfully complete (belief in success) a task have greater self-efficacy (Bandura 1997). The perceived functionality of technology has a decisive impact on this. For example, Strong et al. (2006) found that adapting technology's functionality to the task positively affects the user's belief that he or she can perform the task successfully. The rich Metaverse authoring tool is designed with all the functionalities to create task-specific Metaverse applications in the context of the Industrial-Metaverse. Therefore we hypothesize that:

H1: *The perceived functionality of the rich Metaverse authoring tool is higher than that of the reduced Metaverse authoring tool.*

The outcome results from actions and can be anticipated by users by assessing how well they can behave in a given situation (Bandura 1997). This means users estimate their expected outcomes before taking action. This relationship connects the belief of success and outcome expectations. Positive outcomes can strengthen an individual’s behavior, whereas those who doubt their capability or lack the necessary skills may perceive their actions as pointless and ineffective (Bandura 1997; Compeau et al. 1999). Furthermore, individuals who believe they possess the required skills to perform well in a given context, such as using a computer, are more likely to anticipate positive outcomes compared to those who doubt their abilities (Compeau et al. 1999).

IS studies have found a strong correlation between self-efficacy and perceived usefulness and between outcome expectations and perceived usefulness. For example, Compeau et al. (1999) found that both computer self-efficacy and performance outcome expectations significantly impact usage. Also, in virtual environments such as a Metaverse, a strong correlation has been proven between knowledge-sharing self-efficacy and knowledge-sharing behavior and personal outcome expectations and knowledge-sharing behavior (Hsu et al. 2007). Furthermore, previous HCI studies have found a strong positive influence of the perceived functionality of an interface on its perceived usefulness (Cho et al. 2009). Therefore, since we assume that the belief in success of the rich Metaverse authoring tool is higher, we hypothesize that:

H2: *The perceived usefulness of the rich Metaverse authoring tool is higher than the reduced Metaverse authoring tool.*

The creation of user-generated Metaverse content has a major impact on self-efficacy, as this is closely linked to the enactive mastery experiences. The enactive mastery experiences are the biggest influencing factors on self-efficacy, as they provide the most reliable evidence of whether a user can muster all the resources to accomplish a task successfully (Bandura 1997). Enactive mastery experiences and the creation of user-generated Metaverse content are closely related, because users can create content through their own efforts and actions, such as writing a blog or creating videos, which results in a resilient sense of self-efficacy. In the process of creating user-generated Metaverse content, users are actively involved in achieving an outcome that promotes the acquisition of generative skills (Bandura 1997). Since with both Metaverse authoring tools, novice users can create Metaverse content on their own, the enactive mastery experience will probably remain unchanged. However, since we expect the rich metaverse authoring tool to have a positive impact on both the belief in success and the outcome expectations, we hypothesize that:

H3: *The Metaverse self-efficacy of the rich Metaverse authoring tool is higher than the reduced Metaverse authoring tool.*

Task performance is a key element of Bandura (1986) SCT because both self-efficacy and outcome expectations are closely related to actual task performance. Thus, users with high self-efficacy and positive outcome expectations approach tasks with greater confidence and motivation and persevere in the face of challenges or obstacles, which can lead to better task performance or a higher level of achievement (Bandura 1997). This assumption of SCT has been demonstrated in several studies from different disciplines (Lent et al. 1994; Tams et al. 2018). Therefore, since we assume that the self-efficacy and the perceived functionality of the rich Metaverse authoring tool are higher, we hypothesize that:

H4: *The task performance of the rich Metaverse authoring tool is higher than that of the reduced Metaverse authoring tool.*

In the lab experiment, we used a between-subjects design to test our hypotheses, with different participants testing one of the two Metaverse authoring tools. We chose a between-subjects design to minimize possible learning effects when the same participants use both Metaverse authoring tools sequentially to create instruction, as repetition could introduce bias into the collected data.

As part of our experiment, we collected qualitative and quantitative data using our Metaverse authoring tools. The task performance of the XR-based process guidance systems was evaluated as a dependent variable. In addition, participants evaluated self-efficacy, perceived functionality, and perceived usefulness through self-reports as part of the post-experiment survey. As an independent variable, the feature set of the Metaverse authoring tool was examined using two AR authoring tool prototypes with different levels of richness.

6.5.2 Setup and Procedure

At the beginning of each experiment session, we briefed our participants about our research objective - evaluating our Metaverse authoring tool - and the experimental procedure. In addition, a pre-experiment written survey was used to collect demographic data and insights into participants' previous experiences with XR.

Before starting the experiment, we demonstrated the Metaverse authoring tool to the participants, explaining its features and how to use it. After introducing the tool, a simple demonstration task was presented to the participants. Here the participants had to create content (2D and 3D) independently and then manipulate the 3D content in the real environment. The task was considered complete when the users stated they understood how to use the tool. After this introduction to the tool and demonstration task, no further information on how to use the tool was provided to the participants.

Participants were randomly assigned to one of the two groups (rich metaverse authoring tool or reduced metaverse authoring tool). As the main task of the experiment, we requested participants to assemble a 2x2 IKEA KALLAX shelf following IKEA's paper-based instructions, which contain eight assembly steps. Next, we asked participants to use the Metaverse authoring tool to create an XR-based process guidance system, which means replicating the eight steps of the paper-based instruction and improving this instruction through XR visualizations. After reading this task to the participants, we briefly showed them where each shelf component was placed. The placement of the components was identical for each experiment session. Participants were given 20 minutes to create their XR-based process guidance system. The experimental task was completed when it was completed or when the time ran out.

6.5.3 Data Collection and Sample

We asked participants to complete a post-experiment survey. We used the internal computer self-efficacy questionnaire from Thatcher et al. (2008) to measure self-efficacy. To collect data on the perceived usefulness of the tool, we used the scale of perceived usefulness by Wixom and Todd (2005). The task performance is based on the average of two XR authoring experts' ratings for the XR-based process guidance systems created by the experiment participants.

A total of 57 participants took part in the laboratory experiment. We excluded two speeders and five participants who did not complete the questionnaire. Of the 50 participants, 19 are male, and 31 are female, with an average age of 21.86. Of these student participants, 45 are enrolled in business administration and five in industrial engineering. Although participation in the experiment was voluntary as a reward, participants received three bonus points for a written exam. Regarding their previous experience with XR, 38 participants stated that they have experience using XR to varying degrees, mainly XR games, social media filters, and shopping applications. 12 participants indicated that they had never used any XR application before. Eight participants stated that they'd developed XR applications before. None of the participants used an XR authoring tool before this study. A total of 26 participants used the rich Metaverse authoring tool and 24 participants used the reduced Metaverse authoring tool.

6.6 Results

We conducted a statistical analyzis of the dependent variables collected through our laboratory experiment to test our hypotheses. Given that t-tests postulate normally distributed and homogeneous variables, we tested our variables for normal distribution with the Shapiro-Wilk-Test (Shapiro and Wilk 1965) and for homogeneity of variance using Levene's test (Levene 1960). The two tests show that a normal distribution and homogeneity can be assumed for all examined dependent variables, as all values are significant at the $\alpha < 0.05$ level. In testing our hypotheses, we examine the differences in the mean values of the two different design configurations. For this purpose, we compared the results of the two design configurations using a t-test. Table 17 summarizes the results of the comparison of the two design configurations.

	Reduced Tool		Rich Tool			
Dependent Variable	**M**	**SD**	**M**	**SD**	**t-test**	**Hypothesis**
Metaverse self-efficacy	4,3611	1,2274	3,9744	1,3562	1,054	H1: not supported
Perceived functionality	3,9028	0,8310	4,5	0,9809	-2,313*	H2: supported
Perceived usefulness	5,1875	0,8668	5,4423	0,8869	1,026	H3: not supported
Task performance	2,5833	0,7614	3,0769	0,6276	-2,509*	H4: supported
*p<0.05						
M = Mean; SD = standard derivation						

Table 17. Results of the t-test

Comparing the results of the two design configurations to test our second hypothesis (H1) shows that the actual functionality of the Metaverse authoring tool has a significantly higher positive effect on the performance-related outcome expectation (perceived functionality). Therefore, we assume that hypothesis H1 is supported.

The result of comparing the two design configurations to test our third hypothesis (H2) shows that the functionality of the Metaverse authoring tool has no significant positive effect on the users' perceived usefulness. We detected only a slight (but not statistically significant) difference in perceived usefulness. Since both outcome expectations and self-efficacy influence perceived usefulness (Cho et al. 2009; Hsu et al. 2007), and since we could not prove a significant difference for Metaverse self-efficacy, we assume that there is no statistical significance for perceived usefulness either. Therefore, we assume that hypothesis H2 is not supported.

The result of the comparison of the two design configurations to test our first hypothesis (H3) shows that the functionality of the Metaverse authoring tool has no significant positive effect on the users' Metaverse self-efficacy. Rather, an opposite effect can be observed: the users with the reduced tool show a higher (but not statistically significant) Metaverse-self efficacy.

The result of comparing] the two design configurations to test our fourth hypothesis (H4) shows that the functionality of the Metaverse authoring tool has a large significant positive impact on task performance in the chosen application domain (Industrial-Metaverse). Therefore, we assume that hypothesis H4 is supported.

6.7 Discussion

According to Gregor and Hevner (2013) DSR Knowledge Contribution Framework, our research can be classified as an improvement. We have developed a new solution for a known problem. The enormous impact of XR in organizations has been well-researched for a long time (Choi et al. 2022; Porter and Heppelmann 2017). However, XR has not yet been widely adopted in an industrial context. In line with the literature, we have identified that one possible reason may be XR content creation's complexity (Ashtari et al. 2020; Azuma 2016; Nebeling and Speicher 2018). Similar to software development (Maruping and Matook 2020), where no-code or low-code tools help novice users develop new applications, the Metaverse authoring tools help novice users create XR content. We have shown that the Metaverse authoring tools increase both the enactive mastery experience and the belief in success of novice users, which are important contributors to user engagement for the Industrial-Metaverse.

Compared to existing XR authoring tools like MinimalAR (Laviola et al. 2022), HoloWFM (Damarowsky and Kühnel 2022), or HoloFlows (Seiger et al. 2019), we developed a UMI (Metaverse authoring tool), which on the one hand, enables novice users by creating user-generated content to fully map digital twins (i.e., XR-based process guidance system) for the Industrial-Metaverse and on the other hand enables different novice users to use these digital twins to carry out their work in a process-compliant manner. With the proposed design of the UMI, we first contribute to the call of the research by (Dwivedi et al. 2022), for which goals and under which conditions VR or AR represents the more effective user interface and which hardware is best suited for this application context. On the other hand, we support the development of immersive, interactive, and persistent 3D Metaverse applications through our theoretically based design principles instantiated in a software artifact.

Self-Efficacy is an important aspect of the design of an interface. A lack of self-efficacy can have serious consequences for the acceptance and use of an interface (Schymik et al. 2017). For example, unsuccessful experiences using technologies negatively impact learning new technologies (Johnson et al. 2016). Therefore, the design of interfaces that positively influence self-efficacy is a central design aspect. This study aimed to identify the key sources of self-efficacy for the UMI in the context of the Industrial-Metaverse. In this study, we investigated how the belief in success affects self-efficacy. Although we found a significant difference in the different rich AR authoring tools, we surprisingly did not find a difference in the actual self-efficacy. This could be due to the fact that the belief in success is only one of three sources of self-efficacy. The strongest source of self-efficacy is the enactive mastery experience and is part of both the rich and the reduced authoring tools, as both tools allow users to create metaverse content on their own. In a third design cycle, it would be very interesting to explore how the enactive mastery experience (i.e., the strongest of the self-efficacy sources) affects the creation instead of using the Metaverse content.

Although a significant positive influence of belief in success and perceived functionality on outcome expectations associated with perceived usefulness has been demonstrated in the literature (Cho et al. 2009), we could not confirm this significant influence in our study. We measured a slight but not significant impact. A possible reason for this deviation could be that the participants of the laboratory study had to create an application for the Industrial-Metaverse without having any relation to this context. For participants to evaluate the usefulness of a created application for the Industrial-Metaverse, they need to know the environment and influencing factors associated with the context. This challenge can be addressed through a real-world evaluation of different industrial companies in the third design cycle (Venable et al. 2016).

The understanding of the concept of self-efficacy in the context of the Industrial-Metaverse was broadened and contextualized. To the best of our knowledge, our DSR project is the first to consider user-generated content creation and the associated self-efficacy in the context of the Metaverse. We provide prescriptive knowledge about how the type of content and user interactions in constructed environments affect user engagement. We present a software artifact as a UMI that enables both the creation and use of Metaverse content through three software components (i.e., 3D authoring environment, 2D node editor, and viewer mode) and two theoretically grounded design principles that provide prescriptive knowledge about the impact of self-efficacy in the Industrial-Metaverse.

We were able to use the SCT by contextualizing it in the Metaverse to make a theoretical contribution to the design of UMI, which enables the creation and utilization of Industrial-Metaverse content. We have extended SCT in several ways: in line with internet (Eastin and LaRose 2000) and computer (Compeau and Higgins 1995) self-efficacy, our study has shown that self-efficacy greatly impacts users' intention to contribute to the Metaverse in the context of the Industrial-Metaverse. Existing research on the impact of self-efficacy in virtual teams (Hsu et al. 2007; Pellas 2014) has examined this impact on screen-based interfaces. Our research extends SCT by examining the impact of novice users' self-efficacy when interacting with XR interfaces. Self-efficacy in Metaverse can be distinguished from self-efficacy on the internet, as the use of XR interfaces confronts users with specific challenges, such as necessary spatial knowledge (Nebeling and Speicher 2018). The belief that one can successfully perform a set of behaviors required to use and create Metaverse content goes beyond basic PC, application, and internet skills.

6.7.1 Limitations and Future Research

Although we conducted the DSR project and evaluation described in this research according to established guidelines, there are limitations that require further research. First of all, despite a significant difference in belief in success, we could not identify a difference in self-efficacy. A possible reason for this could be that self-efficacy is closely linked to the cognitive abilities of the users (Bandura 1997), and increasing functionality also leads to an increased mental load. Thus, the lower self-efficacy when using the rich Metaverse authoring tool might also be caused by other theories, such as the Cognitive Load Theory (CLT) (Sweller 1988) or the Media Richness Theory (Daft and Lengel 1986). Therefore, for future research, we recommend considering core CLT aspects such as information overload or split-attention effects when creating user-generated Metaverse content. Next, the DPs we have formulated are only valid for XR interfaces for the Industrial-Metaverse. It cannot be assumed that our DPs are valid on screen-based or VR interfaces which are often associated with the Metaverse in the IS literature without adaptations. Therefore, for future research, we recommend verifying the validity of our two DPs using screen-based or VR Metaverse applications. An additional aspect is that the DPs we propose only refer to the Metaverse authoring tools used by novice users. It cannot be assumed that they are also valid for Metaverse authoring tools used by AR experts. Another limitation to mention is that the evaluation was conducted only with participants who do not correspond to the target group (i.e., service technicians). In order for the results to be richer and more generalizable, the evaluation must be conducted with participants from the target audience. Although two AR authoring experts evaluated the quality of XR instructions created by participants, a representative target group may perceive the quality of XR-based instructions differently. In a two-stage evaluation, the XR-based instructions created by the domain experts could be assessed by other domain experts, which could lead to new and representative results. Finally, it is important to note that the research was conducted from a socio-technical perspective. Looking at the same research from a purely technical perspective such as software interactive interfaces designs could lead to different DPs.

7 The Importance of Separation in the Creation and Usage Phases of Augmented Reality Content Using Social Cognitive Theory (P4)

Title	The Importance of Separation in the Creation and Usage Phases of Augmented Reality Content Using Social Cognitive Theory
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Table 18. Fact Sheet Publication P4

Abstract: Although Augmented Reality-based Process Guidance Systems bring enormous potential savings to organizations, this technology is often not used beyond prototyping. One possible reason is that creating AR content requires advanced programming skills and deep spatial knowledge, which many SMEs lack. To address this challenge, AR authoring tools should enable novice users to create AR content. In this DSR project, we propose an AR authoring tool that novice users can apply as an innovative artifact to solve this problem. We elaborate on the third theoretical grounded design principle based on the social cognitive theory to understand the demands of creating and using AR content. We evaluated the developed software artifact in a field study with 12 participants. Our results show the different sources of self-efficacy in the creation and usage phase of AR content, highlighting the need for separation.

7.1 Introduction

Through the use of Augmented Reality (AR) technology, the appropriate digital information will be displayed in the needed place on-site at the right time (Azuma 1997). This newly emerged human-machine interface (Liu et al. 2017) has led to the appearance of new types of interactions and applications over time. As application areas continue to broaden, so too do the challenges. One of these challenges is the complexity of creating meaningful AR content (Arth and Schmalstieg 2011). For instance, developing an AR application in an industrial context requires in-depth domain knowledge and advanced programming skills. Furthermore, creating and placing 3D elements in the physical environment requires deep spatial knowledge (Azuma 2016). Consequently, technically skilled developers closely collaborate with domain experts to develop AR applications. As a result, 64 % of all AR applications in the engineering sector are individual developments (Palmarini et al. 2018). Individual developments are often not suitable for the use of AR outside of a prototypical evaluation. Even small changes in the process can mean an expensive and time-consuming adaptation of the application.

To counteract these challenges, scientists and practitioners look into so-called AR authoring tools (MacIntyre et al. 2005). These tools allow novice users to create AR content by accessing pre-built 3D models, animations, and annotations (Nebeling and Speicher 2018). The term novice users in this work means users with no programming experience and no AR content creation experience. Nevertheless, these novice users are domain experts in their field, e.g., service technicians.

However, on closer examination, most available Authoring tools are generally intended for experienced and technically skilled software developers, as many functionalities require extensive programming and 3D modeling skills (Nebeling and Speicher 2018). Enabling novice users to develop independent AR content remains a challenge. Therefore, we designed an AR authoring tool based on a no-code approach.

This study addresses the application domain of process guidance systems (PGS) (Morana et al. 2017) in an industrial context since many existing AR applications are used as PGS in this context (Klinker et al. 2018; Kortekamp et al. 2019). A PGS is comparable to a car navigation system, which provides the driver with spatial information as they drive from location A to location B (Morana et al. 2019). Through a PGS, users are guided through their work steps to complete them in a process-compliant manner (Dorn et al. 2010). The AR-based PGS is a new approach to guide users in performing physical processes (Laviola et al. 2022). Here, users are shown the necessary information at the right places and times. By applying these AR-based

PGS, industrial companies can achieve enormous savings potential, for example, by reducing the preparation time and failure rate during the assembly of large aircraft systems (Serván et al. 2011). Thus, an AR authoring tool that enables novice users to develop such AR-based PGS offers great potential.

Although there is already some work on AR Authoring Tools and the PGS, we still see a gap in the existing literature. Researchers have separately instantiated and evaluated AR authoring tools to create AR content and PGS to use AR content. To the best of our knowledge, no study yet combines and compares these aspects and provides a comprehensive overview of how AR authoring tools must be designed to engage novice users to develop AR-based PGS. More specifically, this research aims to understand the different sources of user engagement to create and use AR content in an industrial context to provide design knowledge for future AR authoring tools. To do so, we draw on social-cognitive theory (SCT), concerned with how environmental and cognitive factors influence human behavior in a given context (Bandura 1986). We draw on the SCT since AR content creation is important in SCT, as users create content through their own efforts and actions, leading to higher self-efficacy (Bandura 1997).

Therefore, we want to answer the following research question: *What impact do the different sources of user engagement in creating and using AR content in an industrial context have on the design of AR authoring tools?*

The study follows the design science research methodology (Kuechler and Vaishnavi 2008) to answer the research question. As a result, we contribute theoretically by proposing design knowledge for AR authoring tools for novice users. We also provide a practical contribution with our design principle to assist in implementing similar tools. Finally, we present the different sources of self-efficacy in the creation and usage phases of AR content, highlighting the need to separate these phases.

7.2 Conceptual foundations

7.2.1 Augmented Reality and AR-authoring

Due to intensive research, AR has made significant progress and has been continuously developed by various industries and researchers in recent years. The technology can be found in various applications (van Krevelen and Poelman 2010). Despite these broad applications and technological progress, AR has some technical challenges and limitations (Arth and Schmalstieg 2011). Ashtari et al. (2020) identified eight fundamental barriers that prevent AR creators from getting started. These range from prototyping an initial immersive experience to the difficulties of testing AR applications. Recent research has focused on developing AR authoring tools to reduce the technical barrier to development.

One of the first AR authoring approaches was the application DART in 2005, an extension of Macromedia Director that allows users to specify complex relationships between the physical and virtual worlds (MacIntyre et al. 2005). This first approach leads to various new tools in the industrial sector, such as ACAAR (Zhu et al. 2015), HoloWFM (Damarowsky and Kühnel 2022), HoloFlows (Seiger et al. 2019) or ATOFIS (Lavric et al. 2022).

All these AR authoring tools were inspiration for the development of our tool. However, we have identified a shortcoming in the current tool landscape, as most tools focus on a single concept. For example, the ACAAR (Zhu et al. 2015) and ATOFIS (Lavric et al. 2022) tools focus on the authoring of AR applications. The authors of the ACAAR tool propose a system consisting of two software components. On the one hand, the *Offline Authoring module* is used to create the content, and on the other hand, the *Context-aware AR Services* module provides context-aware visualizations (Zhu et al. 2015). In contrast, the authors of the ATOFIS tool propose an in-situ authoring process in which users perform the authoring exclusively on an HMD (Lavric et al. 2022). The HoloWFM tool focuses on the AR content (i.e., what information the service technicians need to complete their task) (Damarowsky and Kühnel 2022). The HoloFlows tool focuses on connecting the digital world and the physical environment. With the help of this tool, users can connect different IoT devices (Seiger et al. 2019). Through the inspiration of these tools, we have developed a practical tool that connects the shown concepts.

7.2.2 AR-based Process Guidance Systems

PGS are often used to support the user in executing digital processes to work in a process-compliant manner (Morana et al. 2017). However, many physical steps exist in the industrial context where the use of digital PGS is limited. For this reason, the researchers initiated and evaluated AR-based PGS (Hönemann et al. 2023b; Kammerer et al. 2018). AR-based PGS enables users to display the information they need at the right time, anchored in the right place in their physical environment.

Due to the consistent implementation of cyber-physical systems in the industrial context, more and more process data is available to users, which enhances the need for AR-based PGSs. This increasing flood of digital data creates a fundamental disconnection from the physical world (Porter and Heppelmann 2017). While the physical environment is three-dimensional, the digital content on which we base new decisions daily is trapped in a two-dimensional space, such as monitors or pages. This gap between the physical and the virtual world hinders the ability to make the best possible decisions (Porter and Heppelmann 2017). Using AR-based PGS, important information about the process can be displayed to the user at the right time and place in the user's physical environment.

Several examples of AR-based PGS applications are in the field of aircraft manufacturing. For example, the authors Chen et al. (2019) have instantiated an AR application that guides the service operator through the cable assembly process of large spacecraft components. The cable assembly process in this domain is very complex and requires very high accuracy. For this reason, the authors have instantiated and evaluated a new tracking method (Chen et al. 2019). Another software solution in this application domain is the project MOON at Airbus (Serván et al. 2011). The tool supports the service operators in the wiring harness installation by displaying both the work to be performed and the basic critical operating parameters in the physical environment of the operators. As a result, the preparation time could be reduced by 90% (Serván et al. 2011).

7.2.3 Social Cognitive Load Theory

We draw on a social cognitive theory (SCT) (Bandura 1986) as a kernel theory to conceptualize and represent our contributions to design knowledge and to develop our design principles. SCT postulates that the continuous reciprocal interaction between behavioral, cognitive, and environmental factors determines human behavior. Specifically, SCT is concerned with how environmental and cognitive factors influence human behavior in a given context (Bandura 1986). Self-efficacy represents the core of the cognitive factors of SCT, which is a form of self-assessment that influences decisions about what behaviors to engage in and the amount of effort and persistence to exert when faced with obstacles. Individuals with high self-efficacy are more likely to exhibit certain behaviors than those with low self-efficacy. Bandura (1997) proposed that self-efficacy is mainly driven by four different sources: the enactive mastery experience, the vicarious experience, the verbal persuasion, and the physiological and affective states. The enactive mastery experience is the strongest source of self-efficacy and is driven by the repetitive successful completion of tasks (Bandura 1997). Vicarious experiences are created when individuals observe someone with similar abilities performing a task. Verbal persuasion is the thought and reinforcement of a person's belief that they have the ability to complete the task. A person's emotional and physiological state induced by task performance is the final source of self-efficacy (Bandura 1997).

Self-efficacy is crucial in virtual environments created by AR/VR interfaces, with implications for various domains. A large area of research is related to understanding knowledge sharing and knowledge acquisition in these virtual environments (Chiu et al. 2006; Kim et al. 2011). The findings also show that self-efficacy, directly and indirectly, influences knowledge sharing in virtual teams (Hsu et al. 2007). Self-efficacy also significantly impacts whether users want to participate in virtual environments. Individuals with high self-efficacy are more willing to explore and try new experiences within virtual environments, as they believe in their ability to learn and adapt to new tasks and challenges (Pellas 2014). Furthermore, SCT plays a crucial role in AR authoring, as users create AR content through their own efforts and actions during the authoring, which leads to higher self-efficacy (Bandura 1997).

7.3 Research Method

This study is part of a comprehensive Design Science Research (DSR) project (Hevner et al. 2004) focusing on designing innovative artifacts. We propose an innovative solution to a real-world problem (Gregor and Hevner 2013). In particular, it addresses, on the one hand, the lack of design knowledge regarding user engagement during novice users' creation of AR content. On the other hand, it addresses the lack of design knowledge regarding user engagement during the usage of AR content in an industrial context for novice users to carry out their work in a compliant manner.

In this way, we want to improve novice users' access to AR technology. We adapted Kuechler and Vaishnavi (2008) DSR approach and separated the overall DSR project into three successive design cycles. This research focuses on the qualitative evaluation results from the field study from the third design cycle, which are based on the first two design cycles. We balance rigor and relevance in our research by instantiating our AR authoring tool in an industrial equipment supplier (Hevner et al. 2004) through the DSR project and evaluating it.

7.3.1 Design science research project

Although this research focuses solely on the third design cycle, the following section briefly describes the entire DSR project to provide additional information and highlight the overall research goal.

In the **first design cycle**, we examined how AR applications can be integrated into these application domains in two organizations. For this purpose, we conducted a focus group and a think-aloud study in each organization to identify the requirements for AR applications in the respective contexts. Despite the different application domains, the focus groups and the think-aloud studies revealed that users have problems carrying out and documenting their physical tasks in a process-compliant manner. We then used the results from the literature review, focus groups, and think-aloud studies to formulate two initial design principles. We instantiated these initial design principles into two different software prototypes. Followed by evaluating the software prototypes in a case study and a think-aloud study. In line with the literature, our results have shown that using AR-based PGS offers great company potential (Choi et al. 2022; Tang et al. 2003). In addition, we have found that a major problem in practice is not using AR applications but the complex, time-consuming, and cognitively challenging creation of AR content, which requires strong programming skills and deep spatial knowledge (Ashtari et al. 2020).

We began the **second design cycle** with ten interviews with experts in AR content creation to further understand AR content creation. We also read more on SCT to broaden our theoretical design base. We adapted the two design principles based on the SCT because individuals are generally more willing to embrace new technologies due to high self-efficacy. We then instantiated the design principles in an industry-independent prototype. In a laboratory experiment, we examined how the richness of the AR authoring tool affects self-efficacy, belief in success, outcome expectations, and task performance. Since we were able to prove a significant difference in the belief in success but no significant difference in self-efficacy by modifying the tools' richness, we now aimed to seek possible explanations for this discrepancy in the third design cycle. One possible explanation would be the different sources of enactive mastery experience during the creation and use of AR content (Bandura 1997).

In the **third design cycle**, we want to reiterate the findings from the second design cycle with adapted software artifacts in a real-world application context at different industrial organizations. By doing so, we respond to the request of Peffers et al. (2012) for more real-world evaluations of DSR artifacts. Based on the findings of the second design cycle, we adapted and added a design principle and then implemented them in our final software artifact. To compare the findings from the second design cycle with the results from this design cycle, we consider the effect of the AR authoring tool in the same application context with real users and the related real problems in an industrial environment. In the field study, we evaluate the validity of the third design principle instantiated in a software artifact.

7.4 Designing an AR Authoring Tool

7.4.1 Design Requirements and Design Principles

Our formulated design principles (DP) are based on the schema proposed by Gregor et al. (2020), which suggests how DP should be formulated in order to be usefully applied in a real-world context. The authors point out the need to involve actors in formulating the DP so that they provide prescriptive knowledge of “how to do something to achieve the goal” (Gregor et al. 2020). The structure of a DP consists of the aim, the implementer, the user, the context, the mechanism, and the rationale (Gregor et al. 2020).

The first four design requirements, which form the basis for the first and second design principles we propose, are part of the first two design cycles and are addressed in the publication (Hönemann et al. 2023a). To better understand the software artifact, Table 19 shows the four design requirements, the two design principles derived from the SCT, and the interviews from the second design cycle.

Design requirements	Design principles
DR1: Enable novice users to create user-generated AR content.	**DP1:** Design of an AR interface as an AR authoring tool empowering novice users to contribute to the industrial context with user-generated AR content.
DR2: Design of an AR Authoring tool to create AR content.	
DR3: Provide users with abstract 3D elements that can be anchored to the users' physical environment.	**DP2:** Provide the AR interface with a library of abstract 3D elements and allow novice users to add their media to create complete and perceived useful applications in the industrial context.
DR4: Provide novice users with the ability to create their media.	

Table 19. Design requirements and principles from the initial two design cycles

The fifth design requirement aims to separate the AR creation and usage phases "Create user-generated AR content" and "Use AR content" from each other (**DR5**) since the personal experiences of success that influence the novice users' enactive mastery experience differ significantly in these phases. In the AR authoring phase, “Create user-generated AR content”, novice users experience success in the creation of AR content when they have created an application in which they believe that they have created an application that is useful for other parties (Leung 2009). In the AR authoring phase, "Use AR content", on the other hand, success is more likely to be defined by practical benefits such as reducing the error rate and saving time or costs. Therefore, it is only perceived as successful if the application offers visible economic or social added value for novice users (Porter and Heppelmann 2017; Serván et al. 2011; Tang et al. 2003). In addition to the enactive mastery experience, verbal persuasion fundamentally differs in these AR authoring phases. Verbal persuasion in the AR authoring phase, "Create user-generated AR content,” is mainly driven by the user's conviction that they can accomplish the task. Users in virtual teams who are not convinced of their abilities to share knowledge do not perform certain behaviors (Bandura 1986). In this context, creating AR content to guide users through their work in a process-compliant manner represents knowledge sharing (Chiu et al. 2006; Hsu et al. 2007). In the AR authoring phase, "Use AR content", on the other hand, the verbal persuasion is influenced by two factors: the novice users' belief that they have the technical skills to perform the task (i.e., to repair the technical asset) and the quality of the instructions available to them which increases their belief in success (Laviola et al. 2022).

The design requirement aims to consider the differently driven enactive mastery experience and verbal persuasion in creating and using AR content in the industrial context. The design requirement thus forms the final design principle that we propose: ***DP3:*** *The AR interface should provide novice users with a clear separation between creating user-generated AR content and using AR content.*

By initiating the prototypes based on all these approaches, we intend to evaluate these approaches and then adapt the design principles accordingly. Table 20 provides an overview of the fifth design requirement that formed the basis for our proposed third design principle.

Design requirements	Design principles
DR5: The novice user's success and belief in their own abilities differ significantly when creating AR content than when using it.	**DP3:** The AR interface should provide novice users with a clear separation between creating user-generated AR content and using AR content.

Table 20. Design requirement and design principle

7.4.2 Instantiation of the Design

The AR authoring tool is a standalone tablet tool that doesn't require additional software or hardware. This applies to both the creation and use of AR content. The tool adopts a no-code development approach, providing a library of abstract 3D elements and the ability to create custom media. The following chapter provides a detailed overview of the fundamental architecture of the AR authoring tool, which consists of three main software components.

The first software component is the 2D Node Editor. This software component determines the structure and sequence of the AR-based PGS. It represents the initial basis for each instruction to be created. The structure can be defined through three different node types. The first node type is the Info-Node, where only 2D elements can be added to the application. Both 2D and 3D elements can be added to the application in an Instruction-Node. In the case of an Exploration-Node, only location-dependent 3D elements can be added. The left side of Figure 24 gives an overview of the 2D Node Editor, in which a simple AR-based PGS is created.

The contents of the different node types are part of the second software component, the 3D Authoring Environment. This content enriches the previously defined process flows with the necessary content to generate comprehensive AR instructions. Three elements, the 3D elements, the media, and the nodes, form the foundation of the 3D authoring environment. The first element provides the user with a total of seven abstract 3D elements, ranging from a simple arrow, which can indicate a position in the physical environment, to an omnidirectional attention funnel, which acts as a navigation through the users' physical environment (Biocca et al. 2007). The 3D elements can be dragged and dropped to the desired positions, and users always have the opportunity to adjust the position. Adding different media is also part of the second element of the software component. The third element of the software component is the different node types, which all differ in their content. The right side of Figure 24 shows the 3D authoring environment of an Instruction-Node.

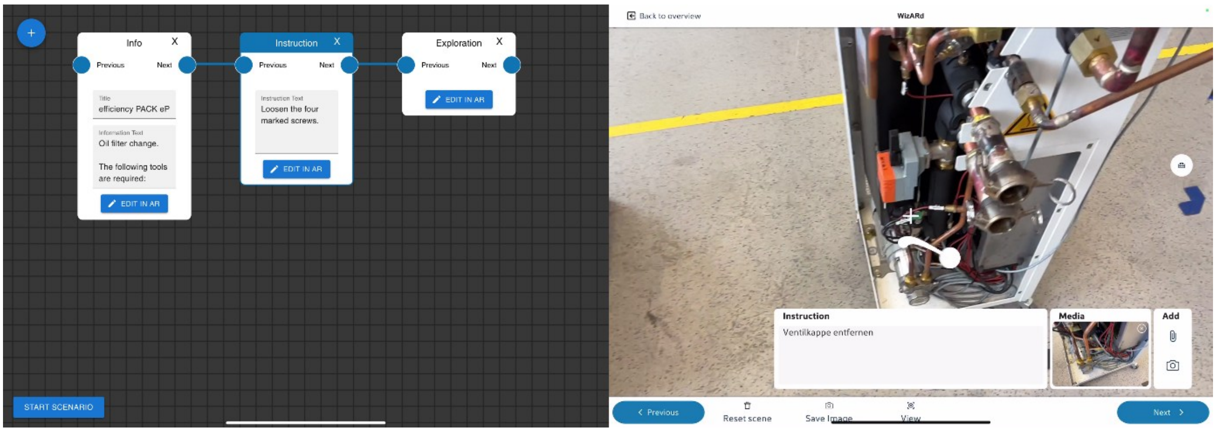

Figure 24. Software Artifact

The content from the 3D authoring environment is passed to a scenario, which can be accessed or created using the scenario manager. The third software component, the Viewer Mode, displays the created scenarios as created without the ability to modify the AR content. The 2D and 3D content is rendered precisely where the creators placed it.

7.5 Evaluation of the Design

To evaluate our DP3 and the utility of our software artifact, we conducted a summative and naturalistic field study with service technicians with different backgrounds (energy technology, measurement systems). We follow the evaluation methods proposed by Hevner et al. (2004). The observational approach, exemplified by case studies or field studies, is well suited for our application domain. In the previous design cycle, we used a controlled laboratory experiment to demonstrate the impact of our proposed two design principles and the software artifact and to demonstrate their application using a quantitative approach. In this third design cycle, we report the results of the interviews with the participants after using the AR authoring tool. The field study enables us to evaluate the impact and validity of DP3 and the utility of the AR authoring tool in an industrial context, which we could not test in the controlled laboratory experiment.

We decided to use interviews as they allow for collecting rich empirical details regarding the different obstacles, impressions, and utilities perceived by the users when creating and using the AR content. In addition, interviews are a means of collecting extensive data and, in our case, can be used to evaluate the potential utility of our AR authoring tool by gathering experts' opinions from practice after using our software artifact.

7.5.1 Setup and Procedure of the Evaluation

We designed the field study with six main elements. The first step in the field study is a short demonstration of the AR authoring tool, so the participants know its features and how to use it. A hands-on exercise follows this so the participants know how to use the tool in practice.

The third step is the main element of the field study. The participants were asked to map a part of the assembly instructions of their technical assets with the AR authoring tool. For this purpose, an assembly step was chosen that is carried out at regular intervals (e.g., as part of semi-annual maintenance) and thus represents a representative task. The task is completed when the instructions have been mapped completely in AR or when the time (20 min) runs out. Since we had to keep to a schedule, we also limited the time to 20 min to ensure that all participants could participate in the study at the selected times. As described in the chapter "Instantiation of the Design", another important aspect of the tool is using AR content.

The use of the content represents the fourth step in the field study. For this purpose, one of the authors of this study created detailed instructions in advance, representing the same assembly step from step three of the field study. The participants then used this instruction to execute the maintenance step.

The fifth step of the field study is the empirical data collection. After using the AR authoring tool, a semi-structured interview was conducted with the participants to get their informed opinions about the tool.

Finally, we handed out a questionnaire for the participants to fill out. In this questionnaire, we asked for demographic data and, as in the laboratory experiment from the second design cycle, for self-efficacy, perceived usefulness, and perceived functionality.

7.5.2 Sample and Interviews Process

The interviews were structured using a basic interview guide, where the interviewer ensured that all questions from the interview guide were covered during the interview. In addition, related discussion topics were allowed to increase the richness of the information collected (Myers and Newman 2007).

The field study was conducted with employees from two different companies in Germany with different backgrounds (energy technology, measurement systems). Rather than using a large sample of novice users, we were interested in understanding how service professionals would use AR authoring tools. We therefore purposefully sampled two industries that differed in their degree of technology requirements and identified 12 participants across two companies for the field study. Five of the 12 participants were women, and seven participants were men. The average age of the participants was 36.73 (SD=7.54) years.

During the semi-structured interview, we asked participants to share their first impressions of using the tool, including its strengths and weaknesses. Next, we asked participants to describe the functionalities and information elements that were important to them during the creation and use of the AR content. Finally, we asked participants about the practicality of the tool and the AR content created, and its advantages over existing systems (i.e., service manuals). The interviews were recorded and transcribed afterward.

We relied on abductive reasoning to analyze the rich data we obtained during the field study (Sarker et al. 2013). The experts' opinions on using and creating AR content with our software artifact were coded using open coding through short descriptive statements that summarize the core idea of the text passage (Wiesche et al. 2017). The subsequent analyzis of the codes revealed several first-order concepts. More abstract second-order themes emerged by evaluating the similarities and differences between the first-order concepts. Table 21 shows an example of this analyzis process with exemplary quotes from the transcripts.

Illustrative quotes from the data	**First order themes**	**Corresponding dimensions of SCT**
"*we also have the older generation, who don't like to have their cell phones attached to anything, so it should be possible to export the instructions in text form*." (#10)	Creating AR content success is based on other parties' use	Different sources of enactive mastery experience
"*This saves time in any case, as it can show more than a service manual*." (#5)	AR content success is based on economic/social advantages	
"*The process of learning how to use these instructions as well as how to create them in such a short time, like in five minutes, was very impressive*." (#3)	Belief in the ability to create AR content	Different abilities of verbal persuasion
"*The video and also the arrows so that you could see exactly where you have to go, what you have to do. That was particularly helpful because then you can actually do it yourself, which is also the goal and purpose of the thing*." (#7)	Belief in the quality of the instructions to work in a process-compliant manner	

Table 21. Illustration of the coding process

7.5.3 Results of the field study

The field study results show how the AR authoring phases "Create user-generated AR content" and "Use AR content" differ in both enactive mastery experience and verbal persuasion. The field study results show how the phases of creation and use of AR content differ for both the enactive mastery experience and verbal persuasion. While the enactive mastery experience during the creation phase is mainly driven by the belief in the usefulness of the content through other parties (can or would the service technician use these AR-based PGS), the enactive mastery experience during the usage phase is predominantly characterized by the expected economic/social advantages (does the AR-based PGS bring a benefit for my organization or for me). The verbal persuasion during the creation phase is mainly driven by the user's belief in their ability to create AR content (do I know the AR authoring tool well enough to create an AR-based PGS). On the other hand, verbal persuasion during the use of AR content is primarily driven by the quality and richness of the AR-based PGS.

Sources of Enactive Mastery Experience. In the AR authoring phase, “Create user-generated AR content” the enactive mastery experience is primarily based on the success of other parties' use of the AR content. No participants had expressed difficulties regarding creating AR content with a handheld device. However, eight out of 12 participants did not perceive creating AR content alone as a success. Instead, they noted in the interviews that the next step should be to provide the created AR content in different forms and on different hardware, as their colleagues have differing needs. For example, some of their older experts want to continue working with paper documents, while others prefer a smartphone or HMD so that they can work hands-free. Thus the perceived success of the AR content created was based on the broad range of possibilities for using the AR content created, which requires a clearer and more versatile separation of the creation and use of the AR content. One expert explained: *“It would be good if the instruction that one has just created with the tool could be exported in some way so that one then receives the instruction, for example, in text form or some other form. So that a technician for their colleagues in the field, the instructions can record here with AR, and that can then be exported into a document.” (#10)*

We found out that in the AR authoring phase, "Use AR content" the source of the enactive mastery experience is mainly based on the economic and social benefits. While only three participants mentioned an economic/social benefit from the quick and easy creation of AR content, nine out of 12 participants highlighted the economic/social benefits of using AR content. One of the biggest advantages that the participants mentioned regarding using AR content are various benefits of the AR content for training and teaching new colleagues. Compared to a video, users can be trained at their own pace and on the physical machine without needing their own trainer. Another advantage that has been mentioned more often is the time and error reduction of this AR content, as by using the AR content, the user is guided step by step through a maintenance/repair process. *“[…] the advantage compared to a recorded video is that you can follow the individual steps independently on the end devices by clicking through these steps based on your individual pace. You're not reliant on the video, but do it as quickly and as slowly as you like […]”* (#1)

Greater versatility of use also plays a crucial role in the actual use of AR content. The social and economic benefits were often linked to the need to expand use across a wider range of hardware. For example, some participants said that they saw an advantage, whether in training or process support if the AR content created could be used on a smartphone or HMD. “*It's better suited for training purposes. You have step-by-step gradations, so with the video, you're kind of sucked through, and you have to pause if you want to know something again, and here it's just nice and slow. The important thing is, and this is always the case with augmented reality, that you have to look at how you get the information and still have your hands free to continue working […]*” (#10)

Sources of Verbal Persuasion. In the AR authoring phase, “Create user-generated AR content,” the verbal persuasion is primarily driven by the participants' belief in their own abilities to create AR content on their own using the AR authoring tool. When asked about their concerns about the process of creating AR content, none of the participants expressed major difficulties in creating AR content. On the contrary, eight of the 12 participants were positive about creating AR content. The participants noted that despite the short introduction and presentation of the tool, it was impressive that they could independently create AR content. However, participants also noted that they could not use the AR authoring tool in some places without this short introduction at the beginning of the field study. For example, the interaction with the 3D elements on the tablet is not intuitive since, in order to move the 3D elements, the tablet has to be moved. “*Despite the fact that I get from you no or only a small instruction to the tool, I could work intuitively with it. I think a short tutorial like a one-pager or a short demo video is enough to work with the tool quickly.*” (#6)

For the AR authoring phase, “Create user-generated AR content” only two participants suggested an improvement so that the tool would further support them in their belief in their own abilities to create AR content. Both commented that many PGS are similar in structure and differ in only a few steps. For this reason, it would be useful if the content could be duplicated. In this way, the time required for the creation process could be significantly reduced.

In contrast, the source of verbal persuasion in the AR authoring phase, "Use AR content" is the participants' belief in the quality and usefulness of the AR content. Here, all participants expressed a need for improvement to exploit the full potential of AR content in their context of use. Suggestions for improvement are analogous to participants' expressed concerns about the source of the enactive mastery experience to the need for more versatile uses of AR content. For example, there are the experts who do not need to be guided step-by-step through a process but only need to look up a step, or the users are unable to operate an iPad due to occupational safety devices, which require the use of an HMD. "*Yes, as I said, there would be for me once the handling of tablet and simultaneous work. So where do I place the tablet and now also with the background that I have oil on my hands, now I need the tablet again […]*" (#1)

7.6 Discussion

In this research, we examine how novice users can create AR-based PGS so that different novice users can use them to conduct physical tasks in a process-compliant manner. We present an AR authoring tool's system architecture consisting of three software components (a 2D node editor, a 3D authoring environment, and a viewer mode) as well as the third theoretically grounded design principle provides prescriptive knowledge about the differences novice users need when creating and using AR content in an industrial environment, highlighting the need to separate these two AR authoring phases.

Following Gregor and Hevner (2013) DSR contribution framework, we consider our contribution as an improvement as we successfully provide a new solution (AR Authoring Tool to create AR-based PGS) to an existing problem (Complexity in AR content creation prevents SMEs from experimenting or using the technology). Similar to software development (Maruping and Matook 2020), where no-code or low-code tools help novice users develop new applications, AR authoring tools help novice users create AR content in their application domain. We have proved the different sources of enactive mastery experience during the creation and use of AR content (Bandura 1997). Thus, we can consider the third DP we proposed as confirmed. For the development of future AR authoring tools in this context, the third DP should be taken into account by separating the creation and use of the content within the tool. Compared to commercial tools such as Microsoft Dynamics 365 Guides (Lavric et al. 2022), where the creation and use of the content are also separated, our design principle, however, suggests that the separation should take place on the AR interface so that the novice users can, for example, also create instruction manuals at the customer site.

In addition, the AR Authoring Tool also provides a practical contribution. The tool represents a valuable tool for SMEs to identify which processes can be meaningfully visualized in AR. The library of abstract 3D elements, the ability to create custom media, and familiar hardware allow novice users from SMEs to represent their processes in AR. These processes can then be used and evaluated by other novice users to carry out their work in a compliant manner.

Although we conducted the DSR project and the evaluation described in this paper according to the established guidelines, potential limitations still require further research. First, the evaluation described addresses only two small processes in an industrial context. In the evaluation, all work instructions could be mapped in augmented reality. Still, we cannot deduce from these two process steps that all work instructions in a manufacturing application domain can be mapped with these AR elements. Therefore, mapping multiple processes in further evaluation may lead to different results. For example, other evaluations in the manufacturing domain could investigate whether media and 3D elements are sufficient to display all work instructions in AR. The second limitation of our study is that the evaluation was conducted with only 12 participants from a representative target group, limiting our findings' generalizability. An evaluation with additional participants may lead to different findings. Therefore, a study with additional participants could be conducted to test our design principles' generalizability further.

8 Designing an Augmented Reality Development Tool for Supporting Physical Process Guidance in the Industrial Metaverse (P5)

Title	Designing an Augmented Reality Development Tool for Supporting Physical Process Guidance in the Industrial Metaverse
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Publication	Journal of Management Information Systems
Status	Revise and Resubmit
Contribution of first author	The first author was responsible for Methodology, Investigation, Formal analyzis, Conceptualization, problem definition, research design, data collection and analyzis, interpretation, and conceptual development and reporting. He further significantly contributed to the creation of the manuscript.

Table 22. Fact Sheet Publication P5

Abstract: Employees use the industrial metaverse to create objects in virtual environments that can then be transformed back into physical artifacts. The augmented reality development tools that make this possible often require programming skills and deep spatial knowledge. However, the complexity associated with creating this content may undermine citizen developers' (i.e., employees who are domain experts) confidence in their ability to infuse domain knowledge into processes they design for the industrial metaverse. To address this challenge, we build on social cognitive theory to propose a theory-driven design for AR development tools for the industrial metaverse that empowers users to create AR content while also strengthening their self-efficacy and outcome expectations. We instantiate our proposed design in a software artifact: the Industrial Metaverse Augmented Reality Development Tool (MetAR). Our evaluation of MetAR with 127 participants demonstrated that separating the AR development process, using content tailored to the meta-design space, and separating the creation and usage phase of metaverse applications increases the performance and self-efficacy of employees immersed in the industrial metaverse.

8.1 Introduction

While many people approach the consumer metaverse with some trepidation (Deloitte 2022), many large industrial organizations are feeling very positive about investing in the industrial metaverse (IM), as they view the IM as a means to squeeze additional value from the infrastructure used to support digitalization (MIT Technology Review Insights 2023). The IM refers to immersive meta-design spaces specifically intended for industrial applications and virtual processes where engineers simulate, manage, and optimize operations to enhance physical value creation. The immersive nature of the IM provides an unprecedented opportunity to observe, interact with, and comprehensively analyze distinct spatial challenges faced by industrial organizations (MIT Technology Review Insights 2023).

However, the concept of the IM goes beyond the passive consumption of the immersive experiences such as virtual training. In the IM, employees are able to create objects in virtual environments that are then transformed into physical artifacts (Qu et al. 2022; Seidel et al. 2022). Conversely, workers must create objects in the physical environment that are then transformed into a virtual artifact. To illustrate this intertwined nature, imagine the following scenario: *A machine tool manufacturer has developed repair and maintenance instructions for their machine tools in the industrial metaverse. Not only can these instructions be used to train new employees in VR, but these virtual instructions can also serve as AR instructions for their field service technicians on how to repair/maintain the machine in the field. With AR instructions, the required information is displayed directly on the machine tool at the right time and in the right place. If the field service technician arrives at the customer site to perform a special repair for which no training or repair instructions exist, the field service technician is able to record an AR instruction during the repair and store it in the industrial metaverse to share it with his/her peers.*

The scenario illustrates several challenges: First, the scenario illustrates that many tasks in the IM are purely physical and can only be carried out in situ. This is always the case when parts of the physical environment are created, manipulated, or customized. These tasks highlight the need for augmented reality (AR) technologies in the IM, as service technicians cannot virtually assemble physical CNC machines using virtual reality (VR) (Park et al. 2023). The scenario illustrates an important need that the IM can potentially fulfill: the need to intertwine physical and virtual environments.

Second, the scenario illustrates that IM applications are not created by AR experts but by engineers or service technicians (henceforth referred to as *citizen developers*). Creating IM applications requires domain knowledge (what an AR instruction for the machine looks like), programming skills, and spatial knowledge to create immersive content and anchor it back in the physical environment (Azuma 2016; Nebeling and Speicher 2018). This shows that AR development tools must be designed so that citizen developers can develop IM applications independently.

Lastly, the IM relies on user-metaverse interfaces to empower employees to design and create objects within virtual environments that are then transformed into physical artifacts, vice versa (Qu et al. 2022; Seidel et al. 2022). User-metaverse interfaces are AR/VR interfaces that allow employees to access the metaverse (Dwivedi et al. 2022). A specific form of UMIs are AR/VR development tools that enable employees to create metaverse content and applications (Manuri et al. 2022). How these AR/VR development tools need to be designed in order to enable citizen developers to create interwoven metaverse content remains a challenge.

While many tools support AR development, they often feature complex functions requiring advanced programming and spatial knowledge, limiting use to experienced developers (Ashtari et al. 2020; Nebeling and Speicher 2018). However, organizations are simplifying AR development with no-code tools, enabling citizen developers to create AR content (Krauß et al. 2021). These tools focus on reducing the need for programming and spatial knowledge. To support this trend, guidance is needed on designing tools that both reduce skill and knowledge requirements and boost citizen developers' confidence in creating immersive IM content (Pace et al. 2020). This is important because creating IM content such as AR instructions requires citizen developers to be confident that they are mapping domain knowledge in AR that can be shared with potential metaverse users (Funk et al. 2017; Zallio and Clarkson 2022). As a result, understanding how to develop tools that build self-efficacy and positive outcome expectations (Chiu et al. 2006; Hsu et al. 2007), which may drive citizen developers' intention to share their domain knowledge, is particularly relevant for IM tool developers. Therefore, we seek to answer the following research questions (RQs): **RQ1:** How can an AR development tool be designed to enable citizen developers to share their domain knowledge while increasing their self-efficacy and outcome expectations? **RQ2:** What are the drivers of citizen developers' self-efficacy and outcome expectations when creating and using metaverse applications for the IM? To answer these research questions, we follow a design science research approach (Hevner et al. 2004; Kuechler and Vaishnavi 2008). Drawing on *social cognitive theory* (SCT) (Bandura 1986) and existing research on AR development tools (Laviola et al. 2022; Zhu et al. 2015), we propose a nascent design theory for AR development tools for the IM. Our theory focuses on three design principles (DP), which we instantiate in a software artifact: the Industrial Metaverse Augmented Reality Development Tool (MetAR). We then evaluated the DPs' validity instantiated in MetAR (Peffers et al. 2018). We evaluated the validity of our three design principles and the benefits of our software artifact in two laboratory experiments and a case study in two companies with 127 participants.

8.2 Conceptual Foundations

8.2.1 Industrial Metaverse

To build conceptual clarity and a better understanding of such interactions in the metaverse, researchers need to develop a contextualized understanding of the metaverse's capabilities, components, and technologies for specific sectors (Dolata and Schwabe 2023; Dwivedi et al. 2022; Peukert et al. 2022). A sectoral perspective is important, as the social and technological requirements differ greatly across applications in different industries (Buchholz et al. 2022; Schöbel and Leimeister 2023). By realizing a deeper understanding of how sectors influence requirements for the metaverse, companies can develop metaverse applications and strategies that strengthen their competitiveness (Dwivedi et al. 2022). To gain a common understanding of the metaverse, we discuss its general application across sectors and then describe the characteristics of the IM.

First, as illustrated by the scenario above, the IM intertwines virtual, augmented, and physical environments. Information, actions, and interactions can be exchanged between environments and influence each other (Alpala et al. 2022; Buchholz et al. 2022). Users must be able to create virtual content and anchor it back into the physical environment as artifacts or processes (Qu et al. 2022; Schöbel and Leimeister 2023; Seidel et al. 2022). A purely virtual world is usually not practically useful, as some tasks cannot be performed virtually (Park et al. 2023).

Second, the metaverse nests many interconnected design spaces (Seidel et al. 2022). One application on its own is not a metaverse. Rather, the metaverse is an ecosystem consisting of interconnected meta-design spaces, and users should be able to move between the individual meta-design spaces in a natural and frictionless way (Nickerson et al. 2022b; Schöbel and Leimeister 2023; Seidel et al. 2022). Meta-design spaces consist of different metaverse applications, each representing a solution to a specific problem. Thus, each meta-design space leads to a different experience (Seidel et al. 2022).

Third, user immersion in the metaverse contributes to the transition between the virtual, augmented, and physical environment (Nickerson et al. 2022b; Schöbel et al. 2023; Schöbel and Leimeister 2023; Seidel et al. 2022). The most frequently discussed way to achieve this immersion is through AR or VR interfaces (Dwivedi et al. 2022). The AR/VR interface selection for the metaverse application to be developed depending on the context is of central importance (Holtmann and Wernike 2023; Shen et al. 2021).

While the metaverse refers to the consumer, enterprise, and industrial realms, the IM is distinct in many ways. First, while the consumer and enterprise metaverse focuses primarily on added social value (Duan et al. 2021; Park et al. 2023), the IM focuses on measurable added industrial value. Thus, whereas the consumer and enterprise metaverse research demands an understanding of social interaction between avatars (Dolata and Schwabe 2023), the IM demands an understanding of the interactions between the physical environment and the virtual and augmented environment to support operations in the physical industry (Yang et al. 2022; Zheng et al. 2022).

Second, demands for representational fidelity in virtual or augmented environments differ across consumer, enterprise, and IM applications (Park and Kim 2022). To illustrate the differences, we draw on the design tensions proposed by Seidel et al. (2022) spatial and artificial tension. Consumer metaverse environments allow users to move without restriction (spatial tension = open ended). Immersing them in metaphysical environments without physical constraints, allowing avatars to fly (Dwivedi et al. 2022). In addition, these environments feature detailed representations of imagined worlds (artificial tension with high imagination and fidelity) (Park and Kim 2022). Enterprise environments, however, are more restricted. For instance, users meet in a virtual office where movement is free but confined (spatial tension = closed), and the design is simpler (artificial tension with low imagination and fidelity) (Park et al. 2023).

IM environments differ significantly, focusing on fusing virtual content with physical machines (Siyaev and Jo 2021). These environments require high fidelity to physical settings, including factors like air resistance, to simulate real processes precisely (Dwivedi et al. 2022). In simple terms, the environments of the IM are subject to strict rules. Like enterprise metaverse, users are spatially restricted (spatial tension = closed), but here the restriction is due to the user's physical environment. IM environments often replicate the physical space exactly (artificial tension with low imagination and high fidelity) (Burghardt et al. 2020). Table 23 shows the difference between the three metaverse realms according to the characteristics proposed by Park and Kim (2022) and the design tensions proposed by Seidel et al. (2022). The creation of IM content is particularly challenging, as the content must exhibit a high degree of representational fidelity and must be anchored in the physical environment.

Metaverse Realms				
		Consumer metaverse	Enterprise metaverse	Industrial metaverse
Definition		Create immersive experiences for entertainment and gaming purposes.	Create immersive communication and collaboration in the workplace and immersive business environments for company interactions with customers and other businesses.	Create interactions between the physical world and the virtual world to broaden the operations in the physical industry.
Application domain		Games and entertainment	White-collar work Knowledge work	Blue-collar work Manual labor
Value		Social value creation	Social + business value creation	Industrial value creation
Focus		Social interaction between people in the form of avatars	Social interaction between people in the form of avatars	Interaction between humans and physical assets
Environment	**Spatial tension**	Predominantly open ended	Predominantly closed	Closed
	Artificial tension	High imagination, high fidelity	Low imagination, low fidelity	Low imagination, high fidelity
Requirements for content creation		High user experience through high-fidelity content	Support exchange between users in a virtual environment	Anchoring in situ domain knowledge in the physical and virtual environment

Table 23. Summary of the Metaverse Realms and Their Different Characteristics

8.2.2 AR Development Tools

AR development tools offer environments for designing, creating, and managing augmented reality applications and experiences by intertwining virtual objects with the physical environment, which requires the creation of 3D and immersive content (Nebeling and Speicher 2018). Some of the works on AR development in the human-computer interaction literature focusing on what are referred to as AR authoring tools are aimed at developers with various skill levels and at different fidelity phases of the resulting applications (Ashtari et al. 2020; Krauß et al. 2021; Nebeling and Speicher 2018).

AR development tools can be seen as falling into clusters. The first cluster contains tools with a higher level of complexity that require extensive programming and scripting knowledge. (Carmigniani et al. 2011). The development process of AR applications with these tools mainly takes place on the desktop. However, an in situ development approach is not usually anticipated (Bashir et al. 2022). In practice, developers use tools from this cluster, such as Unity or Unreal, to create nearly individualized, powerful, immersive applications. The second cluster contains less complex tools requiring little or no programming knowledge. However, these are limited in function as well as scope and often focus on only one specific application context (Krings et al. 2022). With most of the tools from this cluster, the content creation is performed using a handheld or head-mounted display (HMD) (Krings et al. 2022; Rajaram and Nebeling 2022). An example of tools from this cluster used in practice is Microsoft Dynamics 365 Guides, with which AR instructions can be created using HoloLens 2 (Lavric et al. 2022). When analyzing the two clusters, it is apparent that no widely diffused tool adopts a no-code approach that would allow citizen developers to develop different meta-design spaces. In addition, evaluation often focuses on the tool itself rather than how it is used.

8.2.3 Social Cognitive Theory

We draw on SCT (Bandura 1986) as a kernel theory to conceptualize and develop our design principles for an AR development tool. SCT postulates that the continuous reciprocal interaction between behavioral, cognitive, and environmental factors determines human behavior. Specifically, SCT is concerned with how environmental and cognitive factors influence human behavior in a given context (Bandura 1986). Self-efficacy and outcome expectations are a core tenet of SCT. Self-efficacy is a form of self-assessment that influences decisions about what behaviors to engage in and the amount of effort and persistence to exert when faced with obstacles. Individuals with high self-efficacy are more likely to engage in use behaviors than those with low self-efficacy (Bandura 1997). The second core tenet of SCT is personal outcome expectations. Users can anticipate outcome expectations from action by assessing their behavior in a given situation (Bandura 1997). In other words, users estimate their expected outcomes before taking action.

We use SCT as a kernel theory because self-efficacy has proven critical to enabling behavior in virtual environments and physical environments in industrial organizations. This has implications for a wide range of domains, including knowledge sharing and knowledge acquisition (Chen et al. 2012; Chiu et al. 2006; Kim et al. 2011; Lin 2010). Here, self-efficacy is crucial for knowledge sharing in virtual communities because only users who believe they have the ability to share their knowledge in virtual communities will actually do so (Alvarez-Risco et al. 2022; Hsu et al. 2007).

Creating metaverse content for the IM represents an exchange of knowledge in that domain experts map their domain knowledge in AR to share it with potential metaverse users (Funk et al. 2017; Zallio and Clarkson 2022). For domain experts to share their domain knowledge with virtual communities such as the IM, their intentions to do so must be strengthened. An effective approach to encouraging domain experts to participate in virtual communities (Hsu et al. 2007) and create content for these virtual communities (Gangadharbatla 2008) is to strengthen the self-efficacy of domain experts. Individuals with high levels of self-efficacy are more willing to explore and try new experiences in virtual environments, as they believe in their ability to learn and adapt to new tasks and challenges (Al-Adwan et al. 2023; Chiu et al. 2006; Pellas 2014).

8.3 Research Method

We employed a comprehensive design science research (DSR) approach (Hevner et al. 2004), focusing on the design of an innovative artifact for the IM (Gregor and Hevner 2013) and following the guidelines of Jones and Gregor (2007) to develop an IS design theory. We chose this approach because it provides an abstract understanding of what has been learned from designing a software artifact that can serve as a template for the development of similar artifacts (Piirainen and Briggs 2011). We applied the Kuechler and Vaishnavi (2008) DSR approach to conduct our research (see Figure 25).

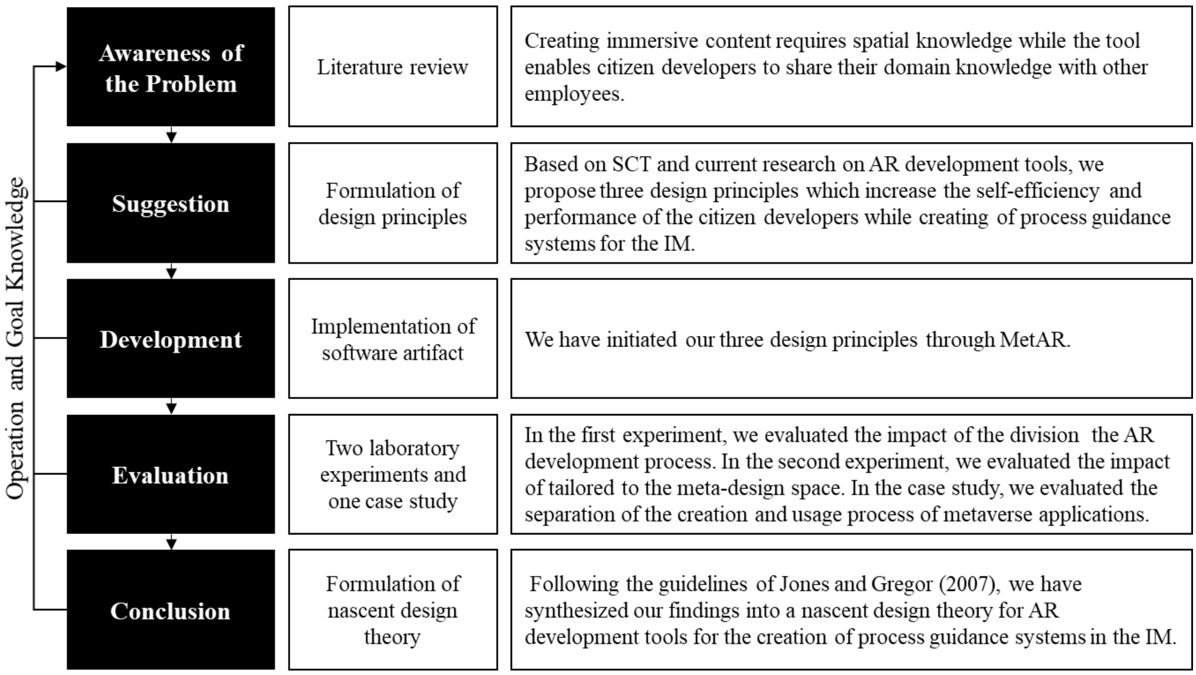

Figure 25. Design Science Research Approach

This approach starts with the identification of a real-world problem that motivates the research. Based on the real-world problem, we used literature on AR development tools and social cognitive theory. We first formulated a set of meta-requirements, which represent the first component of a design theory, which describes a class of goals that apply to the design theory (Walls et al. 1992). In the suggestion phase, we derived design principles (DP) for the AR development tool from the meta-requirements (MR). In the development phase, we initiated our three DPs through MetAR. MetAR helps to present and communicate the design principles and theory and can also be used for testing (Jones and Gregor 2007). We used the evaluation to substantiate our design theory regarding the quality of knowledge outcomes by evidencing that the design principles led to the creation of MetAR, which can be used to solve a class of metaverse content creation development problems (Venable et al. 2016). Since we had operationalized our DPs but not yet applied them, the DPs were instantiated in a generic context as MetAR (Petter et al. 2010). Therefore, we conducted two laboratory experiments to validate our first two design principles. We employed a two-cell experimental setup to validate the impact of the two DPs on AR development tools. The first experiment was designed to assess the impact of our first DP (i.e., the division of the AR development process) on internal and external self-efficacy and task and time performance when creating process guidance systems. Subsequently, the second experiment aimed to validate the impact of our second DP (i.e., the use of content tailored to the meta-design space) on the same set of outcomes. We used experiments because they are particularly suitable for testing different design principles instantiated in different design alternatives (Niehaves and Ortbach 2016). We also used experiments because they represent an artificial and formative evaluation that allowed us to assess at an early stage whether our proposed design principles increased self-efficiency, outcome expectations, and the performance of citizen developers when creating AR instructions (Venable et al. 2016).

Following the laboratory experiments, we responded to the request by Peffers et al. (2012) and the suggestions of the FEDS (Venable et al. 2016) for more real world evaluations of DSR artifacts. We conducted a case study to evaluate the impact of our third design principle (i.e., the separation of the creation and usage process of metaverse applications) and assess the utility of MetAR (Kuechler et al. 2009). In addition, case studies are particularly suitable for assessing the coherence of the use of MetAR in its validated instance (Tuunanen et al. 2024). We conducted expert interviews with domain experts who used MetAR in real work environments. Expert interviews are a form of naturalistic evaluation that is useful for validating theoretical artifacts in organizational contexts (Venable et al. 2016). We validated the third design principle by assessing experts' perceptions of using MetAR and thereby gained a deeper understanding of the sources of self-efficacy that users experience when creating and using metaverse content. In the final phase, we synthesized our findings into a nascent design theory based on the guidelines presented by Jones and Gregor (2007).

Experiment 1: Participants, Design, Procedure, and Measures

Participants and Design

The experiment was conducted in a controlled laboratory setting with the experimenter present at all times. Participants were randomly assigned to one of two conditions, one in which the AR development process was divided into a 2D process editor and a 3D content environment. (MetAR) and the other condition in which the AR development process was merged (MAD-MetAR, i.e., Merged AR development process MetAR). Appendix B and Appendix D contain a detailed description of the MAD-MetAR and MetAR conditions. The tasks were held constant so that the only difference between the treatments was the tool used to complete the tasks.

We decided on a student sample consisting of business economics and engineering students, as they not only represent citizen developers but also future domain experts in the industry. 58 subjects took part in the laboratory experiment (median age 29.71; 33% female). We excluded six hasty responders who did not pass the manipulation check.

Procedure and Stimuli and Measures

Before starting the experiment, we demonstrated the MetAR or MAD-MetAR tool to the participants, explaining its features and how to use it. After introducing the tool, we presented a simple demonstration task. Participants had to use the tool independently to manipulate 3D content by placing and moving AR content across the laboratory room.

As the main task of the experiment, we asked participants to use the tool to create AR instructions. The objective was to replicate the eight steps featured in paper-based instructions for assembling a piece of IKEA furniture (a KALLAX shelf) into AR instructions. The study procedure was single-blinded, as the participants were informed that the usability and functionality of the tool would be evaluated. However, it was not mentioned that the quality of the instructions and time were also evaluation factors. The placement of the components for this shelf was identical for each session of the experiment. Participants were given 20 minutes to create their AR instructions. The experiment was completed when the task was completed or the allotted time ran out.

After completing the experiment, participants were asked to fill out a survey on self-efficacy. Whenever possible, we adapted validated scales from previous research. Therefore, we used the self-efficacy questionnaire from Thatcher et al. (2008) to measure self-efficacy. The task performance of the created AR instructions was assessed using an absolute category rating (ITU 1996, 2008). Two AR experts independently reviewed each created AR instruction and then ranked them on a rating scale from 1 (*bad*) to 5 (*excellent*). The mean value of these ratings was used for the analyzis shown in Section 5.1.2. The time performance was measured in comparison with the existing assembly instructions. The screen recordings were used to determine the step to which the participants were able to convert the traditional instructions into the AR instructions within 20 minutes.

Experiment 2: Participants, Design, Procedure and Measures

Participants and Design

The design, procedure, stimuli, and measures of the second experiment were identical to those used in the first experiment with one exception. The participants were randomly assigned to one of two conditions, one in which content tailored to the meta-design space was used (MetAR) and one condition in which general content was used (GEM-MetAR, i.e., general content for the meta-design space MetAR). Appendix C and Appendix D contain a detailed description of the GEM-MetAR and MetART conditions.

A sample of 57 student subjects took part in the second laboratory experiment (median age 21.86; 62% female). We excluded two hasty responders who did not pass the manipulation check and five participants who did not complete the questionnaire.

Case Study: Data Collection and Analyzis

Data Collection

We collected data from two IM cases. Org 1 builds industrial assets to reuse industrial waste heat. Their goal is to map all of their instruction manuals into the IM to extend their business model. Org 2 builds measurement instruments for industrial process engineering. They seek to map their assembly processes into the IM and commission new measuring systems more efficiently at their customers' sites. We sampled 12 experts in two industrial organizations based on their AR and process guidance systems expertise. We conducted a semi-structured interview with each of them after they had used our AR development tool. In order to gain insights into how AR development tools were used in practice, we allowed the domain experts to use MetAR in their real work environments. In Org 1, we chose a standard process where experts removed a Schrader valve from an energy technology asset. In Org 2, we selected a complex edge case where experts replaced the central control unit of a measurement system. In both cases, experts created instructions themselves with MetAR and used a pre-recorded AR instruction on MetAR in the IM. While the formal interview started after experts had used MetAR, we used a think-aloud strategy and asked experts to share their plans and thoughts while using MetAR.

During the semi-structured interviews, we first asked participants to share their first impressions of using MetAR, including its perceived strengths and weaknesses. Next, we asked participants to describe the functionalities and informational elements that were important to them during the creation and use of the metaverse content. Finally, we asked participants about the practicality of the MetAR, the created metaverse content, and its advantages over existing systems (i.e., service manuals). The interviews were recorded and then transcribed.

We relied on a deductive approach to analyze the rich interview data (Sarker et al. 2013). The experts' views on using and creating metaverse content with MetAR were coded using open coding through 63 short descriptive statements that summarized the core idea of the text passage (Wiesche et al. 2017). We conducted the subsequent analyzis of the codes using existing concepts of IM characteristics and social cognitive theory. Conceptual Design and Design Instantiation

8.3.1 Developing Meta-Requirements Design Principles

We drew on social cognitive theory (Bandura 1986) to define MR for addressing the complexity of creating process guidance systems using AR development tools while enabling citizen developers to share their knowledge with their colleagues. As stated in Section 7.2.3, SCT states that a person performs an action with a personal cognition in a social environment. This personal cognition of the user has two basic determinants that form the basis of our two MRs (Bandura 1986). The first determinate is self-efficacy, which is one's belief in one's ability to plan and execute an action (Bandura 1997) and is a fundamental factor influencing the user's decision to share knowledge in virtual environments like the IM (Chiu et al. 2006; Hsu et al. 2007). Therefore, the first MR we propose is to strengthen the self-efficiency of the citizen developer when creating metaverse content using the AR development tool **(MR1)**. Table 4 provides an overview of the relationship between the meta-requirements, the design principles, and the design features. It does not give an overview of the detailed MRs, DPs, and DFs, which are described in detail in the following section.

Following social cognitive theory, the second determinant of users' personal cognition is their outcome expectations (Bandura 1986). One's outcome expectations are one's own judgments about the likely consequences of their actions, which is a fundamental factor influencing the user's decision to share knowledge in virtual environments like the IM (Chiu et al. 2006; Hsu et al. 2007). Therefore, the second MR we propose is to strengthen the outcome expectations of the citizen developer when creating metaverse content using AR development (**MR2**).

8.3.2 Deriving Design Principles

To increase the self-efficacy (**MR1**) of citizen developers in creating process guidance systems in virtual communities like the IM, the first design principle we propose is implementing a self-regulated learning approach (Zimmerman 1989). From the SCT perspective, the self-regulated learning approach is a process that consists of three sub processes: self-observation, self-assessment, and self-reaction (Bandura and Cervone 1986; Schunk 1989). When users learn to use new technology, they monitor their performance, evaluate their progress toward the goal, and continue their work or change their approach to the task (Schunk 1990). If the self-assessment of goal progress is rated as satisfactory, this positively affects the perceived self-efficacy. The progress toward goals prompts users to set new and more challenging goals for themselves (Schunk 1990).

Studies on self-efficacy have shown that users experience a higher level of self-efficacy when they perform simple, familiar tasks than when they perform more complex and unfamiliar tasks (Chen et al. 2001; Judge et al. 2007). For instance, when using computers, self-efficacy correlates significantly positively with familiarity with tools and the associated tasks (Cassidy and Eachus 2002). With a self-regulated learning approach in which users are initially confronted with familiar tasks, through self-observation, they get the feeling that the ability to perform the tasks is an acquirable skill, which increases the users' self-efficacy to master the task (Tabernero and Wood 1999).

By dividing the AR development process into two separate steps, the citizen developers are first confronted with a known task, the creation of a 2D process, followed by an unfamiliar task, the creation of 3D content, which presents a greater challenge for the citizen developers (Azuma 2016; Krauß et al. 2021; Nebeling and Speicher 2018). The citizen developers can thus follow a self-regulated learning approach to build confidence. Based on this, we formulate our first design principle (DP) using the scheme proposed by Gregor et al. (2020). **DP1:** *To enable citizen developers to create AR content for the industrial metaverse, the 2D creation process and the 3D creation process should be independent of each other so that citizen developers are first confronted with a task with which they are more familiar before then moving on to the more complex task of 3D content creation.*

To formulate our second DP, based on the **MR2**, we drew on the concept of the meta-design space (Seidel et al. 2022). Meta-design spaces consist of various interconnected design spaces, each of which provides a solution to a problem and thus leads to different experiences (Seidel et al. 2022). Since both the use cases and the contexts of the different meta-design spaces differ, it is necessary to provide content tailored to specific meta-design spaces (Buchholz et al. 2022; Dolata and Schwabe 2023). The use of content tailored to the respective meta-design space ensures that citizen developers are able to create the best possible solution for the specific problem to be solved in that meta-design space, such as creating an AR guide or a digital twin. If the tool provides citizen developers with all the functions that are important for the meta-design space, they can create the best possible solution to a problem. This leads to the belief that the citizen developer's colleagues perceive the solutions created to be helpful and will thus be more willing to share their domain knowledge in a virtual community such as the IM (Chiu et al. 2006; Hsu et al. 2007). In the parlance of SCT, these judgments concerning the results of the citizen developer reflect a determinate of personal cognition, the outcome expectation (Bandura 1986).

By providing content adapted to the meta-design space, the outcome expectations of citizen developers are strengthened, as they are able to create the best possible solution for specific problems regarding the meta-design space. We formulate our second design principle using the scheme proposed by Gregor et al. (2020). **DP2:** *To enable citizen developers to create AR for the industrial metaverse, citizen developers need immersive content tailored to the respective meta-design space so that they can create the best possible solution for a specific problem regarding the meta-design space.*

Our third DP is also based on the **MR2**, which strengthens the outcome expectations of the citizen developer when creating metaverse content. We rely on the concept of transition between meta-design spaces (Nickerson et al. 2022b; Seidel et al. 2022). As shown in our scenario from the Introduction and grounded in the AR/VR and metaverse literatures, the different use cases in the IM require different interfaces (Oppermann et al. 2023; Rauschnabel et al. 2022). For citizen developers and users to move between meta-design spaces in a natural way (Nickerson et al. 2022b; Seidel et al. 2022), the metaverse content needs to be displayed on different interfaces. To refer back to our scenario and provide an example, the AR instructions created with our AR development tool can also be used in the IM application to plan and analyze the new factory, and these must be exportable to VR interfaces. Not only do the interfaces differ between the meta-design spaces but also the outcome expectations when creating (Laviola et al. 2022) and using the metaverse content (Siyaev and Jo 2021).

By separating the creation and usage process, it is possible to create the AR content in situ while exporting the created AR instructions so that they can be displayed on different interfaces according to the users' preferences (Clark 2007). This strengthens the citizen developers' feeling that the created AR content adds value to the virtual community and thus strengthens their own outcome expectations (Chiu et al. 2006; Hsu et al. 2007). Based on the transition between the meta-design spaces, we formulate our third design principle using the scheme proposed by Gregor et al. (2020). **DP3:** *To enable citizen developers to create AR content for the industrial metaverse, citizen developers need to be empowered to move between the different meta-design spaces in the industrial metaverse, which requires a separation between the creation and usage process.*

8.3.3 Instantiation of the Design

To instantiate our DPs into a software artifact, we developed MetAR, which comprises three software components. To ensure reproducibility and to provide practitioners with actionable guidance, we demonstrate how our design principles can be mapped to appropriate design features (DF). Below is a detailed description of the software architecture and its three software components (see Figure 26).

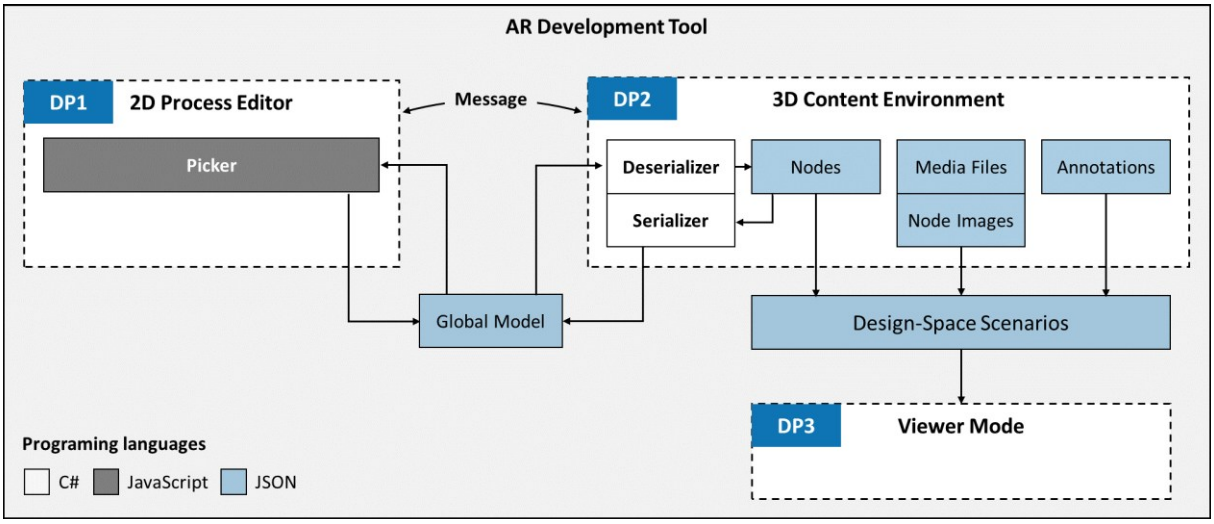

Figure 26. Software architecture of the AR development tool

The Division of the AR Development Process (DP1)

We initiated our three design principles through MetAR. The first DP, proposing the division of the AR development process, is instantiated by the *2D process editor* **(DF1)** and the *3D content environment* **(DF2)**. Figure 27 two shows the final software artifact, MetAR. On the left-hand side of Figure 27, the *2D node editor* is shown, allowing users to create the structure and the sequence of the process guidance system. Using Function 1, users can choose from three different process steps (node types) and add them to the process. The first node type is the *info node*, where only 2D elements (i.e., text) can be added to the application. Both 2D and 3D elements can be added to the application in an *instruction node*. For an *exploration node*, only location-dependent 3D elements can be added. With Function 2, users can initiate the *3D content environment* (on the right-hand side of Figure 27) for the respective node type, in which the users can add the content for this node type. Using Function 3, users can exit the 3D content environment and navigate back to the 2D process editor. Function 4 can be used to manage and navigate through the process steps (**DF3**). Functions 5-7 represent the DFs for the second DP. Function 5 can be used to enrich the process step with 2D digital content such as text (**DF4**). Function 6 can be used to enrich the process step with 3D digital content (**DF5**). Here, users can choose from a selection of 3D objects that can be anchored within the physical environment. With function 7, users can add media to the AR instruction by taking a photo/video or selecting a photo/video from their gallery (**DF6**).

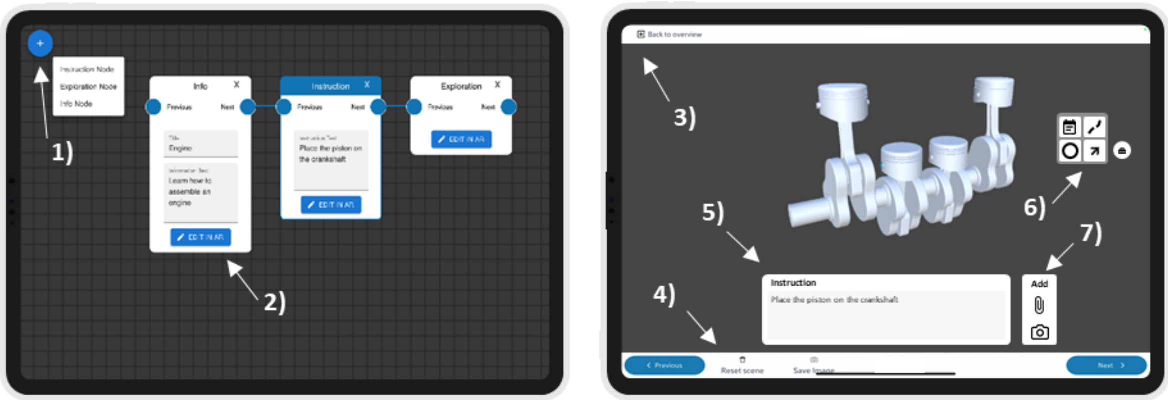

Figure 27. Final Software artifact, MetAR

Content Tailored to the Respective meta-design Space (DP2)

The second DP, proposing the use of content tailored to the respective meta-design space, is instantiated based on the six information types proposed by Gattullo et al. (2020) convey technical documentation as AR-based instructions. They found that with the help of these six information types, any technical documentation could be conveyed into AR-based instructions. Table 24 gives an overview of the six information types and how we integrated them as a software feature in MetAR.

Information type	Description	Software feature
Identify	As the name suggests, this information type can be used to display the identity of an object.	Add media 
Way-to	With this information type, the location of the physical object can be displayed or highlighted directly in the users' physical environment.	Tether 
Orientation	With this type of information, the operation to be performed can be displayed.	Arrow 
Notification	With this information type, additional information can be displayed, which is necessary for an assembly step but also for different conditions or other quality indications.	Instruction Text

Order	With this information type, sequences such as the assembly sequence can be visualized.	Sticky note 
Location	With this information type, an object's orientation and position can be visualized.	Arrow 

Table 24. Information Types Translated into AR Software Features

The Division of the Creation and Usage Process (DP3)

The third DP, proposing the division of the creation and the usage process, is instantiated by the *viewer mode* (**DF7**). In the *viewer mode*, the created process guidance systems can be displayed. As the name suggests, changing or adapting the process guidance systems in the viewer mode is impossible. The designed 2D and 3D content is rendered precisely where the citizen developer places it. The process guidance systems created are saved in a design space. A design space manager allows users to access saved scenarios or create new design spaces (**DF8**).

8.4 Evaluation

In the course of three evaluation episodes, two laboratory experiments employed a two-cell experimental setup to validate our first two design principles and a case study to validate our third design principle. For the first two experiments, we developed testable propositions in the form of hypotheses based on the guidelines proposed in the IS design theory Jones and Gregor (2007). The results of the experiments are then presented. The final section shows the results of the case study.

8.4.1 Experiment 1 on the Division of the AR Development Process (DP1)

Hypotheses Derivation

Based on existing research, we formulated hypotheses regarding the proposed effects of the first DP and evaluated their validity. To review, under the MetAR condition, the development process is separated, while under MAD-MetAR the process is merged (see Appendix B and D for more information). DP1 proposes that separating the 2D and 3D creation process allows developers to first address familiar tasks before moving on to unfamiliar tasks. Recent IS research suggests that self-efficacy in the use of input and output technologies "has two dimensions, internal and external" (Thatcher et al. 2008). While internal self-efficacy is the conviction in one's own abilities to use a tool successfully, external self-efficacy is the conviction to use a tool successfully when one can receive support of any kind (Thatcher et al. 2008).

When implementing a self-regulating learning approach, citizen developers are first confronted with tasks with which they are familiar (Zimmerman 1989). Repeated successful completion of familiar tasks strengthens the user’s enactive mastery experience, which is the strongest source of self-efficacy (Bandura 1986; Tabernero and Wood 1999). Citizen developers first strengthen their internal self-efficacy by confronting a (2D) task with which they are familiar before moving to the unfamiliar task of creating 3D content. Therefore, we hypothesize that this leads to an overall strengthened internal self-efficacy:

> **H1:** Citizen developers creating AR content with MetAR for the IM will achieve a higher level of internal self-efficacy than those using MAD-MetAR.

One approach to achieving self-regulatory learning is scaffolded learning. In this approach, learners are provided with a scaffold that reduces their freedom in order to help them successfully achieve a goal (Wood et al. 1976). The division of the AR development process is a scaffold that deprives learners of the freedom to start with unknown tasks first. Therefore, since the self-regulatory learning approach of scaffolding offers citizen developers support in achieving their goals, we hypothesize that it also strengthens their external self-efficiency:

> **H2:** Citizen developers creating AR content with MetAR for the IM will achieve a higher level of external self-efficacy than those using MAD-MetAR.

Based on SCT, we formulate two further hypotheses on the impact of self-efficacy on the efficient and effective use of a tool. The efficient and effective use of a tool is a core element of Bandura (1986) SCT since self-efficacy is closely related to the actual use of the tool. Therefore, users with high self-efficacy will presumably approach tasks with greater confidence and motivation and persevere in the face of challenges or obstacles and thus realize better task performance or a higher level of achievement (Bandura 1997). This assumption of SCT has been demonstrated in several studies in many disciplines (Lent et al. 1994; Tams et al. 2018). Since we assume that self-efficacy is higher due to the division of the AR development process, we hypothesize:

> **H3:** Citizen developers creating AR content with MetAR for the IM will achieve a higher level of task performance than those using MAD-MetAR.

> **H4:** Citizen developers creating AR content with MetAR for the IM will achieve a higher level of time performance than those using MAD-MetAR.

Results

We conducted a statistical analyzis of the dependent variables collected through our laboratory experiment to test the impact of our second design recommendation for an AR development tool on the citizen developer's internal and external self-efficacy, task, and time performance during the creation of AR instructions. To test our hypotheses, the data was ranked, and a two-tailed unequal variance *t*-test was applied according to the description given by Ruxton (2006). Table 25 summarizes the results of the comparison of the two conditions.

	MAD-MetAR		MetAR			
Dependent variable	**M**	**SD**	**M**	**SD**	***t*-test**	**Hypothesis**
Internal self-efficacy	21.9074	15.3748	31.4600	13.3037	2.392*	H1: supported
External self-efficacy	24.8704	15.5882	28.2600	14.3542	0.816	H2: not supported
Task performance	19.8889	14.0318	33.6400	12.4771	3.740*	H3: supported
Time performance	25.8889	12.6501	27.1600	17.3149	0.300	H4: not supported
*$p < 0.05$						
M = mean; SD = standard derivation						

Table 25. Ranked data results of two-tailed unequal variance t-test (Experiment 1)

The results of the comparison of MAD-MetAR and MetAR (Appendix B and D) show that the division of the AR development process had a significantly positive influence on the internal but not the external self-efficacy of the citizen developers. Nevertheless, the descriptive statistics also show a slightly increased but not significant positive effect on the external self-efficacy of the citizen developers. Furthermore, the results of the comparison show that dividing the AR development process into the 2D process editor and the 3D content environment had a significant positive influence on the quality of the AR instructions created. The results also show that the division of the AR development process did not lead to the citizen developers being less efficient in creating AR instructions; rather, the descriptive statistics indicate that the time performance was almost identical for both AR development tools. We also analyzed the covariates and found no significant differences in AR experience on any of the dependent variables.

8.4.2 Experiment 2 on Content Specific to the Meta-design Space (DP2)

Hypotheses Derivation

We formulated hypotheses regarding the proposed effects of the second DP based on existing research and evaluated their validity. To review, under the MetAR condition, content tailored to the meta-design space was used and under GEM-MetAR general content was used. DP2 proposes that by tailoring the content to the meta-design space, citizen developers can provide the best possible solution to the problem at hand, resulting in citizen developers experiencing higher outcome expectations when creating AR content (Cho et al. 2009). This outcome results from actions and can be anticipated by users assessing how they would behave in a given situation (Bandura 1997). This means that users estimate their expected outcomes before taking action.

This relationship connects one's belief in their success and their outcome expectations. Several IS studies have established this correlation between self-efficacy and outcome expectations. For example, Compeau and Higgins (1995) found that both computer self-efficacy and performance outcome expectations significantly impact usage. Also, in virtual environments such as the IM, a strong correlation has been proven between self-efficacy and personal outcome expectations (Hsu et al. 2007). Thus, due to the increased outcome expectations, we hypothesize that citizen developers will experience higher self-efficacy through tailoring content to the meta-design space:

> **H5:** Citizen developers creating AR content with MetAR for the IM will achieve a higher level of internal self-efficacy than those using GEM-MetAR.

External self-efficacy is based on the user's conviction that they can use a tool successfully if they have support (Thatcher et al. 2008). The SCT literature has shown that training before using a tool has a significant impact on users' self-efficacy (Torkzadeh and van Dyke 2002). Since our demonstration of the MetAR tool and the associated task at the beginning of the experiment was more extensive due to the more extensive nature of the AR development tool, we assume that this increased the external self-efficacy of the participants. Hence, we hypothesize:

> **H6:** Citizen developers creating AR content with MetAR for the IM will achieve a higher level of external self-efficacy than those using GEM-MetAR.

As in the derivations of H3-H4, we assume that tailoring the content to the meta-design space would allow users to experience higher self-efficacy, which we assume would result in better performance. Therefore, we hypothesize:

> **H7:** Citizen developers creating AR content with MetAR for the IM will achieve a higher level of task performance than those using GEM-MetAR.

> **H8:** Citizen developers creating AR content with MetAR for the IM will achieve a higher level of task performance than those using GEM-MetAR.

Results

We conducted the same statistical analyzis of the dependent variables as described in Section 5.1.2. Table 26 summarizes the results of the comparison of the two conditions.

	GEM-MetAR		MetAR			
Dependent variable	**M**	**SD**	**M**	**SD**	***t*-test**	**Hypothesis**
Internal self-efficacy	27,0833	13,9896	24,0384	15,1214	-0.740	H5: not supported
External self-efficacy	22,2291	14,55946	28.5192	13.7248	1.573	H6: not supported
Task performance	21,1875	14,5332	29,4808	12,9642	2.123*	H7: supported
Time performance	24.8542	13,5450	26,0962	15.2637	0.305	H8: not supported
*$p < 0.05$						
M = mean; SD = standard derivation						

Table 26. Ranked data results of two-tailed unequal variance t-test (Experiment 2)

The results of the comparison of GEM-MetAR and MetAR (Appendix C and D) show that the use of content tailored to the respective meta-design space had no significant influence on the internal self-efficacy of the citizen developer. Rather, contrary to our expectations, the results show that the use of content specific to the use case had a negative impact on internal self-efficacy. It is thus particularly surprising that the use of content tailored to the meta-design space had a strong positive and almost statistically significant effect on users' external self-efficacy. The results of the comparison also show that the use of content tailored to the meta-design space had a significantly positive influence on the quality of the AR instructions produced. Additionally, the MetAR participants were able to create the AR instructions faster but not significantly faster despite the more extensive functions of the AR development tool. We also analyzed the covariates and found no significant differences in AR experience on any of the dependent variables.

8.4.3 Case Study on Separating the Usage and Creation Process of IM Applications (DP3)

The results of the case study show how self-efficacy and outcome expectations differ in the creation and usage process of IM applications. While the outcome expectations during the creation process were mainly driven by the belief in the usefulness of the content from the perspective of other parties (can or would service technicians use these AR instructions). In contrast the outcome expectations during the usage process were predominantly characterized by the expected economic/social advantages of using the IM application (would the AR instructions benefit me or my organization). The self-efficacy during the creation process was mainly driven by the user's belief in their ability to create IM applications (Do I know the AR development tool well enough to create AR instructions?). In contrast, self-efficacy during the use of IM applications was primarily driven by the quality and richness of the instructions (Are the instructions good enough?).

Sources of Outcome Expectations

In the creation process of IM applications, our interviews suggest that outcome expectations are primarily based on the success of other parties' use of the IM content. No participants expressed difficulties regarding creating metaverse content with MetAR. However, eight out of 12 participants did not perceive creating content to be useful in and of itself. Instead, they noted in the interviews that the next step should be providing the created content in different forms and on different hardware to accommodate users' different needs. For example, some of the older experts wanted to continue working with paper documents, while others thought using a smartphone or HMD would be preferable so they could work hands-free. Thus, the outcome expectations of the created IM content were based on a broad range of possibilities for using the created applications, which would require a clearer and more versatile separation between the creation and use of the IM applications. One expert explained:

> *"It would be good if the instruction that one has just created with the tool could be exported in some way so that one then receives the instruction[s], for example, in text form or some other form. So that a technician for their colleagues in the field, the instructions can record here with AR, and that can then be exported into a document." (#10)*

Our participants shared that during the usage process of IM applications, the source of the outcome expectations was mainly based on expected economic and social benefits. While only three participants mentioned an economic/social benefit that would be derived from the quick and easy creation of metaverse applications, nine out of 12 participants highlighted the economic/social benefits of using metaverse applications. One of the biggest advantages the participants mentioned regarding the use of metaverse applications was the various benefits for training new colleagues. Compared to the use of videos, IM applications can train users at their own pace on the physical machine itself without needing a trainer to assist them physically. Another frequently mentioned advantage was the potential for reducing errors and maintenance/repair time because the metaverse content guides the user step-by-step through the maintenance/repair process.

> *"... the advantage compared to a recorded video is that you can follow the individual steps independently on the end devices by clicking through these steps based on your*

> *individual pace. You're not reliant on the video, but do it as quickly and as slowly as you like ..."* (#1)

It is clear that versatility also plays a crucial role in the actual use of IM applications. The social and economic benefits cited by interview participants were often linked to the need to expand use across a wider range of hardware. For example, some participants said that it would be advantageous if the created metaverse applications (whether for training or process support) could be used on a smartphone or HMD.

> "*It's better suited for training purposes. You have step-by-step gradations, so with the video, you're kind of sucked through, and you have to pause if you want to know something again, and here it's just nice and slow. The important thing is, and this is always the case with augmented reality, that you have to look at how you get the information and still have your hands free to continue working ...*" (#10)

Sources of Self-Efficacy

In the creation process of IM applications, self-efficacy was primarily driven by the participants' belief in their ability to create metaverse applications using MetAR. When asked about their concerns about creating metaverse applications, none of the participants expressed major difficulties in creating them. On the contrary, eight of the 12 participants responded positively about their ability to create metaverse applications. The participants noted that despite the short introduction and presentation of MetAR, it was impressive that they could independently create metaverse applications. However, participants also noted that they would not have been able to use MetAR in certain contexts without this short introduction at the beginning of the case study. For example, the interaction with the 3D elements on the tablet is not highly intuitive since, in order to move the 3D elements, the tablet itself must be moved.

> "*Despite the fact that I get from you no or only a small instruction to the tool, I could work intuitively with it. I think a short tutorial like a one-pager or a short demo video is enough to work with the tool quickly.*" (#6)

In the usage process of IM applications, only two participants suggested an improvement to MetAR that might further support their belief in their own ability to create metaverse content. Both participants commented that instructions are often similar in structure and differ in only a few steps. For this reason, it would be useful if the content could be duplicated because the time required for the creation process would thereby be significantly reduced.

The source of self-efficacy in the usage process of IM applications was the participants' belief in the quality and usefulness of the metaverse application. In this case, all participants expressed a need for improvement in order to exploit the full potential of metaverse application in their context of use. Suggestions for improvement expressed by participants also relate to the need for more versatility in the use of the metaverse applications. For example, participants pointed out that some domain experts do not need to be guided step-by-step through a process but only need to look up a specific step. Also, they noted that some users are unable to operate a tablet due to occupational safety requirements that require the use of an HMD.

> "*Yes, as I said, there would be for me once the handling of tablet and simultaneous work. So where do I place the tablet and now also with the background that I have oil on my hands, now I need the tablet again …*" (#1)

8.5 Design Reflections

Following the guidelines of Jones and Gregor (2007), we synthesize our findings into a nascent design theory for AR development tools for the creation of process guidance systems in the IM (see Table 27. Nascent Design Theory). Our theory consists of eight components: (1) *the purpose and scope* of the design theory, which is discussed in the Introduction; (2) the *constructs* that originate from SCT; (3) the *principles of form and function,* which provide the basis for the design theory; (4) *artifact mutability,* also discussed in the Introduction; (5) *testable propositions,* which are covered by our hypotheses; (6) *justificatory knowledge,* which is defined by our MRs and DPs; and (7) the *principles of implementation* and (8) the *expository instantiation,* which are addressed by MetAR, the software artifact we developed.

Component	Description
Purpose and scope	The purpose of design theory is to provide prescriptive design knowledge on how to design AR development tools, which citizen developers can use to create process guidance to support employees in decision-making, problem-solving, task execution, or training in the industrial metaverse that needs to be anchored in the physical environment.
Constructs	We propose three DPs for the design of AR development tools for the development of process guidance systems in the industrial metaverse.
Principles of form and function	• **DP1:** To enable citizen developers to create AR content for the industrial metaverse, the 2D creation process and the 3D creation process should be independent of each other so that citizen developers are first confronted with a more familiar task before then moving on to the less familiar task of 3D content creation. • **DP2:** To enable citizen developers to create AR for the industrial metaverse, citizen developers need immersive content tailored to the respective meta-design space so that they can create the best possible solution for a specific problem addressed in the meta-design space.

	• **DP3:** To enable citizen developers to create AR content for the industrial metaverse, citizen developers need to be empowered to move between the different meta-design spaces in the industrial metaverse, which requires the separation between the creation and usage process.
Artifact mutability	The AR development tool is mutable, especially with regard to the general design such as the choice of tracking and anchoring method, the choice of user input, and the hardware. Here, the focus should be on deciding between reducing complexity and broadening the application of the AR development tool.
Testable propositions	• If the AR development process is divided into 2D and 3D • … as well as the use of content tailored to the meta-design space in combination with short tutorials on how to use these 3D elements … • …and separating the creation and use of AR content to ensure that the created content is not limited to one interface… • …will lead to higher self-efficacy and better performance for citizen developers when creating AR content.
Justificatory knowledge	1. A self-regulated learning approach increases self-efficacy. 2. Content tailored to the meta-design space increases outcome expectations. 3. Separation of the creation and usage process allows moving between the meta-design spaces and increases the outcome expectations.
Principles of implementation	To instantiate our DPs into a software artifact, we developed MetAR, consisting of three software components, namely, a 3D content environment, a 2D process editor, and a viewer mode (see Section 7.4.2)
Expository instantiation	The nascent design theory was initiated in a MetAR. A demonstration video can be accessed at: https://wizard.tu-dortmund.de/index.php/bpm22/

Table 27. Nascent Design Theory

8.6 Discussion

Our core contribution is a nascent design theory that offers an explicit description of how AR development tools can be designed for the IM to improve the performance of the creation process while increasing citizen developers' self-efficacy. We developed three design principles, which we instantiated in a prototype, MetAR, that allowed us to evaluate these three DPs.

In our first experiment, we confirmed the first DP, proposing the separation of the AR development process into a 2D process editor and a 3D content environment based on a self-regulating learning process (Zimmerman 1989). In line with the SCT literature for solving complex problems (Tabernero and Wood 1999), we show that a self-regulating learning approach significantly impacted the internal self-efficacy of citizen developers in an IM context. The results of the comparison show a significant positive influence of the separation of the AR development process on both the internal self-efficacy and the performance of citizen developers. Furthermore, the results also show that despite the division and the increased effort involved, it did not lead to a more inefficient process of creating AR instructions.

In our second experiment, we partially confirmed the second DP, proposing the use of content tailored to the respective meta-design space based on user outcome expectations (Chiu et al. 2006; Hsu et al. 2007). While the results show that citizen developers were able to create instructions of significantly higher quality, the results also show, contrary to our expectations, that the use of content tailored to the meta-design spaces had no significant negative impact on internal user self-efficacy. The reasons for this may be multifaceted. One likely reason could be that increasing complexity has a negative impact on the cognitive load of the user (Sweller 1988), which is strongly correlated with self-efficacy (Bandura 1989). However, the descriptive statistics also show that the use of content tailored to the respective meta-design space had a strong positive but no significant effect on the external self-efficacy of the citizen developer. However, this effect is almost significant (p-value = 0.062), and it might be possible to show a significant value if the sample size were to be increased.

The third DP we developed is separating the creation and usage process from IM applications. The results of our case study show that users experience different outcome expectations and self-efficacy when using and creating metaverse applications. A number of citizen developers mentioned that the created AR instructions should be able to be displayed on different interfaces, such as smartphones or HMDs, as the potential users of the AR instructions may have very different requirements for accessing the AR instructions. By separating the creation and usage process, it would be possible to create the AR content in situ and then export the created AR instructions so that they could be displayed on different interfaces according to the user’s preferences. In addition, the display of the created AR content should also allow the content to be used in other meta-design spaces, which emphasizes the natural transition between the different meta-design spaces in the IM (Seidel et al. 2022).

We were unable to demonstrate the significant impact of our first two DPs on the external self-efficacy of citizen developers. Since external self-efficacy is largely dependent on the support offered by a system (Thatcher et al. 2008), tutorials or onboarding within MetAR could strengthen the self-efficacy of citizen developers. We were able to substantiate this intuition in our case study, and the results showed that our demonstration of the tool and the associated task served as a decisive source of self-efficacy in the creation of AR content. By using tutorials, citizen developers can strengthen their belief in a successful outcome (Gangadharbatla 2008). The need for assistance is also supported by the underlying problem of AR development tools, the complexity, and the spatial knowledge required (Ashtari et al. 2020; Nebeling and Speicher 2018). We therefore suggest integrating tutorials in future AR development tools that explain the use of immersive content to citizen developers.

8.6.1 Theoretical and Practical Implications

Our DSR knowledge contribution is a new solution for a known problem, following Gregor and Hevner (2013). While the impact of AR in industrial organizations has been well-researched (Choi et al. 2022; Porter and Heppelmann 2017; Serván et al. 2011), AR has not yet been widely adopted in an industrial context. In line with the literature, we have identified one possible reason for this, namely, the complexity of AR content creation (Ashtari et al. 2020; Azuma 2016; Krauß et al. 2021; Nebeling and Speicher 2018). We demonstrate that by focusing the design of development tools on self-efficacy, industrial organizations can exploit the potential of AR by empowering and increasing employees' intentions to create AR content for the IM. Similar to software development (Maruping and Matook 2020), where no-code or low-code tools help novice users develop new applications, the AR development tools we present can help citizen developers create process guidance systems in the form of AR instructions. We show that our AR development tool increases both the outcome expectations and the self-efficacy of citizen developers, which are important contributors to user engagement in virtual environments (Chiu et al. 2006; Hsu et al. 2007).

Second, our research contributes to the SCT literature by contextualizing SCT to the IM. We contribute to the understanding of how to design AR development tools that enable citizen developers to create objects in a virtual environment and then transform them into physical artifacts (Seidel et al. 2022). We thereby contextualize the SCT to the IM in several ways: So far, SCT research has focused mainly on screen-based interfaces (Chiu et al. 2006; Compeau and Higgins 1995; Hsu et al. 2007). The strongest source of self-efficacy is the enactive mastery experience, driven by repeated successful task completion (Bandura 1997). However, not a single person in our case study considered this to be relevant. Instead, 66% of citizen developers from our case study noted that the creation of AR instructions depends on the successful use of the instructions by their colleagues. This represents another source of self-efficacy, the vicarious experience resulting from individuals observing someone with similar abilities performing a task (Bandura 1997). This source of self-efficacy appears to be particularly important in the IM, originating, perhaps, from the increased immersion caused by the AR interface (Milgram and Kishino 1994). In addition to the spatial knowledge required by increased immersion (Nebeling and Speicher 2018), the citizen developers were able to anticipate how the instructions they created would later be used by other employees. The belief that one can successfully perform a set of behaviors required to create and use metaverse content goes beyond basic computer, application, and internet skills.

Third, our results suggest exporting the created AR instructions to different interfaces. This is important because IM is not just one single immersive application (Nickerson et al. 2022b; Schöbel and Leimeister 2023; Seidel et al. 2022). As shown in our scenario from the introduction and grounded in the AR/VR and metaverse literature, the different use cases in the IM require different interfaces (Oppermann et al. 2023; Rauschnabel et al. 2022). In order for citizen developers to move between the meta-design spaces in a natural way (Nickerson et al. 2022b; Seidel et al. 2022), metaverse content needs to be displayed on different interfaces. For example, the AR instructions created with our AR development tool could also be used in the IM application to plan and analyze the new factory (from the above scenario) but would need to be exportable to VR interfaces.

The results of our DSR project have important practical implications for industrial organizations seeking to extend their processes and business models to the IM. For organizations to be able to do this, employees need to be empowered, and their intention to create immersive content for IM needs to be strengthened. Current industry standards to simplify the AR development process, such as Microsoft Guides (Microsoft 2023), are very limited in their scope, such as hardware and content (Lavric et al. 2022), which contributes to the fact that AR has not yet been widely adopted in organizations (Ashtari et al. 2020; Krauß et al. 2021; Nebeling and Speicher 2018). Against this background, our research can help industrial organizations provide their employees with easier access to IM. Our developed nascent design theory serves as an abstract understanding of what was learned in the design of the AR development tool and could thus serve as a blueprint for the development of similar artifacts in the IM (Piirainen and Briggs 2011).

8.6.2 Limitations and Future Research

Although our DSR project and the quantitative and qualitative evaluation episodes adhered to established guidelines, some potential limitations require further research. First, the three proposed DPs and MetAR are specifically tailored to the IM. It is important to note that these DPs apply only to AR interfaces within the IM context. It is unclear if our DPs also apply to the screen-based or VR interfaces commonly used in the existing literature to access the metaverse. In order to verify the validity and impact of our DPs in this context, we recommend that future DSR investigate and validate the three DPs using screen-based and VR metaverse applications.

Second, the quantitative evaluation episodes from the laboratory experiment and the qualitative evaluation episode from the case study address only one of many processes that AR can support. Addressing different processes in subsequent evaluation episodes may offer more insight into the potential of AR to transform organizations. While the process examined in the case study represents a realistic scenario, an essential aspect of the industrial context has not been taken into account, namely, the work of citizen developers at customer sites. Because boundary and environmental conditions at customer sites can vary significantly and may include significant time constraints, underground or maritime worksites, etc., we encourage researchers to conduct further evaluation episodes in operational settings at customer sites.

Third, it is important to acknowledge that the qualitative evaluation episode in the case study involved a limited number of participants, with only 12 individuals participating. Because the participants were carefully sampled from a representative target group across two organizations, we believe they offered rich insight into the design of AR tools. However, expanding the sample to a greater pool of respondents would increase the generalizability of our findings. Further evaluation episodes with larger participant pools encompassing individuals from various backgrounds would likely yield additional insights that could improve the design process.

Finally, while two AR experts evaluated the quality of AR instructions created by participants following international standards (ITU 1996, 2008), it is important to acknowledge that audiences in practice may perceive the quality of AR instructions differently. In future work, a two-stage evaluation, where domain experts (service technicians) other than the creators assess the AR instructions, could be conducted to obtain additional and novel insights that could lead to better design tools.

This work could be extended in multiple directions related to content creation for the metaverse. This opens up new research avenues, such as automated content creation through technologies such as generative AI and the content requirements of users from different metaverse realms. Another research avenue would be to explore the effects or possibilities of different metaverse realms or immersive technologies such as MR and VR on our three design principles.

8.7 Conclusion

In this paper, we offer a theory-driven process for designing a software artifact and, by synthesizing our results, a nascent design theory for the development of AR development tools for the IM. We derived our three DPs, which form the basis of the nascent design theory, from SCT and the existing literature on AR development tools. Our results show that dividing the AR creation process into 2D and 3D components increases both citizen developers' self-efficacy and performance when creating process guidance systems for the IM. Although we found that the use of content tailored to the meta-design spaces improves performance in terms of creating a process guidance system, this may also have a negative effect on the self-efficacy of citizen developers, thus punctuating the need for tutorials or onboarding with MetAR. By separating the creation and usage process of IM applications, it would be possible to create the AR content in situ and later export the created AR instructions so that they could be displayed on different interfaces according to the user's preferences. Through our work, we offer researchers and managers insight into how users from the IM can be empowered to create objects in virtual environments and then transform them into physical objects. We show that it is important to build tools that enhance citizen developers' self-efficacy, which is a key enabler of participation in virtual communities.

9 Are you Telling the Truth? Detection of Identity Theft through Human Motor Control in the Metaverse (P6)

Title	Are you Telling the Truth? Detection of Identity Theft through Human Motor Control in the Metaverse
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Table 28. Fact Sheet Publication P6

Abstract: A user's digital identity is central to accessing and interacting within the metaverse, making it particularly vulnerable to abuse, such as identity theft. Fraudsters can operate anonymously, not only under a false name but also with a different appearance. Identifying users' true identities is challenging because traditional physical identification methods are difficult to implement in virtual environments, and users often value anonymity in the metaverse. Drawing on the Self-Concept Maintenance Theory and the Activation-Decision-Construction-Action Theory, we propose a method for the unobtrusive evaluation of movement data, which can be used for the early detection of fraudulent behavior due to altered cognitive dynamics. Our findings indicate that individuals moved significantly slower and over greater distances during the action of fraud but not during the fraud's activation, decision, or

construction stages. In addition, our findings indicate that participants move more and slower in the stages before fraud than during fraud.

9.1 Introduction

In a world without a "Pinocchio's nose," where lies leave no obvious trace, the challenge of discerning truth from fraud becomes a high-stakes puzzle, one that demands careful comparison to a baseline. This challenge is rapidly magnified within the emerging digital ecosystem of the metaverse (Schöbel and Leimeister 2023), where expansive opportunities beyond private entertainment sectors, such as gaming and media (Duan et al. 2021), are emerging. These opportunities intersect with the potential to fundamentally transform the world of work (Park and Kim 2022) in a way that users currently have no baseline for comparing completely honest and fraudulent behavior. However, the metaverse's rapid expansion and the absence of a “baseline” for making comparisons in the virtual environment are problematic. Chief among these are data privacy concerns, as users' personal information is increasingly vulnerable to unauthorized access and disclosure. Data breaches pose a serious threat, potentially leading to the misuse and theft of sensitive information (Jaber 2022). A particularly alarming aspect in this context is identity theft, which could have more severe consequences in the metaverse than traditional online environments. Unlike on the internet, where identity theft typically involves the misuse of names and interactions are limited to basic website interfaces, the metaverse provides a highly immersive experience in a virtual world. In this immersive environment, fraudsters could take advantage of users lacking a baseline to mimic not only the appearance but also the behavior and movements of their victims (Tariq et al. 2023).

To overcome the absence of a baseline in the metaverse, one possibility for helping users and system providers recognize identity theft is analyzing data collected from Human-Computer Interaction devices (Hibbeln et al. 2017). Metaverse users often interact with Virtual Reality (VR) controllers, which, through high-precision sensors, could provide insights into user behavior. Recording and analyzing controller movements with millisecond precision makes it possible to infer users' cognitive states (Reinhardt et al. 2019). For example, tracking these movements can be used to create and identify kinematic signatures, spatiotemporal movement data unique to individuals, thus enabling implicit user identification in VR environments. In particular, movement patterns inform the kinematic signatures recorded via head-mounted displays (HMDs) and VR controllers, which offer significant potential for uniquely identifying individuals (Liebers et al. 2024).

In our research context, we define fraudulent behavior specifically as deliberately providing false information in virtual environments. While various terms like "dishonest," "deceptive," or "misrepresentation" appear in the literature, we consistently use "fraudulent behavior" throughout this paper to describe intentionally false inputs in the metaverse (Panicker et al. 2024). This also aligns with established research examining deceptive behavior in human-computer interaction (Roehl and Harland 2022). Although identity theft represents a severe manifestation of fraudulent behavior in the metaverse, we argue that the underlying cognitive processes involved in identity impersonation and simpler fraudulent acts, such as providing fake names or incorrect demographic information such as age, are closely related. Both forms of fraud require individuals to deliberately suppress truthful information, cognitively construct plausible falsehoods, and manage cognitive dissonance to maintain a positive self-image (Mazar et al. 2008). Even minor fraudulent acts are therefore valuable proxies for studying identity theft, as they share the foundational mechanisms of deception. In order to help users and system providers identify fraudulent behavior, this paper explores the use of analyzing VR controller movements to detect dishonest inputs. We present a method for the unobtrusive and scalable evaluation of such inputs, which facilitates the early detection of fraudulent behavior in the metaverse. The controller's movements during user interactions with metaverse applications can be recorded and analyzed without disrupting the interaction itself. If the controller's movements suggest potential dishonest input, such as registering with a false name or age, the system could automatically intervene, for instance, by temporarily blocking the account and requesting verification of the user's identity through an identity procedure (Liebers et al. 2024).

To explain how fraudulent behavior can influence controller movements, we draw on the Self-Concept Maintenance Theory (SCMT) proposed by Mazar et al. (2008) and on the Activation-Decision-Construction-Action Theory (ADCAT) (Walczyk et al. 2014). According to SCMT, individuals engage in fraudulent behavior when they can gain external benefits, but only to the extent that they can maintain a positive self-concept of their honesty. The effort to maintain a positive self-concept while harbouring fraudulent intentions creates a motivational dilemma, which individuals attempt to resolve in predictable ways (Festinger 1957). This effort to resolve the motivational dilemma and overcome cognitive dissonance can affect human motor control (Freeman et al. 2011; Wojnowicz et al. 2009).

While initial evidence from both 2D environments using mouse movement (Jenkins et al. 2021; Weinmann et al. 2022) and 3D environments using Wii video game console controllers (Duran et al. 2010) has demonstrated that fraudulent behavior affects individuals' human motor control, two research gaps remain. First, to the best of our knowledge, no study has investigated fraudulent behavior in virtual environments, which may fundamentally differ from behavior in the physical environment. Second, examining fraudulent behavior by breaking it down into distinct stages could yield new valuable insights, such as identifying the most reliable stage for detecting fraudulent behavior.

Therefore, we investigate how fraudulent behavior influences VR controller movements, focusing on the distance and speed of the controller across the different stages of fraud as outlined in the ADCAT (Walczyk et al. 2014). According to this theory, lying involves four distinct stages: (1) the activation of the truth from long-term memory, (2) the decision whether and how to fraudulently alter the information to be shared, (3) the construction of the fraud, and (4) the action of the fraud (Suchotzki et al. 2017; Walczyk et al. 2014). In summary, our research investigates the following research question:

RQ: *Does fraud action, activation, decision, and construction in the metaverse affect the controller distance and speed?*

To address this research question, we conducted a single-factor controlled experimental study in a VR setting with 22 participants. We analyzed the controller movement data during instances of both honest and dishonest user inputs. In a self-developed VR game, participants were incentivized to make dishonest inputs through two established social mechanisms, rivalry (Cadsby et al. 2016; Jacobsen et al. 2018; Kilduff et al. 2016) and social incentives (Jacobsen et al. 2018; Pascual-Ezama et al. 2013), without explicit encouragement to do so. Our study specifically focused on identifying changes in human motor control, particularly in controller distance and speed, associated with the stages of fraud. Our findings are multifaceted and offer practical and theoretical contributions, including insights into the affective computing literature and guidance for metaverse researchers in designing and analyzing future metaverse applications. The findings indicate that individuals committing fraud move their controllers over greater distances and at slower speeds than those who act honestly. Additionally, our research provides initial insights into how different cognitive dynamics during the various stages of fraud influence controller movements. Specifically, the findings show that individuals who activate, decide, and construct a fraudulent act move the controller over greater distances and at a slower speed than those in the action of fraud.

9.2 Theoretical Background

9.2.1 Metaverse Identity Theft

Cybersecurity experts, along with organizations like UNICEF, have highlighted the need for research on identity theft in the metaverse (Vosloo et al. 2023), a risk that also poses significant concerns for everyday citizens in countries such as the United States and the United Kingdom (van Schaik et al. 2017). Since digital identity is central to access and interaction in the metaverse, its users are vulnerable to the theft or misuse of personal data (Sharma et al. 2024; Tariq et al. 2023). A recent UNICEF report emphasizes these concerns, noting a rise in cyberattacks targeting children, where identity credentials and biometric data are stolen, often resulting in severe lifelong consequences (Pauwels 2022).

Within virtual worlds like the metaverse, identity theft represents one of the most concerning forms of fraudulent behavior (van Schaik et al. 2017). Unlike traditional online fraud where deception might be limited to false usernames or profile pictures, metaverse identity theft involves the impersonation of another user's digital presence. This includes mimicking their appearance through photorealistic avatars, which serve as users' customizable digital representations and primary means of interaction in the metaverse environment. Moreover, identity theft enables fraudsters to leverage the stolen identity to extract additional personal information from victims' relatives and friends (Yang et al. 2023).

The risk for identity theft is high because verifying identity is particularly challenging in the metaverse, as traditional physical identification procedures are difficult to implement in purely virtual environments. One of the appeals of the metaverse is that it affords opportunities for anonymity, where a user’s true identity is separate from that of their virtual avatar (Sharma et al. 2024). This complicates implementing procedures like Know-Your-Customer processes, commonly used in sectors such as banking (Aygun et al. 2022). While many identification methods have been proposed to verify users' identities (Jaber 2022), the likelihood of metaverse users who value anonymity and who do not have fraudulent intentions to circumvent them is high (Sharma et al. 2024; Vernaza et al. 2012).

Due to the complexities of verifying identities in the metaverse and the rising threat of identity theft, we propose a method for the unobtrusive and scalable evaluation of controller movement data, which can be used for the early detection of fraudulent intentions. If fraudulent behavior is suspected using this method, the account could be restricted until the user completes an identification check to regain access.

9.2.2 Detecting Fraudulent Behavior

The literature on fraud detection offers a wide range of methodological approaches. On the one hand, these methods can be grouped into procedures that focus on datasets, such as an e-commerce website (Sun et al. 2020) or digital finance platforms (Guo et al. 2021). We will not discuss these methods of fraud detection based on anomalies and algorithms in more detail, as they do not address the behavioral patterns of fraudsters.

Fraud detection in the metaverse differs significantly from traditional screen-based environments due to the immersive nature of the metaverse. Users interact through embodied avatars, which can induce psychological effects linked directly to the subjective meaning of the body's actions (Pyasik and Pia 2021). Unlike conventional 2D interactions, where avatar movements initiated by keyboard inputs provide no reliable indicators of fraud since they lack a direct connection to human motor control, mouse movements have demonstrated potential as signals of fraudulent behavior due to their closer association with human motor control (Jenkins et al. 2021; Weinmann et al. 2022). These movements are examined for patterns that may be associated with fraudulent behavior. In recent years, this approach has proven to be a valid method for identifying fraudulent activity. However, a metaverse environment and the associated 3D interactions could offer even richer and more sophisticated data for detecting fraud (Hibbeln et al. 2017).

Another contribution to the fraud discourse is more ethical in nature, exploring ethical aspects of cognitive computing and 3D facial tracking as fraud detection capabilities (Sultanuddin et al. 2023). Although this is an ethical approach, the article discusses several other methods for monitoring online examinations, including various facial analyzis techniques (like recognition and expression), monitoring head positioning, tracking eye movements, examining network traffic patterns, and detecting IP address manipulation (Sultanuddin et al. 2023). So, what can be said about fraud detection using body movements is that various parameters of these movements have been analyzed for their suitability to act as a sign of fraudulent behavior (Jenkins et al. 2021; Sultanuddin et al. 2023; Weinmann et al. 2022). To the best of our knowledge, no study has yet investigated how fraudulent behavior in the form of identity theft in the metaverse affects the controller movements of individuals and how the movements of users along the stages of fraud affect them, which is fundamental to understanding the cognitive perception of fraud (Walczyk et al. 2014).

9.2.3 Theories and Hypotheses

We ground our model in cognitive approaches to detecting fraudulent behavior, specifically from assumptions of the SCMT and the ADCAT. Our research model appears in Figure 28.

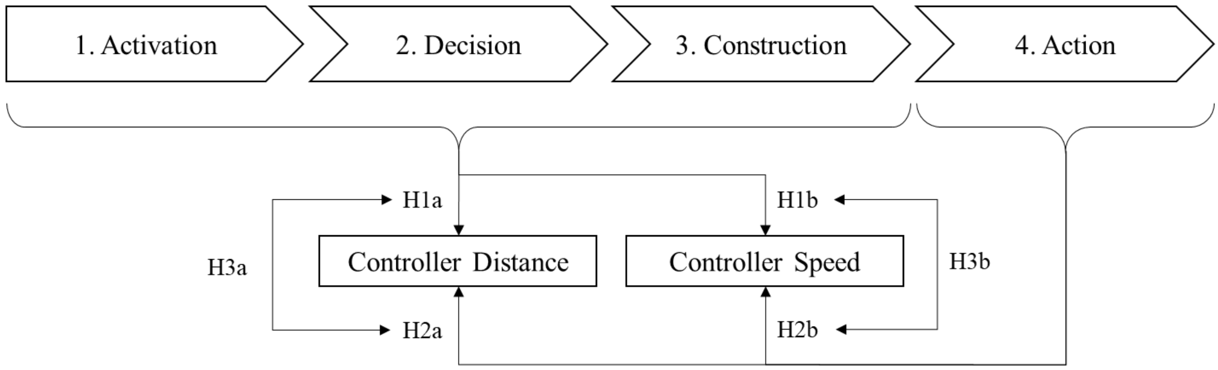

Figure 28. Research Model

SCMT suggests that individuals generally value honesty because it is a crucial component of their internal reward system. Honesty enables individuals to behave morally and maintain their self-concept, their image of themselves (Griffin and Ross 1991; Sanitioso et al. 1990). When individuals fail to uphold their internal standards of honesty, they must adjust their self-concept in ways that can lead to a negative self-perception (Bénabou and Tirole 2004). To avoid this, individuals strive to maintain their internal standards, preventing a negative update to their self-concept and preserving a positive self-image. The SCMT has been used extensively in studies investigating various phenomena and research questions related to fraudulent behavior. For example, explain how students justify using AI tools for academic dishonesty. The theory helped the authors understand how students perceive certain academic behaviors as acceptable depending on whether they can maintain a positive self-image despite committing unethical acts (Bergström et al. 2024).

Within the framework of SCMT, individuals may behave dishonestly when they can gain external benefits, but only to the extent that they can still maintain a positive self-concept. This creates a motivational dilemma in which individuals must balance two competing motivations: the pursuit of external advantages (e.g., financial or social) and the desire to sustain their self-image as honest (Mazar et al. 2008). This internal conflict contributes to fraud being cognitively more demanding than telling the truth (Christ et al. 2009; Suchotzki et al. 2017; Vrij et al. 2006).

However, the cognitive demands of fraudulent behavior are not static; they fluctuate across different stages of fraud. The ADCAT provides a cognitive explanation of the fraud process and helps explain how people analyze the cognitive demands of fraudulent behavior. This theory proposes a framework in which the process of fraud is divided into four stages: (1) the *activation* of the fraud, (2) the *decision* of fraud, (3) the *construction* of fraud, and (4) the *action* of fraud (Walczyk et al. 2014). Throughout these stages, the goal for the individual is to create the impression that the fraudulent individual is, in fact, honest. A key aspect of this process is minimizing the outwardly visible cognitive resources to appear effortlessly honest. This is essential for successfully creating the appearance of honesty while maintaining the fraud (Colwell et al. 2006; Walczyk et al. 2014).

The motivational dilemma between maintaining a positive self-image and pursuing dishonest gains compounds the cognitive demands at each stage of the fraud process. This ongoing internal conflict and the effort to conceal dishonesty can influence human motor control (Freeman et al. 2011; Wojnowicz et al. 2009). Wether individuals commit or intend to commit fraud, they often second-guess their actions out of fear of being caught or because they question whether the fraud aligns with their positive self-image. This ongoing internal conflict leads to uncertain and extended body movements as individuals struggle with their decision to engage in fraudulent behavior (Weinmann et al. 2022). As a result, those engaged in dishonest acts exhibit larger hand movements compared to those behaving honestly.

Given this background, we propose that the cognitive demands of fraud, as explained by SCMT and ADCAT, result in larger hand movements in those who act dishonestly compared to those who are honest. Previous research using data from human-computer interaction devices has confirmed that cognitive load affects individuals' movements outside the metaverse (Hibbeln et al. 2017; Weinmann et al. 2022) and within it (Reinhardt et al. 2019). Hence, we hypothesize that controller distance increases before and during a fraudulent act.

H1a: The activation, decision, and construction of a fraudulent act will increase the total controller distance.

H2a: The action of a fraudulent act will increase the total controller distance.

Fraud stands in contrast to the truth and may slow reaction times as individuals attempt to prevent the truth from being inadvertently revealed (Christ et al. 2009; Suchotzki et al. 2017). Additionally, committing or contemplating fraud is not only more cognitively demanding than telling the truth but also requires recalling and actively holding the truth in working memory while constructing the fraud (Walczyk et al. 2014). This increased cognitive demand and the strain on working memory during fraudulent acts can manifest in a person's actions, such as their gestures or posture (Duran et al. 2010; Vrij 2000). When working memory is overloaded, the brain has less capacity to control movements with precision, leading to uncoordinated actions. To compensate for these irregularities, individuals often slow their body movements to minimize errors and enhance accuracy (Meyer et al. 1988; Weinmann et al. 2022). In addition, slower reaction times resulting from the internal conflict of maintaining a positive self-image while coping with the fear of detection of fraud also lead to slower body movements (Christ et al. 2009; Suchotzki et al. 2017).

Therefore, we propose that the increased cognitive demands and working memory capacity, as explained by the SCMT and the ADCAT, lead to slower hand movements in dishonest individuals than those acting honestly. Previous research using data from human-computer interaction devices has confirmed that these cognitive costs and working memory demands result in slower movements in 2D spaces (Hibbeln et al. 2017; Weinmann et al. 2022) and 3D spaces (Duran et al. 2010). Hence, we propose the following hypotheses:

H1b: The activation, decision, and construction of a fraudulent act will decrease the total controller speed.

H2b: The action of a fraudulent act will decrease the total controller speed.

While the truth is generally *activated* automatically from long-term memory, the *decision* to commit fraud or to make an honest input is the most critical component of the fraudulent behavior (Walczyk et al. 2014). This decision largely depends on motivation, which often involves gaining financial or social advantages while preserving one's self-concept (Mazar et al. 2008). Another important aspect of the fraudulent process, which significantly influences cognitive resources, is the *construction* of the fraudulent act. This stage involves determining how the fraudulent act will be constructed, whether through falsification, ambiguity, exaggeration, understatement, or omission of information (Walczyk et al. 2014). However, during the *action* of fraudulent acts, individuals tend to minimize the use of cognitive resources to appear effortlessly honest (Colwell et al. 2006; Walczyk et al. 2014). A common strategy to create this impression is increasing movement, minimizing intrapersonal distraction, and alleviating anxiety (Walczyk et al. 2014). During the *activation*, *decision*, and *construction* stages of a fraudulent act, individuals are both cognitively challenged and experience greater strain on their working memory, which may result in increased movement distance (H1a and H2a). In contrast, during the *action* stage of a fraudulent act, individuals take steps to appear effortlessly honest, leading to a faster action of the fraudulent act. In summary, we propose the following hypotheses:

H3a: The total controller distance is greater when activating, deciding, and constructing a fraudulent act than when the action of a fraudulent act.

H3b: The controller speed is greater when the action of a fraudulent act than when activating, deciding, and constructing a fraudulent act.

9.3 Methodology

We employed a single-factorial experimental design (fraudulent condition vs. completely honest statement as baseline condition) to investigate the impact of fraudulent behavior on controller movements, particularly controller distance, and speed. In this study, the controller movements when participants made dishonest inputs (fraudulent condition) were compared with the controller movements when participants made honest inputs (baseline condition). The participants had the opportunity to provide dishonest input at two different places in the study (name and score inputs). While the design provided incentives for participants, it did not explicitly encourage dishonest statements. Two well-established social mechanisms, rivalry (Cadsby et al. 2016; Jacobsen et al. 2018; Kilduff et al. 2016) and social incentives (Gerlach et al. 2019; Jacobsen et al. 2018; Pascual-Ezama et al. 2013), were incorporated into the study design. The study was embedded in a virtual reality game context where participants could only achieve low scores due to intentionally unsolvable tasks, under the assumption that their performance would be displayed on a public leaderboard. The university's ethics committee approved the research.

9.3.1 Materials and Laboratory Environment

The first part of this section focuses on the materials used and the laboratory environment. The hardware used for this experiment was a Meta Quest 2 HMD with a resolution of 1832 x 1920 per eye and a refresh rate of 60 Hz and controllers. Participants used both controllers to navigate the virtual environment, and the experiment was conducted standing.

In order to avoid potential priming effects that could trigger unconscious or instinctive responses leading participants to be consistently honest (Koyuncu and Amado 2008), and to activate two social mechanisms essential for the experiment, the laboratory environment consists of two parts.

First, participants were asked to sit in the hallway on arrival at the laboratory. On the opposite wall was a poster advertising the VR game and highlighting the top three participants. Next to these top three participants was a QR code linked to a website with the full leaderboard. This poster intended to activate the two mechanisms mentioned above, rivalry and social incentives, which can lead to fraud (Cadsby et al. 2016; Jacobsen et al. 2018; Kilduff et al. 2016; Pascual-Ezama et al. 2013). Rivalry refers to a relationship between competitors characterized by increased psychological stakes of competition, where people place greater importance on outperforming specific others due to factors like repeated competition or closely-matched past contests (Jacobsen et al. 2018; Kilduff et al. 2016). Social incentives describe situations where dishonest behavior is influenced by social interactions and relationships, for example when people are more likely to engage in fraud to benefit members of their own social group or when their actions affect the payoffs of others (Jacobsen et al. 2018; Pascual-Ezama et al. 2013). By consciously or unconsciously noticing the poster, participants become aware of the implications of the VR game, e.g., "*There is a public leaderboard, and all my friends and classmates can see how well or poorly I did in the VR game*". Second, the lab itself consisted of an empty room where the participants had to put on the VR headset. Any posters or other items in the hallway or the lab that could potentially lead to priming effects and thus determine the participants' performance during the VR exposure were removed.

9.3.2 Stimulus

The stimulus for this study was the self-developed VR game “Quizmaster”. This game began with a short teaser, indicating that the game tests both the participants' skill and intellect and that they could compare their performance with that of other students. In the second scene, participants received an explanation of the game mechanics. The VR game consisted of four mini-games, each comprising four rounds. Participants were given 30 seconds for each round. Figure 29 shows the games realized in VR.

- Anagram: In the first mini-game, participants were shown 5-7 letters on a cube (one letter on one cube) and were tasked with arranging the letters to form a real word.
- Quiz: In the second mini-game, participants were presented with trick questions, and they had to input and confirm their answers in a text field.
- Find Objects: The third mini-game displayed a large bowl containing over 80 3D objects. Participants were tasked with finding and placing a specific object in a designated position.
- Place Objects: Participants were shown a shape and a series of 3D objects in the fourth mini-game. Their task was to align the 3D objects to fit into the given mold.

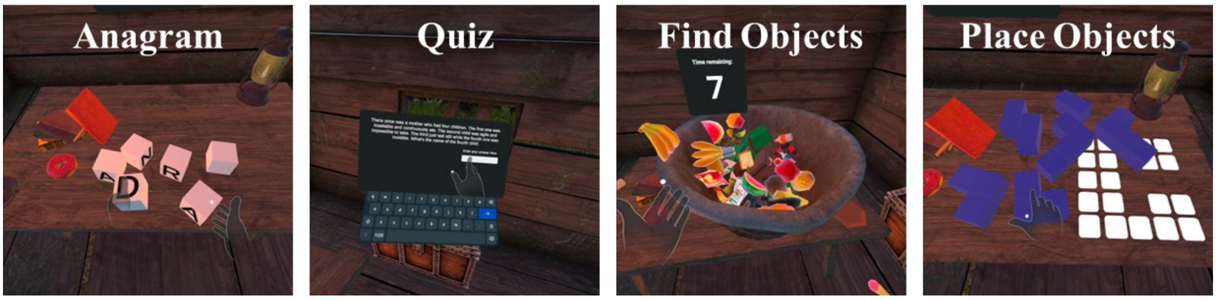

Figure 29. Overview of the developed VR-Game

9.3.3 Participants

A total of 22 participants were recruited for this experiment under the pretext of participating in a VR ergonomics and motion sickness study. The participants are joining a bachelor's-level university course offered to management and engineering students. We opted for a student sample as prior research has shown that data collected from student samples under laboratory conditions are comparably robust to those obtained in real-world experiments (Steelman et al. 2014). In addition, younger individuals represent the primary target demographic for current metaverse applications, further supporting our choice of a student sample. For participating in this experiment, students received three bonus points for the exam they had to write in this university course. Within the experiment, two participants were excluded due to incomplete movement data resulting from a technical error. The remaining 20 participants had an average age of 21.9 years (SD = 2.81). The sample consisted of 75% male and 25% female participants, with 95% being right-handed and 5% left-handed. The VR Experience of the participants was very low. For example, 11 participants stated they had no VR experience at all with an average VR experience of 1.6 (SD = 0.73).

9.3.4 Procedure

After mentioning the materials, the laboratory environment, the stimulus, and the participants, these aspects were arranged to carry out the laboratory experiment as follows. Five minutes after arriving, participants were invited to enter the experimental laboratory, where the procedure and purpose of the study were explained to them. The experimenter reiterated that the chair did not develop the VR game but was an university project. This approach also activates the two social mechanisms that may tempt individuals toward fraud. Participants are made aware that the VR game extends beyond the small context of a department or faculty and that the entire university can participate.

After explaining the procedure and the purported aim of the study and addressing all participants' questions, the participants were provided with a VR headset and controllers. They were instructed to start the "Oculus First Steps" application and go through a short tutorial (5 minutes) developed by Oculus to familiarize themselves with the general VR interactions.

Once the participants were redirected to other virtual worlds within the “Oculus First Steps” application, they were asked to close this application and start the VR game “Quizmaster.” After the VR game was launched, the experimenter informed the participants that they would be leaving the room, which they then did. The participants independently navigated and completed all the tasks presented in the VR game. After approximately 15 minutes, they were prompted within the game to remove the VR headset, signaling the end of the session. Upon removing the headset, the experimenter re-entered the room. Although participants could not perceive the physical environment through the VR headset, our pre-test revealed that the experimenter's presence made them feel they were being observed, discouraging dishonest behavior (Gerlach et al. 2019). Once the experimenter left the room, participants felt reassured that they were no longer being watched, allowing for more natural interaction and behavior within the VR game.

Finally, to preserve the appearance of a VR comfort and motion sickness study, participants were required to complete a post-survey, where the demographics as well as the VR experience was surveyed. The experiment lasted approximately 30 minutes, with participants wearing the VR headset for approximately 20 minutes. Two weeks after the end of the study, participants were fully debriefed via email about the study's true purpose, including the deception about the purpose of the study and the tracking of the controller's movements.

9.3.5 Conditions

The VR game utilized two baseline and fraudulent conditions, determined by participants' inputs and subsequent verification. The first condition involved entering a numerical response. Since all tasks in the VR game were intentionally designed to be unsolvable, resulting in an achievable score of 0, any input above 0 was classified as a fraudulent condition, while inputs of 0 served as baseline conditions. The second condition involved participants entering their name for a supposedly public leaderboard. During post-study verification, we compared the entered names with participants' actual names provided during recruitment. If participants had provided a different name, this input was classified as a fraudulent condition for analyzis. If participants had used their actual name, this served as a baseline condition.

Individuals may conceal their identities for legitimate reasons, such as protecting privacy or avoiding victimization, making identity concealment alone insufficient as an indicator of fraudulent behavior. To explicitly address this, our study employed two distinct input scenarios, usernames and performance scores, to differentiate legitimate privacy concerns from fraudulent intent. The inclusion of both score and name inputs were crucial for distinguishing between privacy-conscious behavior and identity theft. While participants might choose a pseudonym for legitimate privacy concerns in a public leaderboard, deliberately claiming an unachievable score reveals a clear intent of fraudulent behavior. By analyzing the convergence of these two conditions, we could differentiate participants who were merely protecting their privacy (different name but honest score) from those engaging in fraudulent behavior (different name and fraudulent score). For the subsequent analyzis, we therefore only used conditions if the participants made a dishonest (false) statement in both conditions or in the numbers condition only.

9.3.6 Measures

The frequency of dishonest inputs was evaluated as a manipulation check to confirm that the social mechanisms chosen to incentivize fraudulent behavior effectively led to dishonest inputs. Both the participants' inputs in the VR game and their movement data were saved in a JSON file. By comparing the baseline inputs with the actual inputs, we could analyze whether honest information was provided in the baseline conditions and whether dishonest information was given in the fraudulent conditions. Ray interactions were deactivated in the VR game we developed, as the extent of hand movements when using ray casts depends on the distance between the participants and the text input field. In the VR game, the X, Y, and Z coordinates of both the right and left controllers were recorded at 30 frames per second and stored in the JSON file. In addition to movement data, the virtual keys pressed, such as letters and numbers, were also mapped to their respective coordinates. Two specific points in time were of particular importance for the subsequent analyzis and investigation of the hypotheses outlined in the previous section:

Activation, *Decision*, *Construction*: This point in time reflects the participants' behavior as they activate the truth from long-term memory, decide on a fraudulent act, and construct the fraudulent act, corresponding to the first three stages of the ADCAT (Walczyk et al. 2014). During these stages, controller tracking begins when one of the conditions is displayed to the participants and ends when they click on the text input field to begin inputting.

Action: This point in time reflects the participants' behavior during the input of an honest or dishonest input, representing the final stage of the ADCAT (Walczyk et al. 2014). In this stage, controller tracking begins when the first letter or number is entered and ends when the ‘Next’ button is pressed to confirm the input.

Only the dominant hand, which was used for the input, was analyzed for the evaluation. Based on the movement data in X, Y, and Z, we used MATLAB to calculate the controller distance. This was done by determining the distance between consecutive points using the Euclidean distance formula and then summing them to determine the total distance travelled.

Using the calculated total distance and tracked total time, we then calculated the controller speed. The change in distance over the total time determined the average speed. We applied Z-score normalization to the movement data associated with the "*Action*" time points to ensure comparability. By rescaling the data based on the mean and standard deviation of the input lengths (either letters or numbers), we achieved consistent and comparable datasets, independent of the variation in name or numerical input lengths (Singh and Singh 2020). This approach effectively mitigates the influence of outliers and dominant features, ensuring a more robust comparison across both conditions. Figure 30 illustrates the controller's distance during a fraudulent condition (red) and a baseline condition (green) across the activation, decision, and construction stages of the fraudulent act (left side of Figure 30) and during the action stages of the fraudulent act (right side of Figure 30).

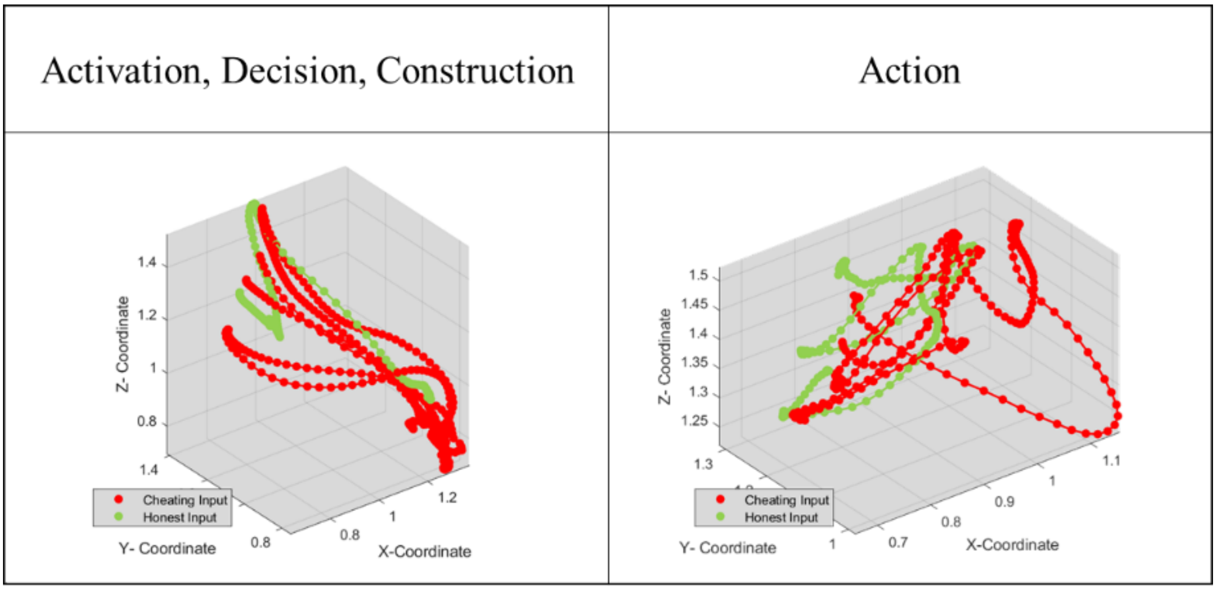

Figure 30. Example Controller Movements of a dishonest and honest input

9.4 Results

Since each of the 20 participants completed two input conditions (number input and text input), resulting in 40 possible responses overall. Five participants did not make an input in the numbers input or text input, so only 35 responses could be included in the evaluation. Overall, participants gave dishonest input in 13 out of 35 possible responses (37%), consistent with the findings of other studies investigating fraudulent behavior (Fischbacher and Föllmi-Heusi 2013; Gerlach et al. 2019). We, therefore, assume that the manipulation check and the social mechanisms we chose to incentivize participants to engage in fraudulent behavior were successful. We conducted a statistical analyzis of the controller movement data collected during our laboratory experiment to test our hypotheses. To compare the effects of nonparametric data, such as controller movement data, we performed an Aligned Rank Transform proposed by Wobbrock et al. (2011), which allowed us to use an independent samples t-test. Table 29 provides the descriptive statistics for aligned and ranked total controller movement and speed data, categorized by honest and fraud inputs and the independent samples t-test results.

Split by Stages of Fraudulent Behavior						
Statistics		Activation, Decision, Construction		Action		
		Mean	SD	Mean	SD	t-test
Distance	35	51.57	11.27	19.43	13.15	10.822*
Speed	35	29.77	19.56	41.23	19.19	-2.438*
Split by Fraudulent Behavior						
Statistics		Honest Input		Dishonest Input		
		Mean	SD	Mean	SD	Mean
Activation, Decision, Construction						
Distance		18.09	10.25	17.86	9.84	-0.067
Speed		18.32	10.22	17.46	9.87	-0.236
Action						
Distance		15.27	8.92	22.61	10.30	2.155*
Speed		20.95	9.37	13	9.28	-2.364*
*p<0.05						
SD = standard derivation						

Table 29. Descriptive statistics of the study and results of the independent samples t-test

The comparison of controller movement data between honest and dishonest inputs during the *activation*, *decision*, and *construction* stages of a fraudulent act shows no significant difference in the total controller distance (*H1a*) or controller speed (*H1b*). Additionally, the descriptive statistics do not indicate any clear trends. As a result, we conclude that both *H1a* and *H1b* are not supported.

In contrast, the comparison of controller movement data during the *action* stage of a fraudulent act reveals that the total controller distance is significantly greater for dishonest inputs than for honest ones (*H2a*). Similarly, the results indicate that controller speed is significantly slower for dishonest inputs compared to honest inputs during this stage (*H2b*). Therefore, we conclude that both *H2a* and *H2b* are supported.

Finally, the comparison between the *activation*, *decision*, and *construction* stages and the *action* stage of a fraudulent act shows that the total controller distance is significantly greater in the first three stages than in the *action* stage. Likewise, the results indicate that controller speed is significantly slower in the first three stages than in the *action* stage. Therefore, we conclude that both *H3a* and *H3b* are supported. We also analyzed the covariates and found no significant differences in VR experience on any of the dependent variables in any phases of a fraudulent act.

9.5 Discussion

Our findings have the potential to enhance security in virtual worlds like the metaverse and aid in the early detection of identity theft by shedding light on unknown aspects of human motor control in the metaverse. We assessed the effects of fraudulent behavior on participants' controller movements in a laboratory experiment using a VR game we developed. We observed that during the execution of fraudulent behavior (i.e., the *action* stage), individuals moved their controllers over greater distances and at slower speeds. Additionally, our results indicate that controller movements were greater and slower during the *activation*, *decision*, and *construction* stages of a fraudulent act compared to the *action* stage. However, within these earlier stages, we found no significant differences in controller distance and speed between honest and dishonest inputs. Our findings offer multifaceted contributions, both theoretical and practical, such as to the affective computing literature and the design and analyzis of future metaverse applications. In the following section, we delve into the theoretical and practical implications, the limitations of our study, and suggestions for future research.

9.5.1 Theoretical and Practical Implications

First, our research responds to the call of Hibbeln et al. (2017), who link mouse movements to negative emotions in their study and recommend extending the analyzis to human movements in a three-dimensional environment, as it provides more sophisticated and nuanced data. Therefore, our results contribute to understanding how cognitive dynamics along the four stages of deceptive behavior affect human behavior (Walczyk et al. 2014). Theory suggests that fraud needs to be constructed, whereas honest behavior is merely retrieved from memory, meaning that individuals who act completely honestly experience the least cognitive demand as they only go through the *activation* stage (Walczyk et al. 2003; Walczyk et al. 2014). In our study, we did not find statistically significant differences between honest and dishonest inputs in the activation, decision, and construction stages (*H1a* and *H1b*). One possible reason could be that participants thought about committing fraud and may have already formulated a fraudulent input but ultimately decided to make an honest input. This would mean that honest individuals also went through all three stages of the fraudulent process, which could have led to a similar cognitive demand. Therefore, we argue that although psychology proposes reaction time in the early stages as a suitable method for detecting fraudulent behavior (Suchotzki et al. 2017), these stages do not seem suitable for identifying fraudulent behavior based on the speed and distance of controller movements.

Second, although numerous HCI studies have investigated the effects of various human behaviors on motor control in recent years (Duran et al. 2010; Gordon et al. 2021; Henrikson et al. 2020; Liebers et al. 2024; Lustig et al. 2023; Reinhardt et al. 2019; Wilf et al. 2024), to the best of our knowledge, we are the first study to theoretically explain and validate how fraudulent behavior in the form of identity theft affects the controller movements in the context of the metaverse along the different stages of fraud. We extend the SCMT and the ADCAT to explain how the increasing cognitive dynamics caused by the motivational dilemma during an identity theft affect individuals' controller distance before and during the fraud. This motivational dilemma leads individuals to question their decisions and actions, resulting in greater controller distance during fraud (Freeman et al. 2011; Wojnowicz et al. 2009). Furthermore, we extend the SCMT and ADCAT to explain how the increasing cognitive dynamics induced by the motivational dilemma during identity theft affect controller speed. As the fraud contrasts with the truth, the dilemma causes response inhibitions to prevent the truth from being accidentally revealed. This is reflected in slower controller speed during the fraud (Christ et al. 2009; Suchotzki et al. 2017).

Third, we provide metaverse researchers with an unobtrusive, scalable, and cost-effective method for detecting and evaluating fraudulent intent, such as metaverse identity theft in a natural setting. Our methodology demonstrates strong ecological validity as it relies solely on analyzing movement data that VR systems already collect through standard controllers, requiring no additional hardware or explicit user actions. This unobtrusiveness is crucial for real-world applications, as users remain unaware of the movement monitoring - just as in our study - allowing for natural behavior patterns. Unlike other fraud detection methods that might alter user behavior through visible security measures, our approach can be implemented without disturbing or becoming aware of metaverse users during their interactions, thereby preserving users' desire for a degree of anonymity in the metaverse (Sharma et al. 2024; Vernaza et al. 2012). Practitioners can incorporate this method into future metaverse applications, and only when fraudulent behavior is suspected, such as a fraudster attempting to impersonate someone else to obtain sensitive data, could further measures, such as personal identity verification, be initiated (Duan et al. 2021).

Fourth, we contribute to the literature on affective computing by introducing the tracking of controller movements as a method for identifying and evaluating fraudulent behavior. Affective computing is a research field focused on developing systems and devices capable of recognizing, interpreting, and responding to human emotions (Picard 1997). In HCI research, various technologies have been explored for emotion detection, such as speech analyzis (Schuller 2018), monitoring heartbeat (Zhao et al. 2018) and analyzing typing behavior on a keyboard (Epp et al. 2011). We propose that tracking controller movements in the metaverse is particularly effective, as most metaverse users already rely on VR controllers for interaction, eliminating the need for additional, expensive sensors like those used for monitoring blood pressure (Kettner et al. 2017). Moreover, tracking controller movements offers a robust method to counter the growing threat of deep fakes (Bhardwaj and Kaushik 2023; Otoum et al. 2024;

Tariq et al. 2023). While physical identification through manipulated live videos can be unreliable, analyzing the movements of metaverse users provides a clearer understanding of their true identity. Fraudulent behavior and its increased cognitive demand and associated working memory demands often manifest in human motor actions (Duran et al. 2010; Vrij 2000). These human motor signals are generally difficult to manipulate, making them a reliable source for detecting fraud.

Finally, we demonstrate that cognitive dynamics triggered by emotions, such as the motivational dilemma of fraud, influence an individual's controller movements (Mazar et al. 2008). This method could also be effective in analyzing controller movements influenced by different emotions (Hibbeln et al. 2017), potentially improving key design and usability factors, such as in the design of VR systems. For instance, motion sickness could be mitigated by using controller movements to precisely track when and under what circumstances motion sickness occurs and identifying the design elements contributing to a stronger motion sickness. Moreover, when combined with other effective approaches like eye-tracking or head movements, our proposed method offers a validated opportunity for multi-method research. This combination can provide a more comprehensive understanding of user behavior (Gordon et al. 2021; Henrikson et al. 2020; Marín-Morales et al. 2023).

9.5.2 Limitations and Future Research

Although our laboratory study adhered to established guidelines, like any research, there are potential limitations that could serve as starting points for further research. First, even though we employed two well-established social mechanisms as incentives for fraud (Cadsby et al. 2016; Gerlach et al. 2019; Jacobsen et al. 2018; Kilduff et al. 2016; Pascual-Ezama et al. 2013), it may be possible that participants did not perceive these mechanisms as the primary reason for their dishonest inputs. Other factors may have influenced their fraudulent behavior. One possible alternative could be that cognitive rather than social mechanisms triggered the fraud (Jacobsen et al. 2018). Cognitive mechanisms are often activated when individuals are mentally fatigued or exhausted. This fatigue can stem from physical strain, especially during tasks requiring high levels of concentration and self-control. As exhaustion increases, individuals are more likely to rely on automatic, immediate decision-making patterns (Jacobsen et al. 2018). Research shows that when self-control is impaired, individuals are significantly more likely to engage in fraudulent behavior (Mead et al. 2009). Since a VR environment is unfamiliar for most participants, it may have contributed to higher fatigue levels. If cognitive mechanisms were the primary driver behind the fraudulent behavior, this could affect motor control differently, potentially leading to different outcomes regarding controller distance and speed. To mitigate this issue, future research could incorporate financial incentive mechanisms alongside established psychological methods when designing future studies (Mazar et al. 2008). This approach would offer a strong incentive for fraud while remaining well-controlled (Gerlach et al. 2019). Furthermore, to identify the sources of cognitive load, such as task-specific demands or general unfamiliarity with the metaverse environment, future research could incorporate psychophysiological measurement techniques, including heart rate monitoring, skin conductance, or neural activity assessments. These methods would provide objective and robust evidence of cognitive load throughout the entire experiment (Nadj et al. 2020).

Second, the baseline condition we chose, in which participants' honest input serves as a baseline condition, is an appropriate baseline condition for our study design. However, another view in the psychology literature is that individuals who behave dishonestly generally behave differently from completely honest individuals (Suchotzki et al. 2017). This underscores the importance of an appropriate baseline condition for developing valid methods for detecting fraudulent input. Our study does not distinguish whether the baseline condition originates from the same individuals acting in the fraudulent condition. Thus, we may be comparing two conditions of individuals who exhibit fundamentally different behaviors, i.e., the movement patterns identified may not be the result of fraudulent intentions but rather general behavioral differences. For future research, comparing the baseline condition with the same participants acting in a fraudulent condition would be valuable. Such a comparison would allow for investigating dishonest individuals' behavior in honest and fraudulent conditions. This approach could lead to more valid fraud detection methods and increase the significance of findings.

Third, our study focused solely on two aspects of controller movements, speed and distance, which might not necessarily indicate fraudulent behavior, as they could also result from unrelated factors such as distraction or task difficulty. Therefore future research could build and analyze clusters to analyze more nuanced behavioral patterns, such as deviations from the shortest movement paths, changes in movement direction, click intensity, or typing rhythm. Incorporating these clusters could provide deeper insights and potentially enhance the accuracy and robustness of fraud detection models.

Finally, this study was conducted with a relatively small sample size (n=22) with a relatively low but realistic number of fraudulent conditions (n = 13) (Fischbacher and Föllmi-Heusi 2013; Gerlach et al. 2019). This implies that some significant findings may have been missed, highlighting the need for a cautious interpretation of non-significant results. Future research using a larger sample size is needed to improve the validity of the results.

Part C

10 Summary of the Results

Through the six publications embedded in this thesis, we addressed the key challenges and research questions that guided our research. The overarching goal of this thesis was twofold. First, it sought to advance design knowledge for AR interaction techniques and for AR authoring tools, particularly within an industrial application domain. The objective was to enable citizen developers to independently and effectively create immersive content while strengthening their intention to share domain knowledge with peers in form of virtual artifacts within the industrial metaverse. Second, the thesis aimed to understand how psychological states, using fraudulent behavior as an example, affect the human motor control of metaverse users and how these effects can be reliably predicted through their movements in order to derive design suggestions for future metaverse authoring tools based on user behavior experienced during interaction in immersive environments.

The findings for each research question are summarized below, followed by a discussion of the theoretical and practical implications of this research in the subsequent sections.

RQ1: *How does different AR interaction techniques on handheld devices affect performance, workload, and satisfaction when creating AR instructions?*

Since the manual anchoring and positioning of immersive content in the physical environment is a crucial component of AR authoring tools, we conducted an experimental comparison of three different AR interaction techniques for tasks related to the development of AR instructions (P1). This study highlighted the importance of evaluating AR authoring tools within the specific context of their intended application domain, as the findings differ significantly from evaluations conducted in generic contexts.

We analyzed the performance differences between the three interaction techniques using metrics such as threshold time, distance error, rotation error, and path error. Beyond performance, we also assessed differences in workload and user satisfaction among the interaction techniques. Additionally, a SWOT analyzis for each interaction technique was conducted, identifying its strengths, weaknesses, risks, and opportunities.

Our qualitative and quantitative findings resulted in eight design guidelines to support the development of future AR authoring tools and the design of AR instructions: These are as follows: (i) When focusing on time when creating the AR application, implement a device-based interaction. (ii) When focusing on precision when creating the AR application, implement a gizmo-based interaction. (iii) When creating an AR application with only 3DOF manipulation (i.e., 2DOF translation and 1DOF rotation), implement a plane-based interaction. (iv) When creating an AR application with many occluded objects, implement a gizmo-based interaction. (v) When creating an AR application over a large area, implement a device-based interaction. (vi) When creating an AR application with many animations, implement a device-based interaction. (vii) Avoid using 2D objects anchored to the physical environment in AR instructions. (viii) Avoid using occluded interactions in AR instructions.

RQ2: *How can an AR interaction technique be designed to improve transparent interaction and representational fidelity when placing AR content?*

To understand how AR interaction techniques can be designed to enable citizen developers to effectively create AR instructions in the context of the industrial metaverse, we conducted a design science research project (P2). This project has led to the development of two theoretically grounded design principles that provide prescriptive knowledge for future AR interaction techniques in this specific application domain: DP1: A natural, consistent, and single-handed AR interaction should be provided with additional guidance to help them gain new capabilities; DP2: The AR interaction should allow citizen developers to create dynamic and static AR content while supporting them in identifying the location of the AR content in the physical environment.

To evaluate the validity of the two design principles, we implemented them in a software artifact in form of an AR interaction technique, a device-based interaction technique. Our findings have shown that the implementation of our two design principles increases transparent interaction and representational fidelity, thereby facilitating the effective creation of AR instructions.

RQ3: *How can an AR authoring tool be designed to enable citizen developers from the industrial metaverse to share their domain knowledge in the industrial metaverse while increasing their self-efficacy and outcome expectations?*

To understand how to strengthen citizen developers' intentions to share their domain knowledge with their peers in form of virtual artifacts within the industrial metaverse, while enablíng them to do so, we conducted two laboratory experiments as part of a comprehensive design science project (P3&P5). These experiments led to the validation of the two theoretically grounded design principles that provide prescriptive knowledge for the design of future AR authoring tools: DP1: The compartmentalization of the AR development process; DP2: The use of content specifically tailored to the meta-design space.

To ensure reproducibility and provide actionable guidance for practitioners, we translated these design principles into six design features: DF1: Use of a 2D process editor; DF2: Use of a 3D development environment; DF3: Provision of process navigation; DF4: Use of a 2D content library; DF5: Use of a 3D content library; DF6: Provision of a media library.

RQ4: *What are the drivers of citizen developers' self-efficacy and outcome expectations when creating and using metaverse applications for the industrial metaverse?*

To understand user engagement when citizen developers share their domain knowledge in form of virtual artifacts in the industrial metaverse, we conducted a case study involving two industrial organizations (P4&P5) as part of an extensive design science research project. The study revealed clear differences in the sources of self-efficacy between the creation and usage phases of immersive content in the industrial metaverse.

In the creation phase, citizen developers' engagement is primarily driven by two sources of self-efficacy. The strongest source is vicarious experience, where citizen developers continuously evaluate how the immersive content should be designed to meet the needs of their peers. The second source is enactive mastery experience, where citizen developers assess their own skills and ability to successfully create immersive content using the AR authoring tool.

In the usage phase, however, engagement is driven by different sources of self-efficacy. The strongest source is verbal persuasion, where users evaluate whether the immersive content provides sufficient support to complete a task effectively. The second source is outcome expectations, where users assess the potential benefits of the immersive content for their work.

By emphasizing the fundamentally different forms of user engagement in the creation and usage phases of immersive content, the study underscores the importance of clearly separating these two phases in future AR authoring tools. Based on these findings, we propose the third theoretically grounded design principle: DP3: The separation of the creation and usage processes in Metaverse applications. We translated this design principle into two additional design features: DF7: Implementation of a viewer mode; DF8: Use of a design space manager.

The software artifact we developed embodies an innovative solution to a known problem. It allows researchers to evaluate design principles and enables practitioners to independently create immersive content, such as AR instructions, to support employees in task completion and process-compliant work within their organizations. The artifact comprises three key components: (i) A 3D content environment (ii) A 2D process editor, and (iii) A viewer mode for previewing and utilizing created content.

Our nascent design theory offers an abstract understanding of the principles and constructs underlying the design of AR authoring tools. It serves as a blueprint for the development of additional AR authoring tools for the industrial metaverse. The theory encompasses the purpose and scope, core constructs, principles of form and function, artifact mutability, testable propositions, justification knowledge, implementation principles, and expository instantiations.

RQ5: *Does fraud action, activation, decision, and construction in the metaverse affect the controller distance and speed?*

To understand how users' physical states in the metaverse influence their human motor control, we conducted a controlled single-factor laboratory study in a VR environment (P6). The study reveals that individuals engaging in dishonest behavior, such as pretending to be someone else, exhibit controller movement patterns characterized by greater distances traveled and slower speeds. Importantly, our findings demonstrate that the phase of the actual fraudulent act is more effective for predicting fraudulent behavior compared to the earlier phases of activation, decision-making, and construction of the fraudulent act. Furthermore, the results indicate that the activation, decision, and construction phases are more cognitively demanding for metaverse users than the action of the fraudulent act itself. This heightened cognitive load during the earlier phases is reflected in increased body movement and, therefore, in larger controller movements. In contrast, during the action of the fraudulent act, users exhibit faster controller movements as they attempt to maintain the fraud and create the appearance of honesty.

The following Table 30 gives an overview of the key findings of this thesis.

P	RQ	Key Findings
P1	RQ1	• Necessity to evaluate AR authoring tools that require little to no programming skills in the intended application domain. • Experimental comparison of three AR interaction techniques for tasks related to the development of AR instructions. - Performance: Threshold Time, Distance Error, Rotation Error, Path Error - Workload and Satisfaction - Strengths, Weaknesses, Risks, and Opportunities • Eight design guidelines to support the development of AR authoring tools and the design of AR instructions. (i) When focusing on time when creating the AR application, implement a device-based interaction. (ii) When focusing on precision when creating the AR application, implement a gizmo-based interaction. (iii) When creating an AR application with only 3DOF manipulation (i.e., 2 DOF translation and 1DOF rotation), implement a plane-based interaction. (iv) When creating an AR application with many occluded objects, implement a gizmo-based interaction.

		(v) When creating an AR application over a large area, implement a device-based interaction. (vi) When creating an AR application with many animations, implement a device-based interaction. (vii) Avoid using 2D objects anchored to the physical environment in AR instructions. (viii) Avoid using occluded interactions in AR instructions.
P2	RQ2	• Prescriptive design knowledge of future AR interaction techniques for this specific application domain through two theoretically grounded design principles. - DP1: A natural, consistent, and single-handed AR interaction should be provided with additional guidance to help them gain new capabilities. - DP2: To create dynamic and static AR content while supporting them in identifying the location of the AR content in the physical environment. • The device-based interaction techniques enhance the transparent interaction and representational fidelity of citizen developers while creating AR instructions. • The device-based interaction techniques enhance the effective creation of AR instructions.
P3 P4 P5	RQ3 RQ4	• Different sources of self-efficacy during the creation phase of immersive content in the industrial metaverse. - Vicarious Experience: Creating immersive content success is based on other parties' use. - Enactive Mastery Experience: Belief in the ability to create immersive content with the help of the AR authoring tool. • Different sources of self-efficacy during the usage phase of immersive content in the industrial metaverse. - Verbal Persuasion: Belief in the quality of the immersive content to work in a process-compliant manner. - Outcome Expectations: Immersive content success is based on economic/social advantages. • The different sources of self-efficacy show the need to separate the two phases in the design of future AR authoring tools. • Prescriptive design knowledge of future AR authoring tools in the industrial metaverse through three theoretically grounded design principles. - DP1: The division of the AR development process - DP2: The use of content tailored to the meta-design space - DP3: The separation of the creation and development process from metaverse applications • Ensure reproducibility and actionable guidelines through eight design features. - DF1: Use a 2D process editor - DF2: Use a 3D development environment - DF3: Use process navigation - DF4: Use a 2D content library - DF5: Use a 3D content library - DF6: Use a media library - DF7: Use a viewer mode - DF8: Use a design space manager. • A software artifact that enables citizen developers to independently create AR instructions within the industrial metaverse consisting of three software components. (i) 3D content environment (ii) 2D process editor (iii) Viewer mode
P6	RQ5	• During a fraudulent act, metaverse users move over a greater distance at a slower speed (controller distance and speed).

		• The fraudulent act phase is more robust for detecting fraud by human-motor control than the activation, decision and construction phases of fraud. • The activation, decision and construction phases of fraud are more cognitively demanding than the fraudulent action, resulting in larger controller movements of the metaverse user. • Trying to appear honest in order to maintain the fraud results in faster controller movements of the metaverse user in the action of the fraudulent act than in the activation, decision and construction phases of the fraudulent act.

Table 30. Overview of the Key findings

11 Discussion

Drawing on the findings summarized from the six publications included in this thesis, we outline key discussion topics relevant to the current state of research in the following sections.

Effective Creation of Metaverse Content with Authoring Tools. While individual aspects of AR authoring tools have been well-researched in recent years, such as which AR interaction techniques allow citizen developers to place immersive content most quickly and accurately (Grandi et al. 2018; Marzo et al. 2014). Other research focuses on how these tools should be designed to enable citizen developers to create immersive content for specific application domains independently (Bräker et al. 2023a; Damarowsky and Kühnel 2022; Laviola et al. 2022; Lavric et al. 2022; MacIntyre et al. 2005; Rajaram and Nebeling 2022; Zhu et al. 2015). At the same time, design-oriented studies are investigating the role of transparent interaction, a dimension of the effective use theory, according to Burton-Jones and Grange (2013) which is critically important for the design of information systems to increase the effectiveness of their use (Ruoff et al. 2023).

Previous studies have traditionally evaluated AR interaction technologies using general tasks (Bergström et al. 2021). However, our analyzis of 60 AR authoring tools in our first study (P1) shows that these tools are rarely developed for general applications but rather for specific application domains (Nebeling and Speicher 2018). Therefore, we propose to evaluate the AR interaction techniques in AR authoring tools designed for the industrial metaverse using domain-specific threshold tasks.

Our first study (P1) provides some initial evidence in support of this proposal. First, we observed performance differences compared to existing studies that do not consider specific application contexts. Second, ignoring the application domain risks overlooking relevant metrics for the intended application domain. For example, our study is consistent with the literature that device-based AR interaction techniques allow significantly faster placement of immersive content. However, contrary to previous literature, we found no evidence that touch-based interactions significantly improve placement accuracy (regarding distance and rotation errors) (Grandi et al. 2018; Marzo et al. 2014; Mossel et al. 2013). Furthermore, the traditional evaluation of AR interaction techniques often focuses solely on the final position of the content. However, in our specific application domain, the creation of AR instructions in the industrial metaverse, as well as dynamic content such as animations, is central (Gattullo et al. 2020; Hoffmann et al. 2021). This further highlights the need for evaluations of the AR interaction techniques that are grounded in the specific application domain.

Our chosen application domain is an AR process guidance system in the form of AR instructions, which are used in the service sector for repair, assembly, or maintenance tasks to support employees in the process-compliant execution of tasks (Klinker et al. 2018; Kortekamp et al. 2019; Laviola et al. 2022; Porter and Heppelmann 2017). We choose to instantiate our initial design principles in a device-based AR interaction technique within our AR authoring tool for three main reasons (P2). First, natural, consistent, and one-handed interaction (initial DP1), along with the ability to create both static and dynamic metaverse content (initial DP2), empowers citizen developers to independently create metaverse content while enhancing transparent interaction and representational fidelity. These factors contribute to more effective use of the authoring tool, which is a central factor in the design of information systems (Burton-Jones and Grange 2013; Ruoff et al. 2023). Second, within the chosen application domain, the service sector, greater interaction efficiency, such as faster interaction, plays a crucial role in the adoption of new technologies in this sector (Allmendinger and Lombreglia 2005; Kundu and Ramdas 2022). Third, device-based interaction allows faster and more natural manipulation by enabling simultaneous control of all rotational and translational axes. This capability is particularly important for creating animations in AR instructions (Gattullo et al. 2020; Goh et al. 2019; Hoffmann et al. 2021; Konopka et al. 2022; Tanikawa et al. 2015).

Fostering the Self-Efficacy in the Creation and Use of Metaverse Content with Authoring Tools. For industrial organizations to fully realize the potential of the industrial metaverse beyond the passive consumption of immersive content (Schöbel et al. 2023; Seidel et al. 2022), it is essential to both enable citizen developers to effectively create metaverse content and strengthen their intention to do so. This content can then be shared and used by peers, representing a form of knowledge sharing (Funk et al. 2017; Zallio and Clarkson 2022), an aspect emphasized in IS research through the study of self-efficacy in virtual communities (Chiu et al. 2006; Hsu et al. 2007). This thesis contributes additional prescriptive design knowledge grounded in Social Cognitive Theory (SCT) through three studies (P3, P4, and P5), which examine how citizen developers use an authoring tool to create metaverse content and how this content is subsequently used by their peers. SCT provides a robust framework for explaining when and why users share knowledge in virtual environments (Chiu et al. 2006). By combining insights from Effective Use Theory and SCT, this thesis aims to offer a holistic perspective on the design of future authoring tools.

The first design principle we propose for the design of future AR authoring tools in the industrial metaverse aims to foster the self-efficacy of citizen developers in creating metaverse content by separating the AR development process into a 2D process editor and a 3D content environment. We empirically validate this design principle in the first laboratory experiment (P3&P5). This design principle is informed by the self-regulatory learning process (Zimmerman 1989), which suggests that citizen developers should first engage with familiar tasks before progressing to unknown and more complex tasks. This self-regulatory learning process enhances the citizen developers' active mastery experience (Bandura 1997). Consistent with SCT literature, our findings demonstrate that incorporating this self-regulatory learning process into an AR authoring tool significantly improves the internal self-efficacy of citizen developers in the industrial metaverse (Tabernero and Wood 1999).

The first design principle we propose for the design of future AR authoring tools in the industrial metaverse also aims to foster the self-efficacy of citizen developers in the creation of metaverse content by using the content tailored for the meta-design space (e.g. for the creation of AR instructions). We empirically validate this design principle in the second laboratory experiment (P3&P5). This design principle is based on the outcome expectations of citizen developers when creating immersive content (Chiu et al. 2006; Hsu et al. 2007). Our findings show that this design principle significantly improves the performance of AR instruction creation. However, it did not have a significant impact on either internal or external self-efficacy. The descriptive statistics however suggest that, contrary to our hypothesis, tailoring content to the meta-design space may have a negative impact on internal self-efficacy. While the reasons for this may be complex, one possibility could be the increased cognitive load caused by the additional features of the AR authoring tool, a factor that is closely related to self-efficacy (Bandura 1986; Sweller 1988).

Neither of these first two design principles significantly influenced the external self-efficacy of citizen developers, which is primarily supported by system-provided assistance (Thatcher et al. 2008). Our findings suggest that tutorials and onboarding elements in AR authoring tools could address this gap. We were able to confirm this proposition in our additional case study, where citizen developers reported that the experimenter's initial introduction to the AR authoring tool and its key features was a key source of self-efficacy for independently creating immersive content. Therefore, tutorials and onboarding features within AR authoring tools can bolster developers' confidence in achieving successful outcomes (Gangadharbatla 2008) while mitigating challenges posed by the complexity of the tools and the spatial knowledge required (Ashtari et al. 2020; Krauß et al. 2021; Nebeling and Speicher 2018).

The third design principle we propose for the design of future AR authoring tools in the industrial metaverse is to foster self-efficacy, both for citizen developers during the creation of metaverse content and for users during the use of this content. This is achieved by clearly separating the processes of metaverse content creation and use (i.e., receiving guidance to perform their work in a process-compliant manner, such as following an AR instruction). We validate this design principle through a case study conducted with two industrial organizations (P4&P5). This design principle is consistent with the different sources of self-efficacy experienced by citizen developers in these different phases (Bandura 1997). During the creation phase, the strongest source of self-efficacy is vicarious experience, as citizen developers consider how to design immersive content to ensure effective use by their peers in the industrial metaverse. Our findings suggest that the accessibility of content across different interfaces is a critical consideration for developers at this stage (Schöbel and Leimeister 2023; Seidel et al. 2022). The separation of these phases is consistent with the metaverse design principles proposed by Nickerson et al. (2022b), as it supports the transformability of immersive content across different interfaces. It also allows for seamless navigation between meta-design spaces, further enhancing the usability and functionality of AR authoring tools for industrial metaverse applications (Nickerson et al. 2022b; Seidel et al. 2022).

Analyze the Use of the Authoring Tools Based on Detecting Human Behavior Through Human-Motor Control. The ability to recognize and analyze human behavioral patterns and psychological states in the metaverse extends the utility of AR authoring tools beyond the mere creation of immersive content. While the impact of human behavior and emotions on human motor control has been increasingly studied in the HCI and IS communities (Duran et al. 2010; Gordon et al. 2021; Henrikson et al. 2020; Hibbeln et al. 2017; Jenkins et al. 2021; Liebers et al. 2024; Lustig et al. 2023; Reinhardt et al. 2019; Weinmann et al. 2022; Wilf et al. 2024), our study (P6) addresses Hibbeln et al. (2017) call to extend these analyzes to three-dimensional environments. As these environments could provide more sophisticated and nuanced data for understanding user behavior with HCI input devices.

Human-motor control data, captured, for example, via VR controllers or other relevant HCI input devices that are relevant to entering and interacting in the industrial metaverse (Dwivedi et al. 2022; Schöbel et al. 2023; Xi et al. 2023), can provide more detailed insights into how users interact within virtual and physical environments. With our study, we contribute to the understanding of how the emerging cognitive dynamics in different psychological states influence human movements by theoretically explaining and empirically validating how fraudulent intentions influence the controller movements of metaverse users. Although the identity of avatars plays a rather minor role in the industrial metaverse (Oppermann et al. 2023; Siyaev and Jo 2021; Yang et al. 2022), fraud motivated by personal benefit (Mazar et al. 2008) remains a serious problem even in this industrial context. Fraudulent acts, such as falsifying task completion, can have severe consequences. A devastating example is the deliberate misassembly of a concrete slab on a highway by a service technician, which ultimately led to a fatal accident (Süddeutsche Zeitung 2020).

According to theory, fraud must be first constructed, requiring higher cognitive demands than honest behavior, which involves only retrieving information from working memory. This means individuals acting honestly experience the lowest cognitive demands, as they only go through the activation phase (Walczyk et al. 2003; Walczyk et al. 2014). With our study, we were able to empirically validate this assumption, showing that individuals who act completely honestly in the action phase move faster over a shorter distance. However, we found no statistically significant difference in the controller movements of users during the activation, decision, and construction phases of fraud. This could be explained by individuals contemplating fraud and constructing it mentally but ultimately deciding to act honestly, resulting in cognitive demands similar to those of committing fraud. One possible explanation for this could be that people have thought about committing fraud and possibly even constructed it but then decided to act honestly at the last second. This would mean that they have gone through all three phases of fraud, which would result in similar cognitive demands as individuals acting fraudulent. Based on these findings, we argue that while theory suggests reaction time in the early stages as a method for detecting fraudulent behavior (Suchotzki et al. 2017), it may be insufficient when relying solely on speed and distance metrics of controller movements.

Nevertheless, the findings of our study, which show clear patterns in controller movements during the action of fraudulent behavior, may be of crucial importance for industrial organizations. These patterns, rooted in cognitive dissonance and self-concept maintenance, could form the basis for detecting behavioral anomalies (Mazar et al. 2008; Walczyk et al. 2014). In safety-critical systems such as infrastructure assembly or maintenance, early detection of fraud could prevent catastrophic outcomes like the example mentioned. Leveraging these insights, industrial organizations can enhance security protocols and maintain both safety and operational integrity in the metaverse.

Our findings also open up a wide range of potential applications for industrial organizations. Controller movement data could be used to detect cognitive strain or stress in employees, providing real-time metrics to evaluate task complexity and employee well-being (Bibbo et al. 2019; Koldijk et al. 2018). This could enable the creation of adaptive work environments that respond to employees' needs (Michalos et al. 2018) and support training programs with targeted measures to improve skills and reduce fatigue (Dobkin 2017).

Furthermore, our non-invasive method for assessing and analyzing psychological states within immersive systems contributes a new approach to design science research (Hevner et al. 2004; Hibbeln et al. 2017). Traditional methods, such as questionnaires or psychophysiological devices, often compromise the ecological validity of real-time interactions. By monitoring human motor control data, our approach allows researchers to infer behavioral changes with high temporal precision while preserving the user experience. This addresses Peffers et al. (2012) call for real-world evaluation, enabling artifact assessments in naturalistic environments. Thus, our research contributes to realizing the potential of the industrial metaverse while setting new standards for design science research and practice in HCI and IS.

12 Implications

In the following sections, we outline the implications of this thesis for both theory and practice. Based on our Design Science Research approach, we provide prescriptive design knowledge for future metaverse authoring tools, along with comprehensive theoretical insights that have practical relevance, thus helping to bridge the gap between research and implementation.

12.1 Implications for Theory

12.1.1 Industrial Metaverse

First, in this thesis, we contribute to the conceptual understanding of the industrial metaverse as a socio-technical system that uniquely integrates virtual and physical environments (P1-P5). We define the industrial metaverse as immersive meta-design spaces specifically tailored to industrial applications and virtual processes, enabling engineers to simulate, manage, and optimize workflows to enhance physical value creation. Unlike other metaverse realms (enterprise and consumer metaverse), it emphasizes measurable industrial value creation through high-fidelity simulations and fused environments (Klöß et al. 2023; Yang et al. 2022). These environments enable the seamless transformation of virtual artifacts into physical processes and vice versa (Seidel et al. 2022), raising new questions for IS research on artifact user interface design, social computing, or the nesting of interconnected meta-ecosystems. It highlights the need for a sectoral perspective to address the specific requirements of industrial applications, such as the interplay between virtual content and physical machines (Dwivedi et al. 2022; Siyaev and Jo 2021). These findings provide a basis for exploring how the industrial metaverse can inform broader IS research and drive digital innovation in industrial contexts.

Second, this thesis contributes to the SCT literature by contextualizing SCT within the industrial metaverse (P3-P5). It advances the understanding of how to design AR authoring tools that foster both the self-efficacy of the citizen developers to create virtual objects, which can then be transformed back into physical artifacts (Seidel et al. 2022) and the self-efficacy of users to consume the created metaverse content. This contextualization is achieved in several ways: To date, SCT research has primarily focused on screen-based interfaces (Chiu et al. 2006; Compeau and Higgins 1995; Hsu et al. 2007; Hsu and Chiu 2004). According to Bandura (1997), the strongest source of self-efficacy is enactive mastery experience, driven by repeated successful task completion. However, none of the participants in our case study from the third and fourth publications deemed this source as highly relevant. Instead, 66% of citizen developers emphasized that the creation of AR instructions relies on the successful use of those instructions by their peers in the industrial metaverse. This highlights another source of self-efficacy:

vicarious experience, where individuals gain confidence by observing others with similar abilities perform tasks successfully (Bandura 1997). This source of self-efficacy appears particularly important in the industrial metaverse, potentially due to the increased immersion provided by AR interfaces (Milgram and Kishino 1994). Beyond the spatial knowledge required by increased immersion (Nebeling and Speicher 2018), citizen developers were able to anticipate how their created instructions would be utilized by their peers in the industrial metaverse. This belief in successfully executing the behaviors needed to create and apply metaverse content extends beyond basic computer, application, and internet skills.

12.1.2 Nascent Design Theory for Authoring Tools in the Industrial Metaverse

Third, according to Gregor and Hevner (2013) DSR knowledge contribution framework, our nascent design theory, developed through publications P1-P5 in this thesis, contributes by providing a novel solution to a known problem. While the potential of AR in industrial contexts has been well-researched (Choi et al. 2022; Porter and Heppelmann 2017; Serván et al. 2011), large-scale implementation of AR by industrial organizations remains limited, with many AR applications failing to progress beyond the prototype stage (Cohen et al. 2018). With our case studies in publications P4 and P5, we were able to demonstrate, in line with the literature, that the complexity of creating immersive content is a significant factor influencing AR adoption (Ashtari et al. 2020; Azuma 2016; Krauß et al. 2021; Nebeling and Speicher 2018). Following the guidelines proposed by Jones and Gregor (2007), to develop our nascent design theory, we highlight that focusing on self-efficacy in the design of AR authoring tools can help industrial organizations exploit the potential of AR. Strengthening citizen developers' intentions and empowering them to create AR content independently for the industrial metaverse could enable a broader engagement and utilization of AR technologies. Similar to software development (Maruping and Matook 2020), where no-code or low-code tools help citizen developers to develop new applications, the AR authoring tool we present can support citizen developers in creating process guidance systems in the form of AR instructions. We show that our AR-authoring tool increases both outcome expectations and self-efficacy of citizen developers, which is an important factor for user engagement in virtual environments (Chiu et al. 2006; Hsu et al. 2007).

12.1.3 Affective Computing

Fourth, this thesis contributes to the field of affective computing by introducing the tracking of controller movements as a method for identifying and evaluating fraudulent behavior (P6). Affective computing focuses on developing systems and devices that can recognize, interpret, and respond to human emotions (Picard 1997). In HCI research, various technologies have been explored for emotion detection, including speech analyzis (Schuller 2018), heartbeat monitoring (Zhao et al. 2018), and typing behavior analyzis (Epp et al. 2011). We propose that tracking controller movements in the metaverse is particularly effective, as most users already interact with VR controllers, eliminating the need for costly additional sensors, such as those used for monitoring blood pressure (Kettner et al. 2017). Additionally, tracking controller movements provides a robust approach to counter the increasing threat of deepfakes (Bhardwaj and Kaushik 2023; Otoum et al. 2024; Tariq et al. 2023). While physical identification methods relying on manipulated live videos can be unreliable, analyzing users' motor signals offers a more accurate way to verify identity. Fraudulent behavior, with its heightened cognitive demands and associated working memory load, often manifests in motor actions (Duran et al. 2010; Vrij 2000). These motor signals are inherently challenging to manipulate, making them a reliable indicator for detecting fraudulent activity.

Fifth, in addition to proposing a new modality for affect detection, this thesis advances the understanding of how affective-cognitive states manifest in user behavior during dishonest interactions, an increasingly relevant focus within affective computing. While numerous HCI studies have investigated how different human behaviors affect motor control in recent years (Duran et al. 2010; Gordon et al. 2021; Henrikson et al. 2020; Liebers et al. 2024; Lustig et al. 2023; Reinhardt et al. 2019; Wilf et al. 2024), to the best of our knowledge, this thesis is the first to theoretically explain and empirically validate how fraudulent behavior, specifically identity theft in the metaverse, affects controller movements (i.e., distance and speed) in the metaverse across different stages of fraud. This thesis extends the SCMT and the ADCAT to explain how the increasing cognitive demands caused by the motivational dilemma during identity theft affect individuals' controller distance before and during fraudulent acts. The motivational dilemma, in which individuals face internal conflicts about their decisions and actions, leads to increased controller distance during fraud as they hesitate and question their behavior (Freeman et al. 2011; Wojnowicz et al. 2009). Additionally, the findings of the thesis extend SCMT and ADCAT to explain how these cognitive dynamics affect controller speed. The conflict between truth and fraud triggers response inhibitions designed to prevent accidental disclosure of the truth. This heightened inhibition is reflected in slower controller speeds during fraudulent actions (Christ et al. 2009; Suchotzki et al. 2017).

12.1.4 Distinguishing Cognitive Effort in the Different Stages of Fraudulent Behavior

Sixth, our research directly contributes to the ongoing debate in cognitive psychology regarding whether truth or lying is the default mode in human communication, thereby responding to the call for further investigation by Suchotzki et al. (2017). While cognitive psychology studies such as Christ et al. (2009) and Verschuere and Houwer (2011) argue that truth is typically activated first and that lying requires suppression of the automatic truth response, scholars from social psychology and behavioral economics suggest that in tempting situations, lying may instead emerge as the more automatic response (Ariely 2012; Bereby-Meyer and Shalvi 2015). Despite these differing perspectives, prior research suggests that although motivation to deceive can facilitate the decision to lie, it does not eliminate the cognitive effort required to construct and execute a fraudulent act (Suchotzki et al. 2017).

Our empirical findings support and extend this claim by explicitly differentiating the cognitive phases, activation, decision, construction, and action, outlined in the ADCAT framework (Walczyk et al. 2014). Specifically, we observe that fraudulent behavior significantly affects human motor control, reflected in increased controller movement distances and decreased movement velocities, but only during the action phase. The preceding cognitive phases show no such motor effects. These results provide empirical confirmation that while motivation may lower the threshold for choosing to lie, it does not reduce the cognitive demands involved in constructing and physically enacting the fraudulent behavior. Our study thus offers evidence for why cognitive effort remains high even under strong motivational incentives and highlights the distinctive role of the action phase in immersive virtual environments.

12.2 Implications for Practice

12.2.1 AR Interaction Techniques and AR Instructions for the Industrial Metaverse

This thesis focused on the design of AR authoring tools for the industrial metaverse, empowering citizen developers to create immersive content independently. A key requirement for this is the ability to position and anchor immersive content within the physical environment, which relies on effective AR interaction techniques (Bräker et al. 2023a). Findings from the first two studies provide insights into user performance, perceived workload, and satisfaction when employing different AR interactions for industrial applications, particularly for positioning immersive elements in the physical environment (P1&P2). Recent research highlights that time is a critical factor in the adoption of new technologies in our chosen application domain, the service sector within the industrial metaverse (Allmendinger and Lombreglia 2005; Kundu and Ramdas 2022). In this context, the device-based technique emerged as the most efficient for creating AR instructions, enabling faster positioning of AR elements in almost any task.

Second, as AR instructions are one of the most important use cases for AR in the industry (Cohen et al. 2018; Klinker et al. 2018; Kortekamp et al. 2019; Porter and Heppelmann 2017), this thesis makes a practical contribution by analyzing user performance across a set of tasks involved in creating AR instructions (Gattullo et al. 2020). Notably, the Orientation task was the easiest for participants, who achieved the highest accuracy in positioning AR elements, as reflected by minimal distance and rotation errors across most interaction techniques. These findings have significant implications for the design of AR instructions. For example, participants found positioning 2D elements (Order task) more challenging than 3D elements (Orientation task). Based on this, we recommend using 3D text to visualize assembly sequences (Order task) and avoiding occluded interactions whenever possible (Location task).

12.2.2 Expand Business Models to the Industrial Metaverse

Third, the findings from the extensive DSR project conducted in this thesis have significant practical implications for industrial organizations aiming to expand their processes and business models into the industrial metaverse (P3-P5). To achieve this, employees of industrial organizations must first be empowered, and secondly, their motivation to create immersive content for the industrial metaverse must be strengthened. Current industry standards, such as Microsoft Guides (Microsoft 2023), aim to simplify the AR development process but remain limited in scope, particularly regarding hardware compatibility and content flexibility (Lavric et al. 2022). These limitations have hindered the widespread adoption of AR in industrial organizations (Ashtari et al. 2020; Krauß et al. 2021; Nebeling and Speicher 2018). Against this backdrop, our research offers a pathway to improve industrial organizational access to the industrial metaverse. The nascent design theory developed in this thesis provides an abstract framework for understanding the design of AR development tools, serving as a potential blueprint for creating similar artifacts in the industrial metaverse (Piirainen and Briggs 2011). By leveraging this framework, industrial organizations can simplify and scale the adoption of AR, equipping employees with authoring tools to more effectively engage with immersive technologies.

12.2.3 Method for Detecting Fraudulent Action within the Metaverse

Lastly, the findings of the final study in this thesis offer a significant practical contribution to metaverse developers by introducing an unobtrusive, scalable, and cost-effective method for detecting and assessing fraudulent intent, such as identity theft, in natural metaverse environments (P6). This methodology demonstrates strong ecological validity as it relies exclusively on analyzing movement data already collected by standard VR controllers, eliminating the need for additional hardware or explicit user input. This unobtrusiveness is critical for real-world applications, as users remain unaware of the movement monitoring, just as in our study, allowing natural behavior patterns to emerge. Unlike traditional fraud detection methods that rely on visible security measures, which may influence user behavior, our approach operates seamlessly in the background, preserving users' desire for anonymity in the metaverse (Sharma et al. 2024; Vernaza et al. 2012). Practitioners can integrate this method into future metaverse applications. Only when fraudulent behavior is detected, such as an attempt to impersonate another user to access sensitive data, would additional measures, like personal identity verification, be triggered (Duan et al. 2021). This ensures a balance between security and user privacy, offering a practical solution for fraud prevention in the metaverse.

13 Limitations

Although our DSR Project and the quantitative and qualitative evaluation persiods employed in the publications of this thesis adhered to established guidelines, the findings are subject to certain limitations. These limitations arise from the chosen methods, the specific application domains, and the data samples used. The following section outlines the most important and overarching limitations of this thesis.

An overarching limitation of this thesis, is the focus on specific use cases that we have selected. Studies P1-P5 are based exclusively on the creation of AR instructions in the industrial metaverse. Therefore, our findings only refer to this specific use case. Considering other use cases could lead to different findings and provide further insights into the usefulness and applicability of the proposed AR interaction techniques, design principles, and artifacts. Similarly, study P6 refers to a specific context, namely, fraudulent behavior. However, the findings show an important link between users' cognitive dynamics and their fraudulent behavior. This link leads us to hypothesize that the method may be applicable to other psychological states of users. Future research could investigate the extent to which the identified methods and approaches are suitable for detecting other psychological states, such as stress, frustration, or concentration difficulties.

Furthermore, based on the use case specifications in this thesis, another primary DSR-specific limitation is that the design knowledge we propose is also only valid for this application context. The first two and the three adapted proposed design principles, the developed software artifacts, and the nascent design theory were specifically tailored for AR interaction techniques and AR authoring tools in the industrial metaverse. It remains unclear whether these principles and the nascent design theory can be generalized to other interfaces, such as screen-based or VR interfaces, which are commonly associated with access to the metaverse in the literature.

Also, the quantitative and qualitative evaluation episodes of our DSR project have some limitations due to the use case specification: the creation of AR instructions as a process guidance system. While this use case represents a realistic scenario, exploring other use cases in future evaluations could provide a broader understanding of the transformative potential of AR technologies for organizations. For instance, the case study did not account for a critical aspect of the industrial context, citizen developers working directly at customer sites. The boundary and environmental conditions at customer locations can vary significantly and could influence task performance and outcomes. Evaluations conducted under these alternative conditions may yield different findings, offering valuable insights into the robustness and adaptability of the design principles and the software artifact.

In the evaluation episodes across multiple design cycles, we applied various quantitative (P1, P2, P3, P5&P6) and qualitative methods (P1, P4&P5), each with inherent limitations. Quantitative methods faced limitations primarily due to *study designs*; for instance, substituting a physical model with a virtual 3D model (P1&P2) could impact task realism, or the chosen baseline conditions (e.g., honest versus fraudulent input in P6) might introduce biases affecting validity. Additionally, our *investigated factors* were constrained to specific social mechanisms, potentially overlooking cognitive influences such as fatigue affecting participant behavior. Qualitative methods introduced potential biases related to the researchers' *personal perspectives*, exemplified by semi-structured interviews where researcher and participant subjectivity could influence results. *Coding and analyzis* in P1 and P5 can similarly be subjective, even though we enhanced reliability through intra- and inter-coder checks and followed international standards. Finally, a common limitation across both methodological approaches was the relatively small *sample sizes*, reducing statistical power and generalizability, underscoring the need for cautious interpretation of the findings.

14 Future Research

Throughout the six publications on the design of AR authoring tools for creating immersive content in the industrial metaverse and the investigation of controller movements of metaverse users, several open questions have emerged that were beyond the scope of the publications included in this thesis. The following section highlights what we consider to be valuable directions for future research.

The industrial metaverse explored in this thesis holds the potential to revolutionize industrial work and significantly expand the scope of industrial value creation. However, the integration of physical and digital environments within fused environments presents distinct technical and organizational challenges, offering a wealth of promising research opportunities.

One key area of focus in information systems research is the design of *dashboards and user interfaces*. These systems provide essential information in both private (Dalén and Krämer 2017) and in industrial contexts (Nadj et al. 2020), serving as decision support tools. Designing user interfaces for immersive technologies that enable access to the industrial metaverse presents a particularly complex challenge. Unlike traditional interfaces, where 2D screens are standard, interfaces in the industrial metaverse vary significantly depending on the use case and the meta-design space. This complexity is further amplified by immersive technologies like AR and VR, which offer fundamentally different user experiences and require specific competencies (Rauschnabel et al. 2022). As a result, interface designs must align with specific use cases while supporting seamless interoperability across interconnected meta-design spaces (Nickerson et al. 2022b; Schöbel et al. 2023; Schöbel and Leimeister 2023; Seidel et al. 2022).

Designers of these interfaces face novel challenges that have received limited attention in IS research. One significant challenge is the potential risk of motion sickness, which can result from increased immersion. User interface design plays a critical role in mitigating this effect, as certain design elements can either exacerbate or reduce it (Fernandes and Feiner 2016). Another challenge involves the design of interfaces in fused environments, where immersive content is integrated directly into the user's physical environment. This integration poses the risk of distracting users and diminishing situational awareness, which can have serious implications in industrial settings, such as when operating complex machinery (Bräker et al. 2023b).

At the same time, immersive interfaces offer new opportunities for analyzis and innovation in industrial applications. By demonstrating that cognitive dynamics triggered by emotions, such as the motivational dilemma of fraud, can influence an individual's controller movements (Mazar et al. 2008), this method has the potential to analyze movements influenced by other emotional states as well (Hibbeln et al. 2017). This could improve critical design and usability factors, particularly in the development of VR systems. For example, motion sickness could be mitigated by using controller movement data to precisely identify when and under what conditions it occurs, as well as pinpointing design elements that exacerbate it. Additionally, combining this method with other approaches, such as eye-tracking or head movement analyzis, offers a validated avenue for multi-method research. This integration can provide a more holistic understanding of user behavior (Gordon et al. 2021; Henrikson et al. 2020; Marín-Morales et al. 2023).

Another significant area of research within the IS community is *social computing*, which is being fundamentally transformed by the industrial metaverse, particularly in the creation of user-generated content (UGC) (Goh et al. 2013). The development of immersive content in the industrial metaverse raises new and intriguing questions. Similar to traditional social media platforms, where UGC does not require implementation by programmers, the industrial metaverse demands that immersive content be created by engineers and service technicians rather than AR/VR/MR experts. However, the development of such immersive content remains highly complex, requiring programming skills and advanced spatial understanding (Nebeling and Speicher 2018). As a result, approximately 64% of all AR applications in industrial contexts are custom-developed (Palmarini et al. 2018).

To address this challenge, the HCI community is focusing on the development and research of authoring tools on different immersive interfaces like VR or MR. These tools enable both developers and non-developers to create and publish immersive content for various platforms and hardware types (Konopka et al. 2022; Nebeling and Speicher 2018). Similar to traditional software development (Maruping and Matook 2020) and the creation of AI-based systems (Elshan et al. 2023), no-code and low-code approaches are becoming increasingly critical for AR/VR/MR authoring tools. These technologies allow non-developers to independently create immersive content for the industrial metaverse (Konopka et al. 2022), directly involving employees in the design process of industrial metaverse applications.

However, this shift introduces challenges that go beyond enabling employees to create immersive content. Employees must also be incentivized to share their domain-specific knowledge with colleagues in the industrial metaverse in the form of virtual artifacts, a phenomenon central to IS research (Chiu et al. 2006). Furthermore, the industrial metaverse and its associated immersive technologies offer an opportunity to explore and develop a domain-specific language (DSL). Such a DSL would enable employees to represent their reality within meta-design spaces using constructs tailored to their specific domain (Salado-Cid et al. 2024). At the same time, it would account for the unique requirements and characteristics of the various immersive technologies, ensuring both usability and relevance in these environments.

Another critical area of research within the IS community, *ecosystems*, introduces new challenges and questions due to the industrial metaverse, which focuses on the nested structure of meta-ecosystems (Schöbel and Leimeister 2023). This is particularly significant as industrial value creation in the industrial metaverse increasingly relies on shared meta-ecosystems, where diverse actors and meta-design spaces are orchestrated to collaboratively create value (Lusch and Nambisan 2015).

The trading and sharing of virtual artifacts created within the industrial metaverse play a central role in this process. These artifacts, generated within a specific meta-design space, must also be accessible in other meta-design spaces as needed. A key focus is on secure data management and the reliable exchange of these virtual artifacts (Guo et al. 2024). This is particularly critical when the process expertise of manufacturing companies, often stored in digital twins, is shared or traded, necessitating adherence to the highest industrial security standards. The challenge is compounded by the possibility of sharing virtual artifacts beyond the organization's boundaries, requiring mechanisms to verify the existence, authenticity, and ownership of these artifacts (Sunyaev et al. 2021).

An additional challenge arises from fused environments, where virtual objects can be created in virtual environments and subsequently transformed back into physical artifacts or processes, and vice versa. This necessitates the standardization of ecosystems, including all actors and meta-design spaces involved. Unlike traditional platform ecosystems, both software and hardware components must be seamlessly integrated. Uniform or open standardization across all components is essential to ensure the functionality of physical artifacts when transformed from virtual processes (Li and Treat 2024). For example, accurate standardization is critical to displaying assembly, maintenance, or repair steps in the correct location on a physical machine, ensuring these artifacts function as intended in real-world applications.

15 Conclusion

We are witnessing how the industrial metaverse is transforming work in industrial environments and expanding the scope of industrial value creation through its fused environments that integrate people, spaces, and machines both digitally and physically. The concept of the industrial metaverse goes beyond the passive consumption of immersive experiences. Within this realm, employees can create virtual objects in virtual environments, which can subsequently be transformed back into physical artifacts or processes, and vice versa. The aim of this thesis was twofold: first, to develop prescriptive design knowledge for empowering citizen developers to independently und effectively create these virtual artifacts while also incentivizing them to do so, and second, to enhance understanding of how immersive authoring tools can contribute to further industrial value creation, such as by analyzing controller movements to promote a human-centered workplace. To achieve this, the thesis integrates literature on the industrial metaverse and immersive authoring tools with qualitative and quantitative data, applying a comprehensive Design Science Research approach. Initially, we empirically evaluated which AR interaction technique is most effective and efficient for enabling citizen developers to independently create AR instructions in the industrial metaverse, complemented by the proposition of prescriptive design knowledge for future AR interaction techniques. Subsequently, through the second design cycle in the DSR project, we proposed additional prescriptive design knowledge for an AR authoring tool, presented as a nascent design theory instantiated in a software artifact. This tool empowers citizen developers to create AR instructions in the industrial metaverse while strengthening their intention to do so. Finally, we demonstrated that cognitive dynamics triggered by emotions influence controller movements captured by an immersive authoring tool. Our findings contribute to the literature on AR authoring tools, the metaverse, affective computing, social cognitive theory, and theories related to fraud. They also provide practical insights for industrial organizations developing new authoring tools for the industrial metaverse. We hope these findings will inspire further exciting research and discourse on the industrial metaverse.

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Appendix

Appendix A: MAD-MetAR (P5)

Merged AR development process MetAR (MAD-MetAR) is the first variant of our software artifact in which the AR creation process is not separated into 2D by a 2D process editor and 3D by a 3D content environment. Figure 31 shows the software artifact MAD-MetAR. With the button in the upper left corner, participants were able to create a new process step within the 3D content environment.

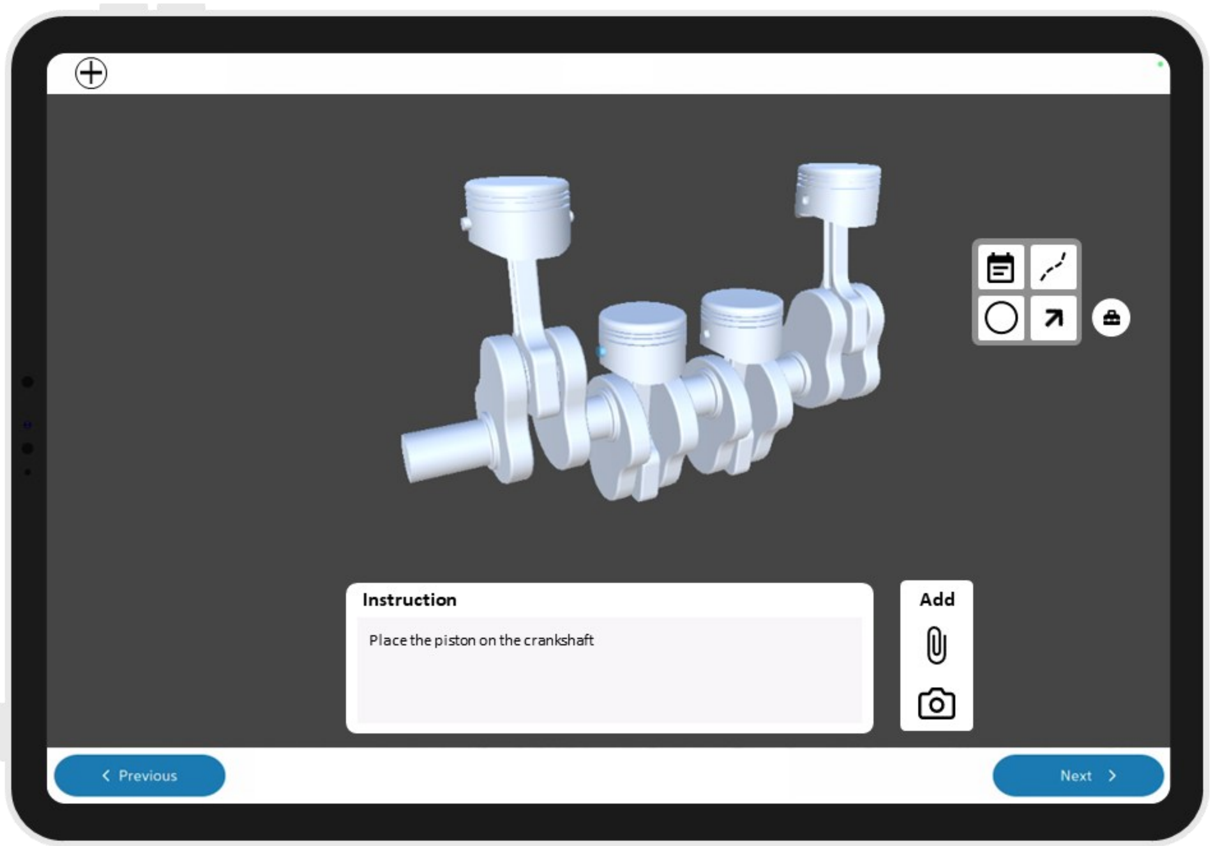

Figure 31. Software Artifact MAD-MetAR

Appendix B: GEM-MetAR (P5)

General content for the meta-design space MetAR (GEM-MetAR) is the second variant of our software artifact in which the content is not adapted to the respective meta-design space Figure 32 shows the software artifact GEM-MetAR divided into a 2D process editor and a 3D content environment. The right side of Figure 32 shows that participants are not able to add their own media to the application and that only one AR element is available to them.

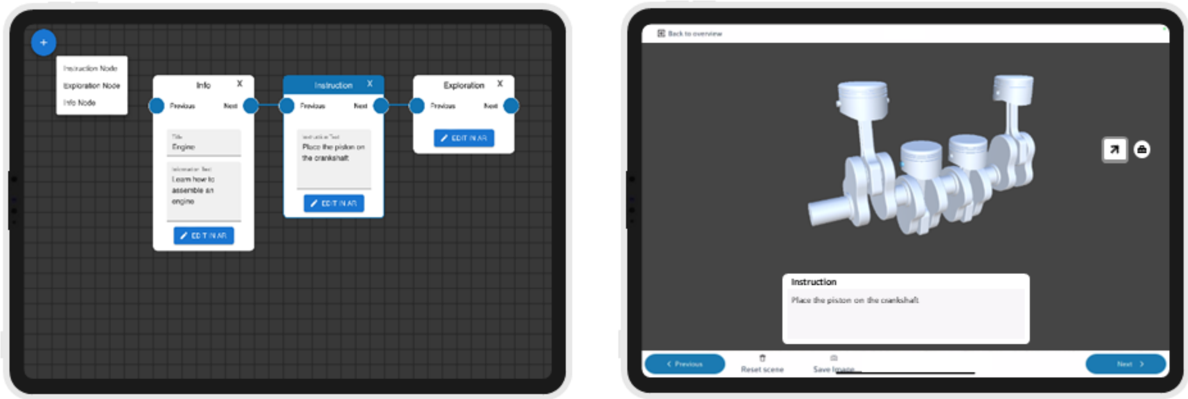

Figure 32. Software Artifact GEM-MetAR

Appendix C: MetAR (P5)

Industrial Metaverse Augmented Reality Development Tool (MetAR) is our final software artifact, in which both the AR development process is divided into 2D and 3D, and content tailored to the meta-design space is used. Figure 33 shows the 2D process editor and the 3D content environment of our final software artifact, MetAR. On the right side of Figure 33, it can be seen that users can add their own media and choose between four AR elements.

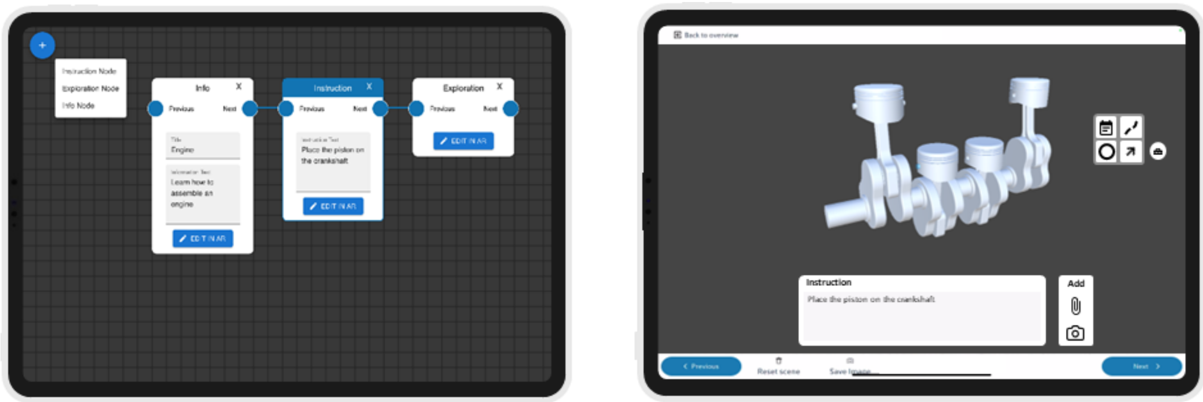

Figure 33. Final Software Artifact MetAR

Appendix E: Laboratory Environments (P5)

Before starting the experiment, we demonstrated the MetAR or MAD-MetAR to the participants, explaining its features and how to use it (see Figure 34). After introducing the tool, we presented a simple demonstration task. Participants had to use the tool independently to manipulate 3D content by placing and moving AR content across the laboratory room.

Figure 34. Demonstration of thes software artifact

As the main task of the experiment, we asked participants to use the tool to create an AR instruction. The objective was to replicate the eight steps featured in a paper-based instruction manual for assembling a piece of IKEA furniture (a KALLAX shelf) into an AR instruction (see Figure 35).

Figure 35. Using the software artifact to create an AR instruction

Appendix F: Survey Items for the Laboratory Experiments (P5)

All items were measured on a 7-point Likert scale, where 0 is the lower end, and 7 is the upper end. Table 31 shows the survey items used in the laboratory experiments.

Internal Self-efficacy (Compeau & Higgins, 1995; Thatcher et al., 2008)	Thinking about using the tool, please rate whether you could create XR instructions if (1 = Not at All Confident, 7 = Totally Confident): ISE1: There was no one around to tell me what to do. ISE2: I had never used a package like it before. ISE3: I had just the built-in help facility for reference.
External Self-efficacy (Compeau & Higgins, 1995; Thatcher et al., 2008)	Thinking about using the tool, please rate whether you could create XR instructions if (1 = Not at All Confident, 7 = Totally Confident): ESE1: I could call someone for help if I got stuck ESE2: someone else helped me get started ESE3: someone showed me how to do it first

Table 31. Survey items used for the laboratory experiments

Appendices References

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