# Understanding Immersive Environments for Visual Data Analysis

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Marc Satkowski

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Technische Universität Dresden

Fakultät Informatik
Insititut für Software- und Multimediatechnik
Interactive Media Lab Dresden

# Understanding Immersive Environments for Visual Data Analysis

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| *Erstgutachter und Betreuer* | Prof. Dr.-Ing. Raimund Dachselt<br>Interactive Media Lab<br>Technische Universität Dresden |
| *Zweitgutachter* | Prof. Dr. Dieter Schmalstieg<br>Institut für Visualisierung und Interaktive Systeme<br>Universität Stuttgart |
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**Marc Satkowski**
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Supervisors: Prof. Dr.-Ing. Raimund Dachselt

**Technische Universität Dresden**
*Interactive Media Lab*
Institute of Software and Multimedia Technology
Faculty of Computer Science
Nöthnitzer Straße 46 01187 Dresden

# Abstract

Augmented Reality enables combining virtual data spaces with real-world environments through visual augmentations, transforming everyday environments into user interfaces of arbitrary type, size, and content. In the past, the development of Augmented Reality was mainly technology-driven. This made head-mounted Mixed Reality devices more common in research, industrial, or personal use cases. However, such devices are always human-centered, making it increasingly important to closely investigate and understand human factors within such applications and environments. Augmented Reality usage can reach from a simple information display to a dedicated device to present and analyze information visualizations. The growing data availability, amount, and complexity amplified the need and wish to generate insights through such visualizations. Those, in turn, can utilize human visual perception and Augmented Reality's natural interactions, the potential to display three-dimensional data, or the stereoscopic display.

In my thesis, I aim to deepen the understanding of how Augmented Reality applications must be designed to optimally adhere to human factors and ergonomics, especially in the area of visual data analysis. To address this challenge, I ground my thesis on three research questions: (1) How can we design such applications in a human-centered way? (2) What influence does the real-world environment have within such applications? (3) How can AR applications be combined with existing systems and devices?

To answer those research questions, I explore different human properties and real-world environments that can affect the same environment's augmentations. For human factors, I investigate the competence in working with visualizations as visualization literacy, the visual perception of visualizations, and physical ergonomics like head movement. Regarding the environment, I examine two main factors: the visual background's influence on reading and working with immersive visualizations and the possibility of using alternative placement areas in Augmented Reality. Lastly, to explore future Augmented Reality systems, I designed and implemented Hybrid User Interfaces and authoring tools for immersive environments. Throughout the different projects, I used empirical, qualitative, and iterative methods in studying and designing immersive visualizations and applications. With that, I contribute to

understanding how developers can apply human and environmental parameters for designing and creating future AR applications, especially for visual data analysis.

# Zusammenfassung

Augmented Reality ermöglicht es, die reale Welt mit virtuellen Datenräume durch visuelle Augmentierungen zu kombinieren. Somit werden alltägliche Umgebungen in Benutzeroberflächen beliebiger Art, Größe und beliebigen Inhalts verwandelt. In der Vergangenheit war die Entwicklung von Augmented Reality hauptsächlich technologiegetrieben. Folglich fanden head-mounted Mixed Reality Geräte immer häufiger in der Forschung, Industrie oder im privaten Bereich anwendung. Da die Geräte jedoch immer auf den Menschen ausgerichtet sind, wird es immer wichtiger die menschlichen Faktoren in solchen Anwendungen und Umgebungen genau zu untersuchen. Die Nutzung von Augmented Reality kann von einer einfachen Informationsanzeige bis hin zur Darstellung und Analyse von Informationsvisualisierungen reichen. Die wachsende Datenverfügbarkeit, -menge und -komplexität verstärkte den Bedarf und Wunsch, durch solche Visualisierungen Erkenntnisse zu gewinnen. Diese wiederum können die menschliche visuelle Wahrnehmung und die durch Augmented Reality bereitgestellte natürlichen Interaktion und die Darstellung dreidimensionale and stereoskopische Daten nutzen.

In meiner Dissertation möchte ich das Verständnis dafür vertiefen, wie Augmented Reality-Anwendungen gestaltet werden müssen, um menschliche Faktoren und Ergonomie optimal zu berücksichtigen, insbesondere im Bereich der visuellen Datenanalyse. Hierbei stütze ich mich in meiner Arbeit auf drei Forschungsfragen: (1) Wie können solche Anwendungen menschenzentriert gestaltet werden? (2) Welchen Einfluss hat die reale Umgebung auf solche Anwendungen? (3) Wie können AR Anwendungen mit existierenden Systemen und Geräten kombiniert werden?

Um diese Forschungsfragen zu beantworten, untersuche ich verschiedene menschliche und Umgebungseigenschaften, die sich auf die Augmentierungen derselben Umgebung auswirken können. Für menschliche Faktoren untersuche ich die Kompetenz im Umgang mit Visualisierungen als “Visualization Literacy”, die visuelle Wahrnehmung von Visualisierungen, und physische Ergonomie wie Kopfbewegungen. In Bezug auf die Umgebung untersuche ich zwei Hauptfaktoren: den Einfluss des visuellen Hintergrunds auf das Lesen und Arbeiten mit immersiven Visualisierungen und die Möglichkeit der Verwendung alternativer Platzierungsbereiche in Augmented Reality. Um zukünftige Augmented Reality-Systeme zu erforschen, habe ich schließlich Hybride Benutzerschnittstellen und Konfigurationstools für immersive Umgebungen entworfen und implementiert. Während der verschiedenen Projekte habe ich empirische, qualitative und iterative Methoden bei der Untersuchung und

Gestaltung von immersiven Visualisierungen und Anwendungen eingesetzt. Damit trage ich zum Verständnis bei, wie Entwickler menschliche und umbebungsbezogene Parameter für die Gestaltung und Erstellung zukünftiger AR-Anwendungen, insbesondere für die visuelle Datenanalyse, nutzen können.

# Acknowledgment

Over the last few years, I often felt a bit like Sisyphus: Tackling this hill named "Dissertation" over and over again. On my way to the top, I pushed onwards, struggled, and tumbled down several times. Paper rejections, re-orientations of my research focus, and especially the COVID pandemic were the "disasters" looming over several segments of this path. If I had been alone, this would be the end of the story – a boulder of ideas and contributions, hopes and wishes that would never reach closure. But I was fortunate enough to have many dear people around me who supported me throughout this story – either through the constant warm words, cheerings from the sideline, or by helping me push the boulder on this long path for a while. This section is for all of you!

First, I want to thank *Raimund Dachselt*, who enabled me to start this journey. Your feedback was always valuable, the discussions were fruitful and constructive, and the chats were engaging and interesting. Generally, through your supervision, I learned to shape my thoughts while acquiring the necessary skills to bring them to paper. But simultaneously, you gave me enough time and space to develop my own processes, opinions, and skills. For all of that, I'm really grateful.

I would also like to thank *Dieter Schmalstieg* for agreeing to serve as the second reviewer for my thesis and for the time and effort he put into it.

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> *"You are my safe haven / my place to return / my anchor in a storm / my beacon that ever burns"*

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# Publications

During the work on this thesis, the following publications have been published (all peer-reviewed, in reverse chronological order). Where applicable, the material used in this thesis is indicated at the beginning of each chapter.

## Full-Paper Conference Publications

- Weizhou Luo, Zhongyuan Yu, Rufat Rzayev, **Marc Satkowski**, Stefan Gumhold, Matthew McGinity, and Raimund Dachselt. "PEARL: Physical Environment based Augmented Reality Lenses for In-Situ Human Movement Analysis". In Proceedings of: *ACM Conference on Human Factors in Computing Systems (CHI)*. Hamburg, Germany, April 23–28, 2023. [Luo+23]
- **Marc Satkowski**, Rufat Rzayev, Eva Goebel, and Raimund Dachselt. "ABOVE & BELOW: Investigating Ceiling and Floor for Augmented Reality Content Placement". In Proceddings of: *21st IEEE International Symposium on Mixed and Augmented Reality (ISMAR)*. Singapore, October 17-21, 2022. [Sat+22b] *Material from this publication appears in Ch. 5.*
- Franziska Kessler*, Sebastian Lorenz*, Felix Miesen*, Jonas Miesner*, Florian Pelzer*, **Marc Satkowski***, Amseln Klose, and Leon Urbas. "Conducive Design as an Iterative Process for Engineering CPPS". In: *13th International Conference on Applied Human Factors and Ergonomics (AHFE)*. New York, USA, July 24-28, 2022. [Kes+22]
  **The first six authors contributed equally.*
- Ricardo Langner, **Marc Satkowski**, Wolfgang Büschel, and Raimund Dachselt. "MARVIS: Combining Mobile Devices and Augmented Reality for Visual Data Analysis". In: *ACM Conference on Human Factors in Computing Systems (CHI)*. Yokohama, Japan, May 8–13, 2021. [Lan+21] *Material from this publication appears in Ch. 6.*
- **Marc Satkowski** and Raimund Dachselt. "Investigating the Impact of Real-World Environments on the Perception of 2D Visualizations in Augmented Reality". In Proceedings of: *ACM Conference on Human Factors in Computing Systems (CHI)*. Yokohama, Japan, May 8–13, 2021. [SD21] *Material from this publication appears in Ch. 4.*

## Late Breaking Work and Short-Paper Conference Publications

- Mats Ole Ellenberg*, **Marc Satkowski***, Weizhou Luo*, and Raimund Dachselt. "Spatiality and Semantics - Towards Understanding Content Placement in Mixed Reality". In Proceedings of: *Extended Abstracts of the 2023 CHI Conference on Human Factors in Computing Systems (CHI EA)*. Hamburg, Germany, April 23–28, 2023. [Ell+23] **The first three authors contributed equally.* *Material from this publication appears in Ch. 7.*
- Katja Krug*, **Marc Satkowski***, and Raimund Dachselt. "Point Cloud Alignment through Mid-Air Gestures on a Stereoscopic Display". In Proceedings of: *Extended Abstracts of the 2023 CHI Conference on Human Factors in Computing Systems (CHI EA)*. Hamburg, Germany, April 23–28, 2023. [Kru+23] **The first two authors contributed equally.*
- **Marc Satkowski***, Franziska Kessler*, Susanne Narciss, and Raimund Dachselt. "Who benefits from Visualization Adaptations? Towards a better Understanding of the Influence of Visualization Literacy". In Proceddings of: *IEEE VIS: Visualization & Visual Analytics 2022*. Oklahoma City, USA (Hybrid), 16-21 October, 2022. [Sat+22a] **The first two authors contributed equally.* *Material from this publication appears in Ch. 3.*

## Poster Publications

- **Marc Satkowski**, Weizhou Luo, and Raimund Dachselt. "A Visualization Authoring Model for Post-WIMP Interfaces". In: *Poster Track of IEEE VIS: Visualization & Visual Analytics 2021*. Virtual, October 24–29, 2021. [SLD21a] *Material from this publication appears in Ch. 6.*
- **Marc Satkowski***, Weizhou Luo*, and Raimund Dachselt. "Towards In-situ Authoring of AR Visualizations with Mobile Devices". In: *2021 IEEE International Symposium on Mixed and Augmented Reality Adjunct (ISMAR-Adjunct), Poster Track*. Bari, Italy (virtual), October 04-08, 2021. [SLD21b] **The first two authors contributed equally.* *Material from this publication appears in Ch. 6.*

## Workshop Publications

- **Marc Satkowski**, Julián Méndez. "Fantastic Hybrid User Interfaces and How to Define Them". To be published in: *2023 IEEE International Symposium on Mixed and Augmented Reality Adjunct (ISMAR-Adjunct), Workshop Track*. Sydney, Australia, October 16-20, 2023. [SM23] *Material from this publication appears in Ch. 6.*

- Julián Méndez, **Marc Satkowski**, Rufat Rzayev. “How Does Explainability Look in Hybrid User Interfaces?”. In: *2023 IEEE International Symposium on Mixed and Augmented Reality Adjunct (ISMAR-Adjunct), Workshop Track*. Sydney, Australia, October 16-20, 2023. [MSR23]
- **Marc Satkowski**, Wolfgang Büschel, and Raimund Dachselt. “Experiences with User Studies in Augmented Reality”. In: *Workshop on Evaluating User Experiences in Mixed Reality, on ACM Conference on Human Factors in Computing Systems (CHI)*. Yokohama, Japan, May 8–13, 2021. [SBD21] *Material from this publication appears in Ch. 7.*
- Ricardo Langner, Ulrike Kister, **Marc Satkowski**, and Raimund Dachselt. “Combining Interactive Large Displays and Smartphones to Enable Data Analysis from Varying Distances”. In: *AVI 2018 Workshop on Multimodal Interaction for Data Visualization*. Grosseto, Italy, 2018. [Lan+18]

## Supervised Student Theses

The following student theses that I have co-supervised during the time of my Ph.D. work contributed in part to this dissertation (in reverse chronological order):

- Sivanon Visutarporn. *Supporting Mixed Reality Collaboration through Avatars*. Student Research Project. 2023
- William Thimm. *Supporting Gaze Awareness in Collaborative Mixed Reality Environments*. Student Research Project. 2023
- Julian Hildebrandt. *Use of Micro-Gestures to Manage Virtual Content in AR*. Bachelor Thesis. 2023
- Layla Azmy. *Layout Concepts for Data Visualization Placement in Immersive Office Environments*. Bachelor Thesis. 2023
- Niclas Rosteck. *Exploration of Multimodal Interaction Techniques in Augmented Reality with the HoloLens 2*. Student Research Project. 2022
- Mats Ole Ellenberg. *Exploring Layout and Placement Strategies for Augmented Reality Visualization in Immersive Environments*. Master Thesis. 2022
- Sebastian Kranz. *Exploring Multimodal Interaction in Augmented Reality with a Spatially-Aware Mobile Device for Immersive Analytics*. Master Thesis. 2022
- Niklas Harbig. *Freehand Gestures for Augmented Reality via the HoloLens 2*. Student Research Project. 2022
- Lukas Stracke. *Design and Development of Hybrid Display Layout Strategies for Data Visualization and Exploration in Augmented Reality*. Diploma Thesis. 2022
- Pavel Taterentsev. *Task-based Adaptation of Visualization Systems*. Bachelor Thesis. 2021

- Jingyan Xiedu. *Designing Interaction Concepts for Authoring Augmented Reality Visualizations with Mobile Devices*. Bachelor Thesis. 2021
- Mats Ole Ellenberg. *Augmented Reality and Interactive Displays: Exploring Configurations and Transitions*. Student Research Project. 2021
- Lukas Stracke. *Development of a Taxonomy for the Topic of Adaptation in Augmented Reality*. Student Research Project. 2021
- Robert Ludwig. *Development of an Interactive Application for Open Coding of Qualitative Data*. Bachelor Thesis. 2021
- Vincenz Herz. *Visualization Views on Large Interactive Displays: Positioning and Layout*. Student Research Project. 2021
- Christian Riedel. *Perception of AR Visualization with dynamic Data in real-world Environments*. Master Thesis. 2020
- Vincent Schmidt. *Competence-based Adaption of Visualizations*. Master Thesis. 2020
- Wilhelm Schacht. *Management of Multiple Visualization Views in a Multi-Display Environment*. Master Thesis. 2020
- Sophia Urban. *Layout and Presentation of Attribute Visualizations for Production Machines in Augmented Reality*. Bachelor Thesis. 2019
- Niclas Zellerhoff. *Adaptive Parameter Visualizations in Cyber-Physical Production Systems*. Bachelor Thesis. 2019

I want to thank the students for their interest in the topics and contributions to the research.

# Index of Abbreviations

## General Terms

| | |
|---|---|
| **AR** | Augmented Reality |
| **MR** | Mixed Reality |
| **VR** | Virtual Reality |
| **XR** | XReality |
| **HMD** | Head-Mounted Display |
| **OST** | Optical See-Through |
| **VST** | Video See-Through |
| **FoV** | Field of View |
| **UI** | User Interface |
| **HUI** | Hybrid User Interface |
| **IA** | Immersive Analytics |
| **VL** | Visualization Literacy |
| **FC** | Feature Congestion |

## Terms with Enumerations

| | |
|---|---|
| **RQ** | Research Question |
| **S** | Study |
| **P** | Participant |
| **C** | Concept |
| **H** | Hypotheses |
| **BG** | Background |
| **PQ** | Perception Question |
| **FQ** | Focus Question |
| **DR** | Design Recommendation |

## Study and Analysis Terms

| | |
|---|---|
| **TCT** | Task Completion Time |

| | |
|---|---|
| **ER** | Error Rate |
| **EA** | Absolute Error |
| **EP** | Percentage Error |
| **TA** | Task Accuracy |
| **M** | Mean |
| **SD** | Standard Deviation |
| **VC** | Visual Complexity |
| **ID** | Information Density |

# Contents

# Introduction & Motivation

# 1

Throughout the last decades, we have seen a steady increase in technological advances, enabling various computing devices to enter our everyday lives. This gave a growing and diversifying set of users access to an ever-growing digital information space. Children growing up in current times can already learn how to interact with the available devices at a young age and therefore become "digital natives" [@Bil23; HE10]. In general, computing devices used in everyday life can range from embedded microcontrollers to sophisticated, standalone devices. For the latter, we already have access to a rich set of diverse devices, like smartphones, tablets, desktop computers with monitors, laptops, or smartwatches. While some of the devices were invented with mostly personal use in mind, they also find application in work-related tasks [Mar+22; Bru+18]. Unfortunately, all those mentioned devices are limited to presenting information on 2D displays, further limited by their available display space. Additionally, the interaction metaphors employed to access the devices are somewhat abstract, as seen with controllers, mouse and keyboard, to touch interaction. While the latter allows for more direct interaction, it does not satisfactorily mimic how humans interact in the real world.

### Mixed and Augmented Reality

One possibility to enable a more natural presentation of virtual information can be stereoscopic displays. Examples can be seen in 3D cinema or on stand-alone devices like the LookingGlass [@Loo]. Regarding a more natural interaction, hand-tracking devices like the Leap Motion Controller [@Magb] can be facilitated for gestural interaction. At the same time, the research area of Mixed Reality (MR) [MK94; Rau+22] describes a more holistic approach, combining both new input and output technologies. It is defined as an *"environment [...] in which real-world and virtual world objects are presented together within a single display"* [MK94]. Furthermore, Milgram and Kishino's [MK94] present both Virtual (VR) and Augmented Reality (AR) within one continuum. While the former separates the user from the real world by placing them in a completely (primarily visual) virtual world, the latter's devices enrich a real-world environment via the presentation and placement of virtual content. In general, this can be achieved by projecting virtual content onto the real-world environment, embedding display technologies directly into the environment, altering a video stream taken from the real environment, or by adding visual content via transparent glasses. Additionally, AR and VR most prominently use head-mounted displays (HMD). Especially for VR, HMDs have become more commonly available, as seen with the Meta Quest [@Met] or Vive Pro [@HTC]. At the same time, AR HMDs are developed, like the Varjo XR3 [@Var], Magic Leap [@Maga], Nreal Air [@Han], or Microsoft HoloLens [@Mica]. Especially through AR systems, users can simultaneously immerse themselves within the real and virtual space and its content. The presented information can directly be situated, overlayed, or even embedded into the surrounding [WJD17], also in relation to other computing devices and the already existing device ecology [RED20]. Lastly, since HMDs are body-worn, they can also be equipped with additional sensors for, e.g., scene understanding, hand, eye, or device tracking, or even for biometrical data collection. This enables a more natural integration into and interaction with the virtual space.

### Visualizations in Mixed Reality

In parallel with the growing number of devices humans can interact with, the availability, amount, size, and complexity of information have also increased. This data can relate to personal information (e.g., personal health data [Ami+17]), but also within a professional context, e.g., exploring key performance indicators [Bru+17]. Since humans can hardly make decisions or inform themselves based on raw data, it becomes necessary to preprocess, encode, and present the data in different ways. Using a visual presentation makes encoded information more easily consumable, i.e., to be explored, analyzed, and understood by humans, supporting the goal of studying underlying relations and effects. Information visualizations can be used to present information in a structured and visually appealing manner and therefore *"help people to carry out tasks more efficiently"* [Mun14]. In general, visualizations enable the externalization of the available information while simultaneously using the visual perception of humans [TS20]. Such visualizations are mainly presented on commonly used devices like desktop or mobile devices. However, as we move closer towards Natural User Interfaces [PD15] and a 3D output space, the way to present and analyze visualization has to be adjusted.

The use of information visualization within MR or AR for the purpose of data analysis is subsumed under the term Immersive Analytics (IA). The term was initially described by Chandler et al. [Cha+15] in 2015 as follows: *"[Usage of] new interaction and display technologies [...] to support analytical reasoning and decision making[, while] allow[ing] users to immerse themselves in their data"*. Mariott et al. [Mar+18] further specified the description as *"the use of engaging, embodied analysis tools to* *support data understanding and decision making"*. In general, adopting visualizations into AR enables the use of comparably new interaction techniques (e.g., gestures, gaze), spatial placement of content, promoting physical navigation [BNB07], and the presentation of information in the third dimension for the purpose of data analysis (e.g., [Kra+21]). However, another essential feature is the possibility of displaying the virtual content integrated into the real world [MK94]. This embedding allows relating data directly to a physical referent in the real world, which could create, use, or only be linked to currently visible content. Lastly, this augmentation of workflows can also concern and enhance already existing data analysis scenarios, which are currently conducted on more commonly used devices like desktops and tablets [RED20].

### User-Centric System Design

Looking at the new device types for MR and AR like HMDs and the growing number and complexity of information, users need to adapt far more often to changing factors than in the past. This includes factors like the environment and context devices are used in, the system and device setup that is available to users, or type of visualizations and their underlying data. For example, it is imaginable to analyze and interact with information in front of a production system [Pae+15]. There the visual texture of the production machine or the lighting conditions and noises in the immediate environment can change. Also, changes in the underlying data or even the state of the user themself, like stress or fatigue, are possible as well. With such a growing set of possible influencing factors and characteristics in mind, it becomes apparent that creating a design or system to cater to every possible situation and person (i.e., one-size-fits-all) will no longer be possible. With that said, a more user-centric approach to designing and implementing applications should be considered, even as adjusting a system to every possible factor (combination) is impossible. Therefore, it is essential to identify and decide which factors are the most promising to investigate further and rely upon while designing systems and visualizations is necessary.

## 1.1 Research Goals & Questions

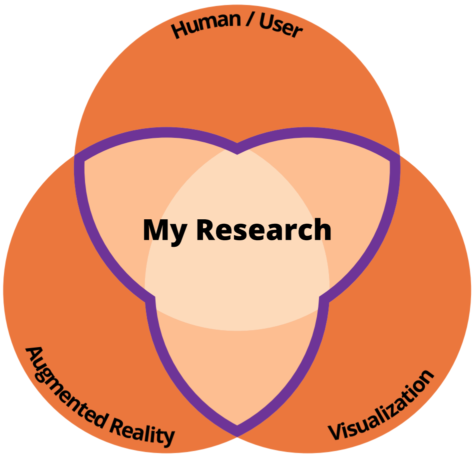

**Fig. 1.1.:** My research can be situated in the cross-section of the research areas depicted. Those are motivated by the research questions and will be further grounded by Ch. 2.

Many challenges arise based on the capability of AR devices to transform the existing real world into user interfaces. At the same time, those capabilities can differ based on possible application domains AR devices can be used in, both in personal and professional environments. It is especially interesting to envision a future with an increasing amount of immersive environments for visual data analysis as such an application domain. Overall, it is possible to state that my research scope lies within the cross-section of three research areas (see Fig. 1.1), namely AR, AR visualizations, and the humans and users of AR devices.

Since the amount of possible factors that can influence the design of future AR systems is staggering, in my thesis, I want to investigate exemplary factors across three different groups (those will be derived in Sec. 2.3). Generally, they focus on the characteristics of (1) the individual person using an AR system for visual data analysis, (2) the real-world, physical environment this system is used in, and (3) the system itself that AR is incorporated in. More concretely, those three groups of characteristics allowed the derivation of the following three research questions (RQ).

### RQ1: What factors should be considered for designing AR applications in a human-centered way?

While AR research has grown over the recent years [Mer+20] and has already tackled many problems, plenty of open issues still exist to address and focus on. As AR devices are personal devices and HMDs move closer to a user's body, it is essential to consider the human aspects. Among others, the perception of AR content and visualizations [Kim+18; Ens+21], the cognitive processes associated with exploring visualizations [ZDB08; Ens+21], or the general user interface design and their interaction [ZDB08; Kim+18] can be highlighted. In general, there are *"still many challenges in human factors"* [Kim+18] which lead to *"questions that involve human aspect [to] gain focus in MR/AR research"* [Mer+20]. Those challenges are further kindled through the increasing accessibility of information and technical systems since more people can easily engage with both. This growing engagement leads to an increasingly diverse number of possible users, which can differ in a more extensive spectrum of user-specific characteristics and properties. With that said, in my thesis, I focus on a few factors that could be of interest to the design of future AR and visualization systems. More specifically, I look into knowledge gaps on how to read visualization, visual perceptual challenges in immersive environments, or even body-specific properties like height, which result in physical ergonomics.

### RQ2: What influences does the environment have within AR applications?

AR systems can be used in various real-world environments compared to commonly available desktop setups [Kim+18]. In general, applications and their supported tasks are similar across both setups, like, analyzing industrial production data in a production plant [Hei+20], reviewing patient health data in a hospital [Bic+07], or checking emails and other messages in public transportation [Med+22]. However, the degree of integration of the presented information can differ. AR applications enable the presentation of virtual content close to potential real-world objects of interest and can directly embed and overlay elements in the surroundings. Yet, this surrounding can highly differ between possible real-world environments AR is utilized in, like an industrial production plant, office, surgery room, or living room. The differences can be derived from the possible environmental parameters, like the presence and texture of objects and surfaces (e.g., tables), number of other people present, or the existence of moving entities. Those, in turn, will affect how the virtual information can be perceived, consumed, and worked with. In my thesis, I focus on factors of the real-world physical environment, which are always present in AR applications. Those include the visual background that any given environment constitutes of and surfaces in the environment, like floor and ceiling.

### RQ3: How can AR applications be combined with existing systems and devices?

While AR already has high relevance in research communities [Kim+18; Ens+21], it is not well-known or used by the general public. Especially HMDs are currently not widely available on the consumer market. Similar to the development of smartphones, it is imaginable that AR devices will co-exist with other commonly used appliances in the future. However, the capabilities of AR systems, i.e., input and output, strongly differ from other devices, like desktop workspaces or mobile devices. This leads to missing knowledge of users on how to interact with such a system and how to combine the different device types within one global device ecology. The latter also includes the question of how to construct immersive environments in the first place. With that said, my thesis focuses on a possible combination of an AR HMD with other systems, creating a so-called Hybrid User Interface (HUI). To be more precise, throughout this thesis, I use AR in combination with mobile devices for studies, explore and describe how a possible combination from a developer's view could look like, and illustrate first concepts on how to use the capabilities of different devices within such a system for interaction.

## 1.2 Thesis Scope

Taking the research questions into account, the scope of this thesis lies within the investigation of possible characteristics of the users, the environment, and the system that can influence AR application usage and development. Therefore, this thesis addresses the human-centered use and creation of immersive applications regarding the following aspects:

### Optical See-Through Augmented Reality

Within this work, I will mainly focus on AR HMDs. I selected one subclass of AR HMDs, the optical see-through (OST) displays, which add mostly opaque virtual content into the field of view (FoV) of the wearer of such devices. This device class was chosen because it provides several benefits, like freeing up a user's hands and not altering their visual perception through displays. Specifically, I used the Microsoft HoloLens 1 and 2 [@Mica] throughout all projects that implemented an AR application.

### Information Visualizations & Data

An essential part of immersive analytics is the visual representation of data through information visualizations. In my research, I mainly investigated 2D visualization for user studies, while 3D visualizations were integrated into developed visualization systems and prototypes. In general, I did not design new visualization types but mainly used rather basic (e.g., line charts, bar charts, scatter plots) and already existing visualizations. The data presented in visualizations were either randomly created, constructed based on open-access databases like gapminder [@Gap], or hand-crafted to mimic real-world datasets. Additionally, the data complexity was used as a factor within the conducted studies or as a motivation for creating designs and visualizations.

### Data Analysis Tasks

The process of analyzing and exploring visualization consists of many different tasks that a reader can perform. However, the tasks themselves can be split into low-level and high-level tasks. The former can be seen as primitives primarily performed on single visualizations. At the same time, the latter focuses on a more complex question that is achieved by combining various low-level tasks and using several visualizations simultaneously. I mainly focused on low-level analysis tasks [AES05] for the studies conducted in this thesis. On the other hand, I used high-level tasks and general analysis goals of a complete IA system to inspire and motivate system and interaction designs.

### Single User Focus

AR is utilizable in collaborative processes independent of the specific application domains used in this thesis. However, as this thesis tries to create a user-centric understanding, the research projects mainly concentrate on single users, reducing the number of confounding factors and affecting the study design.

## 1.3 Methodological Approach

I conducted the research presented in this thesis across several research projects. While the projects are independent and self-contained, they are connected through the general focus presented in this thesis (see Fig. 1.2 and Fig. 2.12 on page 23). Furthermore, all the projects followed similar methodological approaches, which I will now describe.

### Research Model & Literature Review

Throughout the research projects, I analyzed existing related work. This involves a thorough literature review for which I collected relevant literature through keyword-based search queries and forward and backward searches through citations. First, I created a general foundation for my thesis (see Ch. 2) before I extended this foundation to cover specific research directions in each research project. Those extensions include topics like the competence to read and understand visualization, i.e., visualization literacy (see Sec. 3.2), the visual perception of humans and its corresponding research in AR (see Sec. 4.2), the usage of alternative AR placement areas, i.e., ceiling and floor (see Sec. 5.2), the extension of existing display systems, i.e., hybrid user interfaces (see Sec. 6.2), and the authoring and constructing of visualizations (see Sec. 6.4.1).

### Empirical Investigations & User Evaluations

The primary tool to generate findings and research results throughout my dissertation was conducting empirical studies and user evaluations. Before conducting the studies, the relations between dependent and independent study variables were mapped out and partly presented in parameter models. The type of conducted user study varies between the research projects and include basics pilot studies (see Ch. 5), fully fletched quantitative user studies(see Ch. 3, 4, and 5), qualitative user evaluations (see Ch. 5), as well as expert evaluations (see Ch. 6). I applied a manifold of empirical and qualitative procedures to analyze the generated data. Those include the use of parametric (e.g., ANOVA) and non-parametric statistical tests, correlation, linear regression, and linear mixed models, as well as qualitative analysis (e.g., affinity diagramming [HH15] and thematic analysis) or the generation of memos and code books based on interviews, protocols, and video files. Those studies and their analysis enabled me to reveal relations and significant effects between characteristics, user performance, and experience values, as well as the general usefulness of the presented systems and designs. To allow other researchers to verify my findings and reproduce the studies, most of the collected study data, the prepared study material (see appendix Ch. A, B, and C), and study prototypes are provided with this thesis or the corresponding publications.

### Visualization & Interaction Design Spaces and Concepts

Mainly with the last project of this thesis (see Ch. 6), several concepts and designs for either the presentation of information or for the interaction with visualizations in AR were created. The creation followed an iterative design process, which included the discussion and tests of the authors but also the inclusion of experts with expert interviews and reviews. Especially noteworthy is that those concepts were always created as a combination of AR HMDs with traditional mobile devices like smartphones and tablets.

### Prototype & System Development

Throughout this thesis, I created several prototypes, which were either used as study tools (see Ch. 4 and Ch. 5) or meant to explore the possibilities of AR data analysis systems (see Ch. 6). I created the prototypes and applications by using several different devices, which includes the Microsoft HoloLens 1 and 2 [@Mica], the motion capturing system OptiTrack [@Nat], various mobile devices like tablets and smartphones, and dedicated desktop computers working as servers. Henceforth, various technologies and programming languages, including JavaScript, C#, Unity, and Python, were utilized.

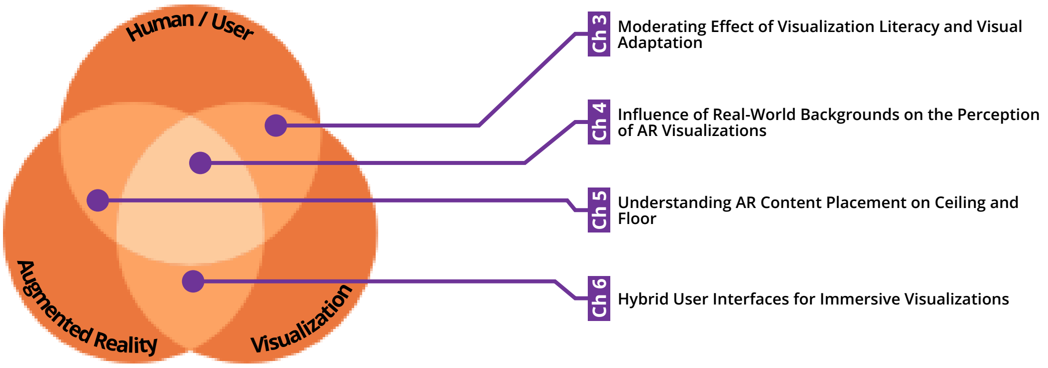

**Fig. 1.2.:** The following research projects and sections are located within the thesis' research scope.

## 1.4 Thesis Outline & Contributions

My thesis consists of seven chapters, including four research project chapters. Those four are related to different research projects, which can also be situated within my previously presented research scope (see Fig. 1.1). In the following, I will summarize the remaining six chapters.

**Chapter 2** provides the theoretical foundation for this thesis. The literature analyzed in this chapter follows three general directions, Augmented Reality and immersive environments (see Sec. 2.1), general visual data analysis and Immersive Analytics (see Sec. 2.2), and human factors and ergonomics (see Sec. 2.3). With the first two areas, I lay the foundation to understand the challenges faced while using AR, especially for information visualizations. In the latter, I will highlight the need for a stronger focus on human-centered AR research.

**Chapter 3** describes a research project focused on understanding the effect of user competence (i.e., visualization literacy) in combination with different visualization styles on scatter plots and bar charts. As the competence to work and understand visualizations is independent of the device type they are presented on, I decided not to use AR for this project. This allowed a first look at the fundamental issues caused by the increasing number of visualization users and the number of visualization types. With that, this chapter presents an empirical online study, and the evaluation of the collected data via linear mixed models.

**Chapter 4** presents a research project centered around one of the basic features of AR devices: the integration of virtual visual content into real-world scenes. Especially the potential influence of the environmental parameter of the real-world background and its visual features, i.e., luminance or color, are of interest in this project. For that, two studies were conducted. One focused on the influence of the visual background and the visual complexity of the visualization while the second focused on the impact of the visual background and a split-focus task design. Both studies were evaluated through various statistical tests.

**Chapter 5** investigates alternative placement areas for virtual AR content beyond the eye level, i.e., on the ceiling and the floor. By exploring the placement areas as environmental parameters, it is possible to reduce the amount of content in the user's FoV by placing it on the available and accessible spaces above and below the FoV. With that, this chapter presents a small survey on the use of ceiling and floor in the current literature, a definition of the placement, and the physical ergonomic parameters for placing content in either area. Following, two studies were conducted, one exploring how the ceiling and floor can be used in future AR applications while another defines optimal and preferred placement parameters for content in both areas. Lastly, a list of design recommendations on how both areas should be used in future AR systems is also presented.

**Chapter 6** explores how AR HMDs can co-exist and work in unison with other existing device classes in the current device ecology. I implemented such Hybrid User Interfaces (HUIs) for visualizations, focusing on an analysis or authoring workflow. The former workflow presents handcrafted visualizations spanning the different devices, while the latter enables in-situ visualization creation in any given immersive environment. Both workflows and systems demonstrate how a symbiosis of varying device types can be imagined and realized. With that said, the chapter investigates the term HUIs and the two described prototype systems in more detail.

**Chapter 7** reflects and evaluates the findings and results of the different research projects within the presented research scope and questions. Additionally, the chapter will discuss the limitations of my approaches and findings and highlight opportunities for future research focused on human-centered future AR applications.

# Background & Research Scope

# 2

In this chapter, I will describe the general scope of my research, which includes the areas highlighted by the previously defined research questions (see Fig. 1.1). For that, I will start in Sec. 2.1 with an overview of Augmented Reality (AR), its connection to Mixed Reality (MR), and its dependency and relation to the real-world environment. Next, I describe in Sec. 2.2.1 the term Immersive Analytics (IA) before I detail the use of immersive visualizations within IA systems. Following, I highlight in Sec. 2.3 the need for ergonomic and human-centered design, present a small model describing characteristics related to AR systems, and shortly describe adaptive and responsive visualization design. At the end of this chapter, in Sec. 2.4, I will summarize the described background and relate back to my research questions.

In addition to the related work presented here, each research project will offer its own small background section to set the project's scene. To be more precise, those additional sections include related work to competences and visualization literacy (see Sec. 3.2), human visual perception in AR (see Sec. 4.2), the use of ceiling and floor in immersive environments (see Sec. 5.2), hybrid user interfaces (HUIs) (see Sec. 6.2), and visualization authoring (see Sec. 6.4.1).

## 2.1 Augmented Reality & Immersive Environments

As the main focus of my thesis lies within the space of Augmented Reality (AR), I first want to introduce this technology. For that, I will first describe and show different definitions for AR and other related terms (see Sec. 2.1.1), second, outline usable technologies to achieve AR (see Sec. 2.1.2), before, third, highlighting the relationship between AR and immersive environments it can create (see Sec. 2.1.3).

**Fig. 2.2.:** The Virtuality Continuum presented by Milgram et al. [MK94] describes Mixed Reality (MR).

### 2.1.1 Definitions & Introduction

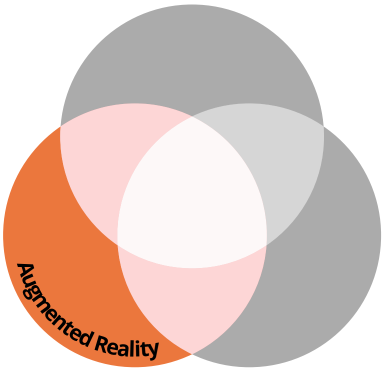

**Fig. 2.1.:** *Augmented Reality* is the first and major part of my research scope.

AR enables *“user to see the real world, with virtual objects superimposed upon or composited with the real world”* [Azu97]. Other augmentation the real world are also possible [Rau+22; SH16], like extending and altering haptics, audio, olfactory, or even gustatory information. However, AR entirely focuses on the visual extension by virtual information. Milgram and Kishino also describe this as AR *“refers to any case in which an otherwise real environment is ’augmented’ by means of virtual (computer graphic) objects”* [MK94]. Azuma [Azu97] defines AR more closely, as AR systems have to follow three characteristics: combination of real and virtual, interactivity in real time, and the registration in 3D.

However, AR does not exist in isolation. It is often related to Mixed Reality (MR) and Virtual Reality (VR). Compared to AR, VR provides a *“fully synthetic or fully virtual view”* [SHN19] which completely occludes the visual real-world environment. This difference can also be seen while looking at the Virtuality Continuum (see Fig. 2.2) of Milgram and Kishino [MK94], which they describe as an *“environment [in] which real world and virtual world objects are presented together within a single display”* [MK94]. Both VR and AR can be seen on opposite sides of this spectrum. However, even as MR has been the research focus for quite some time, uncertainty exists about what the term describes and encapsulates. To tackle that problem, Speicher et al. [SHN19] present a taxonomy of six MR notions. Those describe MR as, e.g., a continuum, a synonym for AR, a stronger version of AR, or a combination of AR and VR within one system.

While Speicher et al. [SHN19] highlight that they believe that no single definition of MR can be expected in the near future, attempts still exist to achieve this. First, Skarbez et al. [SSW21] re-iterate over the Virtuality Continuum [MK94]. Within their work, they describe MR utilizing three dimensions called Extent of World Knowledge, Immersion, and Coherence. Those dimensions, as well as their combination, are further related to different feelings users within MR environments can experience,

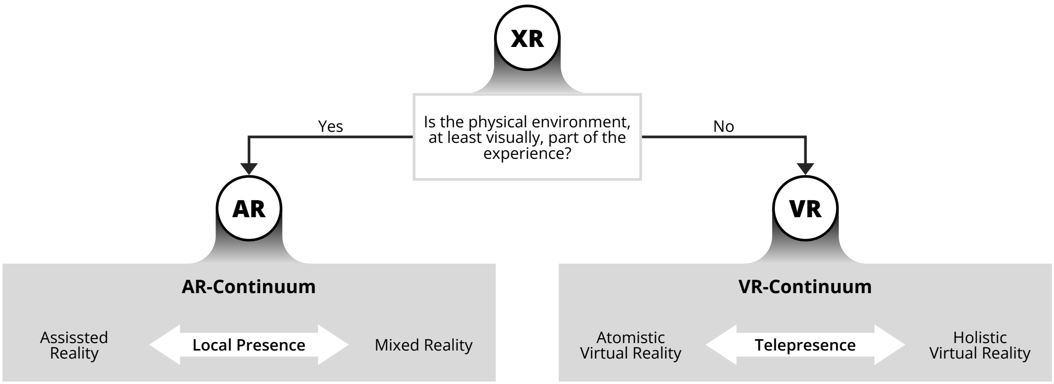

**Fig. 2.3.:** The XReality (XR) framework for Augmented (AR) and Virtual Reality (VR), presented by Rauschnabel et al. [Rau+22].

like world awareness, presence, or mixed reality illusion. On the other hand and more recently, Rauschnabel et al. [Rau+22] describe xReality (XR), where the *"X represents a placeholder (similar to an X variable in algebra) for any form of new reality"* [Rau+22]. They see both VR and AR as part of XR while conceptually separated. Following, they present an AR continuum (see Fig. 2.3), where MR is one extreme on this scale which can be reached by an increased level of local presence.

## 2.1.2 Augmented Reality Systems

Several technologies and systems enable the visual augmentation of the real world. Those display types (see Fig. 2.4) can differ regarding how the virtual content is combined with the environment, how dynamically the augmentation can be changed, or if the presented content is publicly visible. They can additionally be categorized according to the distance from the eye of a user to the display [SH16], with world, body, and head space.

### Embedded Displays

The most direct way to integrate virtual information into the real world is by embedding monitors and displays within the environment and the world space (e.g., [Mat+20; Sch+15; Tom+08]). In general, embedded monitors allow for augmenting a pre-defined area with arbitrary virtual information. As the displays are directly integrated into the real-world objects to augment, such a combination results in a simple way to achieve spatial coupling. The so-displayed virtual content has a relatively high resolution while being spatially limited to its display area. Furthermore, as those displays are mostly integrated into specific surfaces or objects,

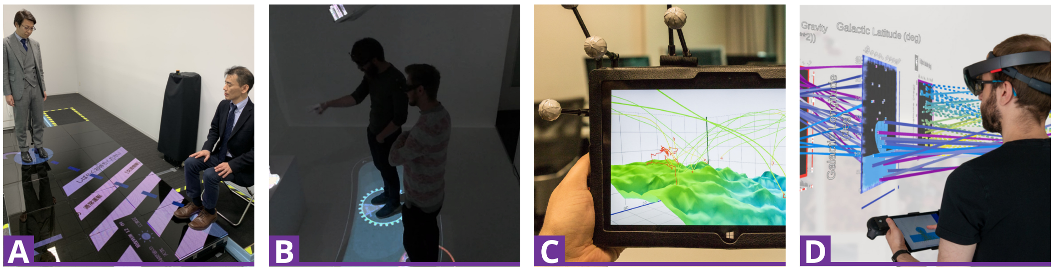

**Fig. 2.4.:** Possible technological setups to augment the real world. **(A)** A guiding system for elevator halls using embedded interactive floor displays [Mat+20]. **(B)** A floor-based user interface in a museum context, which makes use of stationary projectors [Sch+18]. **(C)** A mobile AR system for the exploration of 3D visualizations and spatial interaction [Büs+17]. **(D)** A HMD AR application for the visual data analysis of 3D parallel coordinate visualization consisting of linked 2D scatterplots [Hub+21a].

it is impossible to apply the same augmentation by moving the displays to another entity. Lastly, embedded screens are always visible to everyone in the surrounding.

### Projected AR

In comparison, projectors are not directly installed on any given surface but instead placed within the nearby surrounding, affecting real-world space (e.g., [Fuj+13; Sch+18]). Meanwhile, there also exist mobile projection solutions, which are coupled to a specific user. This can be achieved by, e.g., wearing a handbag [LTM11], a belt, or even by using a drone to follow the user [Kni+18].

In comparison to embedded screens, projectors allow for a more flexible augmentation. It is possible to easily change the augmented objects by moving them in and out of the projection area. To be more precise, spatial AR [BR11] alters the appearance of surface vis changes in texture, details, shadows, and shading [SH16]. Although projections can work with arbitrary shapes, the approach is prone to occlusion by surface geometry or other objects. While using several projectors can alleviate this problem, the geometry must be known for this to work. Lastly, similar to the embedded screens, the projector solution still presents all information publicly.

### Handheld AR

Augmentation is also achievable by handheld devices, like tablets or smartphones, which move the augmentation towards the body space (e.g., [Büs+17; MSS11; SW07; GS12]). As such devices have permeated our everyday life, they can allow access to AR for a broader user base. Readily available frameworks (e.g., ARCore [@Goo], ARKit [@Inc]) further support this for the most prominent operating systems Android and iOS. The augmentation is achieved by using the rear cameras of handheld devices and altering the so captured video stream with virtual information and content. This approach to achieving augmentations is called video see-through (VST). Different systems need to be used to enable the correct alignment and distortion of the virtual content to the real-world video stream. Those include marker-based outside-in tracking, use of internal components like gyro-sensors, depth cameras, and in general, computer vision approaches. Handheld devices are moveable within a given environment, but the provided augmentation is not limited to a specific area or surface. However, as the augmentation can only be applied and shown on the handheld device's display, the extendable area at any given time is somewhat limited. Furthermore, as such a device has to be held by the user, it becomes more challenging or even impossible to interact with the real-world environment without changing the field of view or putting the device out of hand.

#### Head-mounted AR

Finally, visual augmentation can be achieved by displays directly mounted to a user's head (e.g., [But+18; Sza+98; Huy+22]) - so-called head-mounted displays (HMDs). Dependent if the system uses displays or glasses in front of the users' eyes, the achieved augmentation is called VST or OST, respectively. Similar to handheld devices, the former alters a recorded video stream. For the latter, virtual information is projected into opaque glasses, only extending the real world by adding new visual information. Comparing both VST and OST HMDs, VST devices allow for more convincing and simpler alteration of the real world, while OST still allows seeing the physical surrounding as it is. Both see-through types often have separate displays for each eye, enabling a stereoscopic view. As HMDs are worn, they free up the hands, which are now useable to interact with the real and virtual worlds. This can be done using specific controllers or more natural means, like hand gestures, gaze, or speech.

### 2.1.3 Immersive Environments & Use Cases

Independent of the technology used to enable augmentation, the virtual content always has to exist in parallel with the real-world environment. Additionally, while VST devices can overlay the video stream with completely opaque information, OST devices cannot achieve the same level of opaqueness. With that said, the visual environments play an important role in how the users perceive the virtually presented information. Depending on how visually complex the virtual and the real-world environment are, a combination of both needs to solve visual perceptual load issues, as the *"perception has a limited capacity, which automatically proceeds until exhausted"* [MFD13]. Such issues can become especially prominent in AR systems, as the use cases of AR are manifold and can vary regarding several factors.

AR's application domains and scenarios are diverse and affect the environment in which such a system is used. In general, an environment contains *"physical, [...], organizational, social and cultural factors surrounding one or more persons"* [Int11]. Typically proposed application domains of AR [SH16] are industry and construction [Mos+19; SMZ20], architecture [RED20], maintenance and training [BPR20], education [Wu+13], medical [DUF22], personal information display [Lu+20], navigation [Win+14], television, advertising and commerce, games, or data analysis [Cor+19]. Within each environment or use case, the visual background, presence of furniture or objects, presence of other persons, lighting conditions, space to move, need to use tools, or more factors are affected and differ from any other scenario.

## 2.2 AR Visualizations & Immersive Analytics

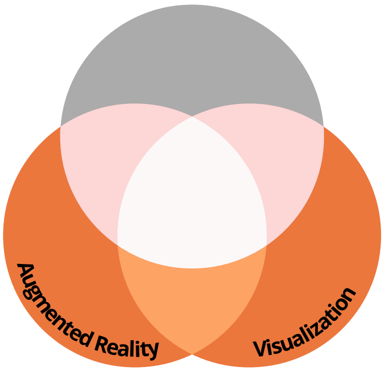

**Fig. 2.5.:** *Visualizations* are a specific content type in AR applications, as seen in Immersive Analytics.

In AR applications, it is possible to present a wide variety of different content types. One such type is visualizations, which *"provide visual representations of datasets designed to help people carry out tasks more effectively"* [Mun14] by *"enabling the viewer to detect patterns quickly and leading to deep insights"* [TS20]. As the name implies, visualizations use visual channels to encode underlying and abstract information or datasets to take advantage of the strengths of the human visual system [TS20; Rob+14]. Furthermore, they help with *"the rise of big data and the ever-present wish to gain an in-depth understanding of the world"* [Rob+14]. Visualizations cannot only be presented within traditional mediums like books or desktops but have also moved to more novel systems like AR. Such *visualization beyond the desktop* [Rob+14] allow for *beyond mouse and keyboard* [Lee+12] interaction and can embed and situate the visualizations directly within the immediate environment. Therefore, I will first, describe the research area of Immersive Analytics (IA) (Sec. 2.2.1) before detailing immersive visualization within IA applications (Sec. 2.2.2).

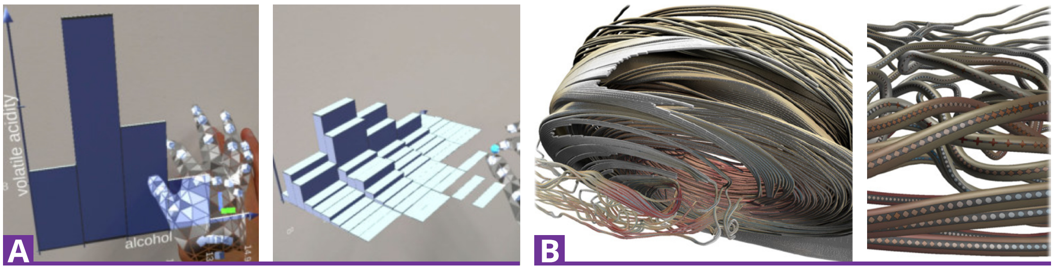

**Fig. 2.6.:** AR visualization can facilitate the stereoscopic capabilities of HMDs to present 3D visualizations. **(A)** Demonstrate the interactive transition between a commonly used 2D bar chart and a 3D bar chart [Lee+22]. **(B)** Presentation of trajectories with additional information encoded on the tubes [Rus+23].

### 2.2.1 Immersive Analytics

Supporting the ability to make sense of data through immersive visualization is subsumed under the term Immersive Analytics (IA), which was first coined by Chandler et al. [Cha+15].IA is described as *“the use of engaging, embodied analysis tools to support data understanding and decision making”* [Mar+18]. Furthermore, the virtual information within such applications can also be situated [Whi08] or embedded [WJD17] into objects within an environment. The former describes data visualizations to be related to, based on, and presented in the physical context [Whi08] while the latter even *“spatially integrates information more tightly with relevant objects, people, or locations”* [WJD17]. This close coupling of information and the real world benefits analysts as *“tools for presenting and exploring data in-context in our everyday environment have the power to change how we approach almost any task”* [WJD17]. The usage of situated visualizations that are *“related to and displayed in its environment”* [WF09] in IA application can be called situated analytics (SA) [Shi+23]. SA allows organizing information to objects, places, or even persons in the real-world environment, enabling a higher understanding, sensemaking, or decision-making [ElS+15; Mar+18; Tho+18].

Generally speaking, presenting (situated and immersive) visualizations within IA systems has several benefits, allowing us to facilitate human capabilities otherwise limited by traditional setups. This includes a more engaging analysis through embodied data exploration and facilitating the users’ body and environmental awareness and skills [Jac+08] to explore information in immersive environments. An example is physical navigation, which benefit has already been demonstrated within other systems, like wall-sized displays [JH15; BNB07]. Furthermore, IA can also be conducted collaboratively, facilitated by the possibility of AR systems to simultaneously see the virtual information and the other collaborators in person.

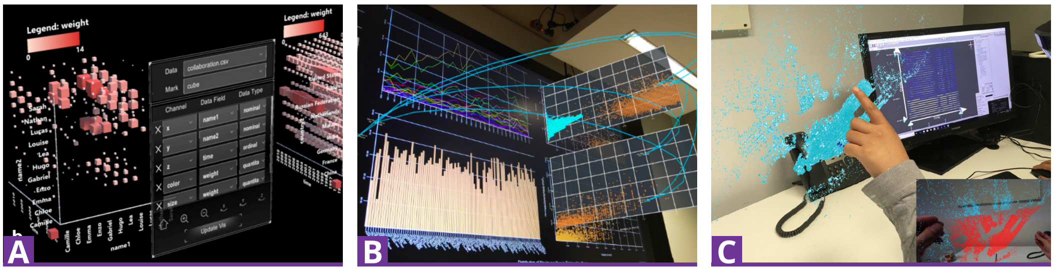

**Fig. 2.7.:** Three published AR visualization frameworks written in the Unity 3D engine. **(A)** Configurable XR visualizations inspired by Vega-Lite [Sic+19]. **(B)** A framework that allows to configure visualization in the unity editor and build to combine AR content and large vertical displays [RFD21]. **(C)** A scalable toolkit that enables the creation of multidimensional data visualizations [Cor+19].

Besides the possible benefits of IA, many open challenges make using AR productively tricky, as described by Ens et al. [Ens+21]. Those challenges include more fundamental areas like accurately placing visualizations in space or interacting with single visualizations or the whole system. However, as they are fundamental, they also apply to general AR research [Kim+18; KSF10] or neighboring areas like situated analytics [Mar+18]. Other challenges revolve around enabling collaboration, defining application scenarios, and evaluating users of IA systems and the context they are used in. Especially the latter highlights the general need for not only IA but AR research in general to design application human centered [Kim+18; Mer+20].

### 2.2.2 Immersive Visualization & Frameworks

Before IA was even defined, immersive visualizations had already been researched for several decades, as Fonnet and Prié [FP19] describe in their survey. Looking at this survey, IA allows analyzing a manifold of data types, like spatio-temporal data, multi-dimensional data, or graphs and trees. Generally, such visualizations lead to a higher spatial immersion, as it is possible to display information in 3D. This includes the extension of classical 2D visualizations like bar charts and scatter plots [Lee+22] or the presentation of inherently multi-dimensional data like trajectories [Rus+23] (see Fig. 2.6). Analysts can explore those data types by visually representing them through immersive visualization techniques, including 2D or 3D visualizations [Lee+22], node-link diagrams [BVD19], trajectories [HBV20], or heatmaps [BLD21; Ngu+17]. Additionally, more fundamental visual components are used in IA systems to present values [Mad+16] but also connections between different visualizations or real-world objects, such as links [BVD18] or traces [HGB22]. To analyze both the visualizations and their underlying data, IA also has to support

**Fig. 2.9.:** Three other visualization frameworks or systems which make use of the former. **(A)** A toolkit for situated analytics [Fle+22], building upon IATK [Cor+19]. **(B)** A analysis toolkit tailored for study data investigation based on spatio-temporal data [BLD21]. **(C)** A web-based framework for immersive analytics using WebVR, React, and D3.js [BJR21].

general analysis tasks [FP19], like navigate, select, filter, or aggregate. Furthermore, finding clusters and outliers, estimating trends [Cor+19], or annotate data and visualizations [BLD21; RFD21] are essential as well.

Several frameworks have been proposed over the last years to enable the easy creation and configuration of immersive visualizations and environments (see Fig. 2.7 and 2.9). DXR [Sic+19], u2vis [RFD21], and IATK [Cor+19] (also to an extend ImAxes [Cor+17]) allow the creation of simple 2D and 3D visualizations in AR. Building upon the latter, RagRug [Fle+22] is a toolkit directly designed for situated analytics. While the previously mentioned frameworks were built for the Unity 3D engine, approaches to utilize WebVR for platform-independent visualization also exist, like VRIA [BJR21]. Based on the idea of such frameworks, toolkits or complete analysis systems can be created. ReLive [Hub+22] is a mixed immersion tool combining views in VR and on a desktop PC. Stream [Hub+21a] lets a user explore 3D parallel coordinate plots with the help of a tablet. Lastly, MIRIA [BLD21] enables the collaborative exploration of spatio-temporal study data.

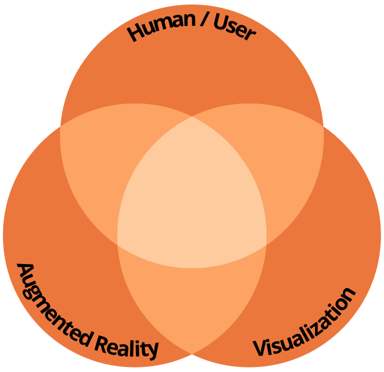

**Fig. 2.8.:** *Users* of AR systems have special needs, as ergonomics describes.

## 2.3 Human-centered & Adaptive Design

While Augmented Reality (AR) has been a research subject for a prolonged time, it has yet to reach the consumer market in such a way that it is easily accessible by developers and users. Following that, there are *"still many challenges in human factors"* [Kim+18] which lead to *"questions that involve human aspect [to] gain focus*

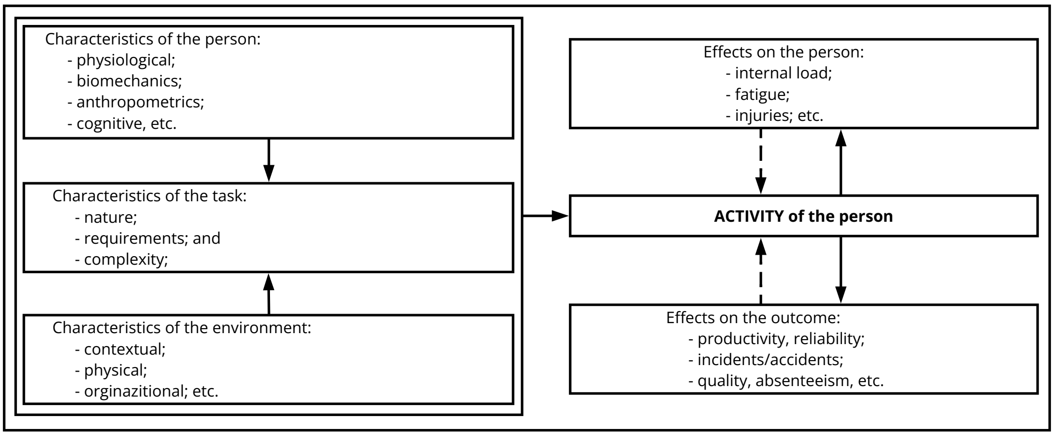

**Fig. 2.10.:** Exemplary factors to take into account for an ergonomic design [Int11]. The person's activity is central to the system's functionality and, when designed ergonomically, can help optimize system performance.

*in MR/AR research"* [Mer+20]. Those include, among others, the perception of AR content and visualizations [Kim+18; Ens+21], the cognitive processes associated with exploring visualizations [ZDB08; Ens+21], the general user interface design and their interaction [ZDB08; Kim+18], or the design of spatially situated visualizations [Ens+21]. With that said, transforming a pure technology-centric into a human-centric approach becomes increasingly important (see Fig. 2.8). Therefore, I will first describe and detail what ergonomics and human-centered design are (Sec. 2.3.1) before presenting a model focused on various characteristics (Sec. 2.3.2). Following, I will shortly detail the areas of adaptive and responsive visualization and system design (Sec. 2.3.3).

## 2.3.1 Ergonomics & Human Factors

Ergonomics - also called *human factors* - can be described as *"the understanding of interactions among human[s] and other elements of a system"* [Int11; KZ21; Kar05]. Within this holistic and human-centered approach, traditional domains of specialization exist, which are described by Karwowski [Kar05]:

- *Physical ergonomics* is mainly concerned with human anatomical, anthropometric, physiological, and biomechanical characteristics as they relate to physical activity.
- *Cognitive ergonomics* focuses on mental processes, such as perception, memory, information processing, reasoning, and motor response, as they affect interactions among humans and other system elements.

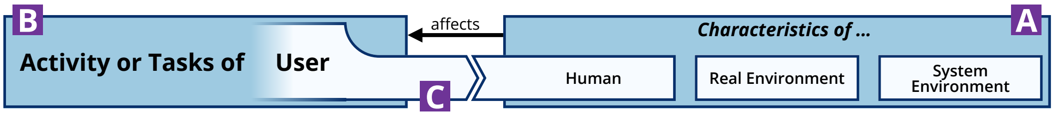

**Fig. 2.11.:** Representation of for this thesis important ergonomic and human factors. **(A)** The system environment, real environment, and human characteristics affect **(B)** the user's activity and state within an application. **(C)** Simultaneously, the user's state is fed back into the characteristics.

- *Organizational ergonomics* (also known as macroergonomics) is concerned with the optimization of socio-technical systems, including their organizational structures, policies, and processes

Further areas of ergonomics also exist that all together aim to *"optimize human well-being and overall system performance"* [Int11]. The ISO norm 26800 [Int11] describes a general approach and concepts for such a conducive and ergonomic design. This approach relies on the person's characteristics, the task, and the environment. Subsequently, these characteristics affect the user and the user's current task (see Fig. 2.10).

## 2.3.2 Ergonomics for AR Systems

Following the ISO norm [Int11], I want to focus on the characteristics of the environment and humans. Furthermore, the former can be split into two specific sets of environmental properties: system environment and real-world environment (see Fig. 2.11).

### System Environment

With research advances in the field of IA, the use of AR for visual data analysis has become more promising. However, other already existing devices (i.e., hardware), applications (i.e., software), or whole systems (i.e., a combination of hard- and software) will still play a vital role in the future. Therefore, IA applications must coexist and work in unison with such systems. Typical environments often used for visual data analysis are desktop setups [BE14; SGL08], large wall displays [LKD18; BNB07], or mobile devices [LHD17; BE14; Chi06]. Due to the great variety of such systems, integrating AR devices into these environments has to consider several properties. Essential examples of such are, the number of devices, the use of their input and output capabilities, or if they can be moved within the environment.

#### Real Environment

Users within AR applications must engage parallelly with the virtual and real-world space. Especially for areas like embedded visualizations [WJD17] or situated analytics [ElS+15; Shi+23], the relation between the virtual and real world becomes increasingly interwoven. AR devices can find applications in many scenarios, but the environment accompanying an application domain can also differ. Domains can include industrial production plants [Mos+19; AS18], grocery shopping in a supermarket [BMD18; GVH18], general medicine and surgeries [Gsa+23; Bic+07], or data analysis in an office [Hub+22; Lee+22]. Following those, properties like the available movement space, the presence and number of objects or people, the lighting conditions, or the color or texture of real-world objects can also highly differ.

#### Human

AR applications and systems are designed to be used by humans and to support the same in solving tasks. However, possible users can differ, especially regarding various application domains. With that, the capabilities or properties of each user can vary. For example, knowledge to operate a tool or how to read and evaluate a visualization can be diverse. However, also general human properties [Til02], like the handiness, the height, or even the well-being, level of fatigue, or concentration are important to consider.

### 2.3.3 Adaptiveness & Responsiveness

The term ergonomics also includes the definition of human-centered design, which considers that components of a system *"are fitted to the characteristics of the intended users, operators or workers, rather than selecting and/or adapting humans to fit the system, product or service"* [Int11]. Adjusting a system to a user can be actively triggered by the user, also known as adaptable systems *"which the individual user can explicitly tailor to their own preferences"* [Jam09]. On the other hand, the system can also automatically initiate such an adjustment after detecting user needs changes. This can also be labeled as user-adaptive systems, which *"adapt [the system's] behavior to individual users on the basis of processes of user model acquisition and application that involve some form of learning, inference, or decision making"* [Jam09]. A specific subset of adaptation is responsiveness which is defined as the ability to *"adapt themselves automatically to external contextual requirements"* [Hor+21b]. It is often used in the context of mobile devices like smartphones or tablets since such device types introduced new form factors and input capabilities to existing

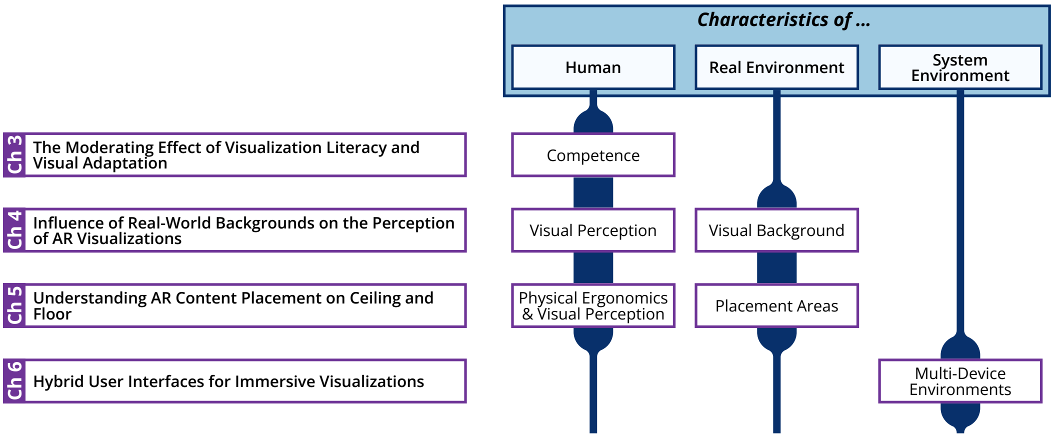

Fig. 2.12.: An overview of specific properties of ergonomic characteristics, which were investigated throughout the research projects of my thesis.

applications. However, responsiveness is also described to *"[automatically adapt] to various factors, such as changed device characteristics, environment, usage context, data, or user requirements"* [Lee+21], which is more similar to the previously presented definition of adaptation.

Returning to the focus of this thesis on AR applications for visual data analysis, adaptiveness and responsiveness are essential concepts to consider for their design. To make visualizations, which can also be seen as a system to adapt, means to give them *"the ability to change [...] depending on various user features that can be explicitly provided or inferred from the trace of user actions"* [AB13]. While the AR research area still lacks a clear focus on developing adaptation techniques, the research community is already aware of the need to adjust AR systems based on human factors [Kim+18; Mer+20; Ens+21].

## 2.4 Summary

Within this section, I laid the foundation and presented the motivation for the research projects I will describe throughout the following chapters. Specifically, I detailed AR and IA's current state and research challenges. The latter includes topics [Kim+18; Ens+21; SH16] like how to improve tracking, define application scenarios, or improve display technology. However, I want to focus on a more human-centric approach [Mer+20]. Specifically, I want to identify possible factors worth considering when creating AR and IA applications in the future.

Following the characteristics that I described in Sec. 2.3.2 (see Fig. 2.11), I can illustrate another grouping of my research projects (see Fig. 2.12). This grouping does not rely on the general research areas (see Fig. 1.1) but follows human, system, or real-world environmental factors. Those three groups also align with my research questions presented in Sec. 1.1. However, as the three characteristics are still rather broad, I will focus on specific properties within each of the groups. With that said, the following chapters will describe research focused on the following parameters for each characteristic (see Fig. 2.12):

**Human:** Competence as Visualization Literacy (see Ch. 3); visual perception of AR content (see Ch. 4 and 5); physical ergonomics of head and eye movement (see Ch. 6)

**Real Environment:** Visual background as visual clutter (see Ch. 4); available placement areas of ceiling and floor (see Ch. 5)

**System Environment:** Heterogenous multi-device AR setups, i.e., Hybrid User Interfaces (see Ch. 6)

# 3

# The Moderating Effect of Visualization Literacy and Visual Adaptation

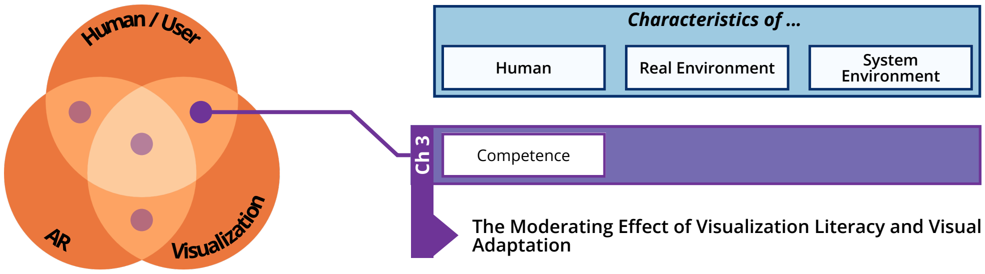

**Fig. 3.1.:** This research project (Ch. 3) is situated in the Visualization and Human/User cross-section. Within this project, I focus on human competence in form of visualization literacy.

Visualizations are a tool designed to support humans in understanding underlying data and generating insights. This visual data analysis process depends on correctly reading, interpreting, and understanding a given visualization. This set of abilities can also be described as a specific competence named Visualization Literacy (VL). I want to explore in my thesis the visual data analysis using AR HMDs, VL is independent of the output medium the visualizations are shown on. With that in mind, I first want to explore the influence of VL decoupled from the device class used (see Fig. 3.1). Henceforth, with the here presented research project we[1] will explore the influence of VL on user performance and experience. To achieve this, we contribute the following:

- A detailed motivation for this research project (Sec. 3.1), including related background (Sec. 3.2) revolving around the term VL and psychological aspects.
- A quantitative online study (Sec. 3.3) focused on VL and a visual adaptation approach, i.e., de-emphasis, for bar charts and scatter plots. This includes the study design, its operationalization, and the results.

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[1] "We" in this chapter relates to the author Marc Satkowski, as well as Franziska Kessler, Susanne Narciss, and Raimund Dachselt as co-contributors to this research.

- A discussion of the findings and insights (Sec. 3.5) and the used measurements of VL. Additionally, I will describe the implications of the insight to AR visualization systems.

Parts of the research presented in this chapter have previously appeared in:

**Marc Satkowski***, Franziska Kessler*, Susanne Narciss, and Raimund Dachselt. "Who benefits from Visualization Adaptations? Towards a better Understanding of the Influence of Visualization Literacy". In Proceddings of: *IEEE VIS: Visualization & Visual Analytics 2022*. Oklahoma City, USA (Hybrid), 16-21 October, 2022. [Sat+22a] **The first two authors contributed equally.*

*Own Contribution:* The project was done in close collaboration among the first two authors, resulting in the study design, execution, and evaluation. Further, the discussion between all authors helped shape the publication regarding motivation, discussion, and general reasoning. Consequently, I hold a shared contribution with Fransika Kessler to all parts.

*Applied Changes:* This chapter presents an extended version of the study, its results, and a discussion. All parts of the paper and the appendix can be found embedded throughout this chapter.

## 3.1 Motivation

Visualizations permeate our everyday life as we are confronted with them early in school and later as adults on websites, personal mobile devices, or in work contexts. We continuously learn and improve our abilities to deal with existing visualizations or adapt to new or altered types we encounter. However, this high number of visualization types makes it hard to learn and understand the intricacies of every type. At the same time, the diversity of users is also increasing. The combination of both may result in deficiencies in understanding specific visualizations. In general, the competence and the cognitive process related to the ability to read, understand, and comprehend visualizations have been summarized and conceptualized under the term Visualization Literacy (VL) [Boy+14] or data visualization literacy [BBG18]. As the VL level can differ between users and even between various visualization types for each user, one cannot take it for granted that every person can understand specific visualization instances equally well. This makes designing visualizations tailored to the individual user's needs essential.

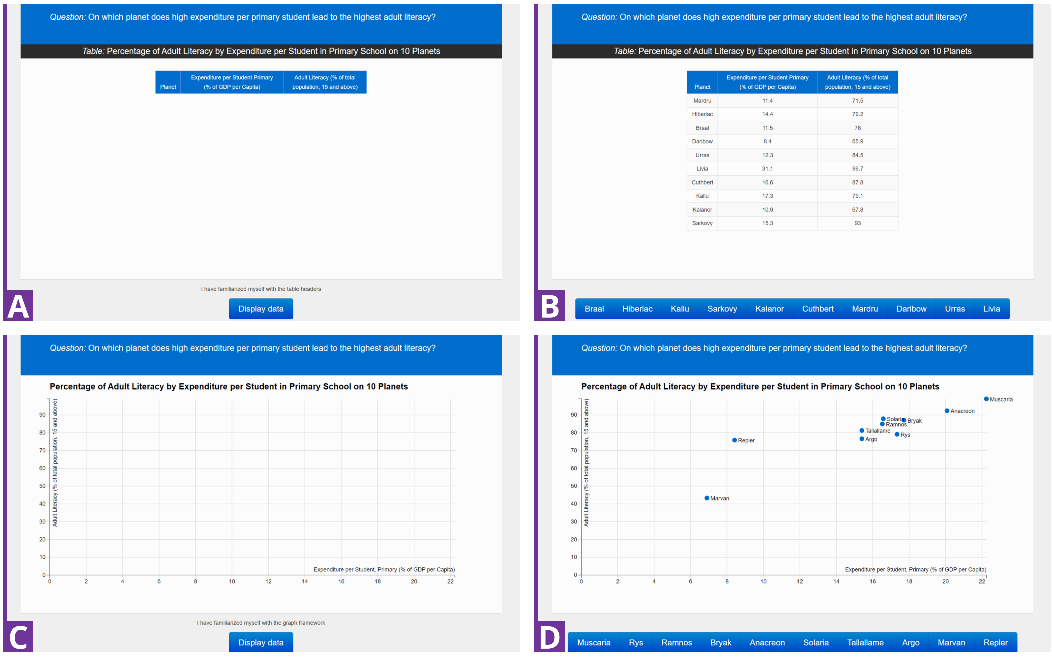
One possibility to counter possible shortages and to support users when working with visualizations is to adapt a given visualization to the characteristics of the current user. That is, considering the current user's characteristics and changing how the visualization is presented. The aim of tailoring how information is presented to the user's needs is to enhance the probability of successfully conveying the information. Several aspects can be adapted to a user, such as changing visual channels [HB10], using metaphors [ZK08], as well as altering the layout or even completely changing the visualization type [Zie+13]. How adaptations of visualizations affect the performance and user experience is likely to be affected by the VL level of the individual user. In the instructional psychology community, the concept of aptitude-treatment interaction [MCS78] has been studied extensively. It describes the effect that the same instructional strategy (i.e., treatment, or here the adaptation of a visualization) can be more or less effective for individuals depending on their specific abilities. Hence, optimal learning results are reached when instructions match the individual's aptitude. To our knowledge, the moderating role of VL level on the effectiveness of an adaptation on performance and usability perceptions has not been investigated yet.

We argue that understanding whether visualization adaptations are helpful for and perceived differently by users depending on their level of VL will be an important step in designing visualization support. Therefore, we investigate the differential effect that providing visualization adaptations have on participants' performance and user experience via an experimental study. We chose to study two visualization types, bar charts and scatter plots, as those are one of the most basic and widespread forms of visualization [SED19] and therefore represent an appropriate starting point for investigations. We selected the highlighting approach *De-Emphasis* [Car+14] as our adaptation strategy due to its simple and lightweight nature. Since we are one of the first to investigate the relationship of VL and adaptations, the choices were made to explore possible effects on a fundamental level before future research can take a look into more complex visualizations or adaptation strategies.

## 3.2 Background: Competence & Visualization Literacy

One of the most interesting and important skills of humans is their ability to understand and comprehend visual stimuli. This capability is also known as visual literacy, the *"ability to understand, interpret and evaluate visual messages"* [BD94] and consists of various dimensions for visual thinking, learning, and communication [Aan04; Tru99]. Further visual competencies, like visual production, perception, interpretation, and reception [Mül08] can also be seen as parts of this literacy. However, reading information visualizations doesn't solely rely on this kind of literacy. Instead, it requires an extended skill set, as described in Visualization Literacy or Data Visualization Literacy [BBG18]. Boy et al. [Boy+14] describe Visualization Literacy as *"the ability to confidently use a given data visualization to translate questions specified in the data domain into visual queries in the visual domain, as well as interpreting visual patterns in the visual domain as properties in the data domain"*. Different measurement approaches can be used to identify how well a person can work with a given visualization. In the following, we will highlight two of those while shortly mentioning other for this work less-fitting options as well.

Boy et al. [Boy+14] developed an assessment that is based on the Item Response Theory and calculates a value between -2 and +1 for one of three visualization types: line charts, bar charts, and scatter plots. Each visualization type can be assessed individually in a period of around 12 minutes via a total of twelve tasks (combination of question and static visualization). The tasks were constructed by six task types (min, max, variation, intersection, average, comparison) with two levels of distraction (for line charts and scatter plots), congruency (for line charts), or samples (for bar charts). Before the visualization itself is shown, the testees have time to get familiar with the question asked and the axis (or table outline) of the visualization (see Fig. 3.2). After that, the testees have eleven seconds to answer the presented multiple-choice question.



*Question:* On which planet does high expenditure per primary student lead to the highest adult literacy?

*Table:* Percentage of Adult Literacy by Expenditure per Student in Primary School on 10 Planets

| Planet | Expenditure per Student Primary (% of GDP per Capita) | Adult Literacy (% of total population, 15 and above) |
|---|---|---|
| Mardru | 11.4 | 71.5 |
| Hiberlac | 14.4 | 79.2 |
| Braal | 11.5 | 78 |
| Daribow | 8.4 | 65.9 |
| Urras | 12.3 | 84.5 |
| Livia | 31.1 | 99.7 |
| Cuthbert | 16.6 | 87.8 |
| Kallu | 17.3 | 79.1 |
| Kalanor | 10.9 | 67.8 |
| Sarkovy | 15.3 | 93 |

I have familiarized myself with the table headers

I have familiarized myself with the graph framework

**Fig. 3.2.:** The VL assessment of Boy et al. [Boy+14]. **(A)** and **(B)** show the base test on tables within each of the individual tests. **(C)** and **(D)** present one task which is part of the assessment of the VL for scatter plots. Lastly, **(A)** and **(C)** show the view of the preparation phase for each task, where only the axis or table header is shown.

The VLAT [LKK17] is a combined assessment using twelve different visualization types over a set of 53 multiple-choice questions and can generate a score between 0 and 53. To complete the test, the testees need around 35 minutes. Examples of visualization types used are line charts, bar charts, and scatter plots, but also more complex types like treemaps or stacked area charts. Further, the questions were created by eight visualization tasks presented by Amar et al. [AES05] (e.g., retrieve value, find extremum). The used multiple-choice questions were selected based on a content validity ratio, item difficulty index, and item discrimination index.

Lastly, also further VL assessments can be found [FJL22]. Those include assessments for treemap visualization [FDL20] or box plots and histogramms [DGO05]. Additionally, other tests exist that are not openly available, like the assessment of Maltere et al. [MSH15] or Börner et al. [BBG18], which is only provided as an online course. The latter describes a framework, its typology, and a process model used to create and define VL exercises and assessments. The typology is based on seven core types (e.g., data scales, visualization types, graphic variables, interaction). At the same time, the process model depicts the key processes necessary for data visualization construction and interpretation.

Overall, the level of prior knowledge and competencies affect how well a task can be accomplished and how difficult and strenuous the users will perceive the processing of the task. Therefore, assistance and support in the form of adaptations offered to the user are likely to have a different effect on individuals with either high or low levels of competence. More precisely, additional support may not be beneficial in every case but depends on the user's expertise level. The expertise reversal effect [Kal07; Kal+03] describes the phenomenon that instructional support positively affects individuals with low prior knowledge, whereas the effect on experts can be detrimental. This has been explained based on cognitive load theory [Swe88]. As external information and internal knowledge from long-term memory need to be integrated, the additional information that may be redundant for experts employs extra strain on their working memory. This increases cognitive load instead of reducing it and consequently diminishes experts' performance. In the context of information visualization, users with low levels of VL may benefit from specific support strategies, such as additional information or explanations on how to interpret the visualizations. In contrast, users with high VL may experience detrimental effects for the same support strategy.

## 3.3 Qualitative Online Study

In this study, we want to shed light on the moderating role of Visualization Literacy and of adapting visualizations on users' performance and user experiences. More specifically, we manipulated the presentation state (*Adapted* and *Non-Adapted*) of two Visualization Types (Bar Chart and Scatter Plot) in a randomized 2x2 factorial design. In the *Non-Adapted* condition, they were presented in their original format, that is, without highlighting any information in particular. In the *Adapted* condition, irrelevant information was de-emphasized to increase the salience of the relevant information (see Fig. 3.3). This adaptation approach was selected due to its simplicity, as it uses the pop-out [Mun14] effect of highlighting important groups of data points.

### 3.3.1 Study Goals & Hypotheses

Based on the summary of the related work and our described motivation, we generated three hypotheses:

| Low-Level Analysis Task | | Example Questions |
|---|---|---|
| Task 1 | Task 2 | |
| Filter | Derived Value (Average) | What is the average Life Expectancy for the **5 Latin American** Countries below? |
| Filter | Range | What is the range of Values for Children per Women in **OECD** Countries? |
| Filter | Derived Value (Sum) | What is the sum of GDP per Capita for all Countries with a GDP per Capita **above 3000$** in the year **2015**? |
| Filter | Derived Value (Average) | What is the average Child Survival Rate for **East-European & Centr.-Asian Countries**? |
| Filter | Derived Value (Count) | In how many regions is the Life Expectancy of **2006** above **70** years? |

Tab. 3.1.: All 5 task groups used in our study, which were created via a combination of two low-level analysis task [AES05]. The example questions represent one instance of this task group. The bold highlighted words in those questions were altered between the different repetitions, i.e., between the conditions. All questions and their answers are additionally presented in the appendix: Tab. A.1 and A.2.

**H1** **(Main effect of VL on task performance)** We expect participants' performance to get better with increasing VL.

**H2** **(Interaction effect of VL and Adaptation on task performance)** We expect the participants' task performance to increase while working with *Adapted* visualizations. At the same time, this effect should be pronounced for participants with lower VL.

**H3** **(Interaction effect of VL and Adaptation on user experience)** We expect that the user experience while working with *Adapted* visualizations increases for participants with lower VL. At the same time, the user experience decreases for participants with higher VL.

### 3.3.2 Participants

Our online experiment had a total response rate (participants finishing the experiment after starting it) of $38.4\,\%$ and a total of 43 completed data sets were submitted. All participants had a chance to win one of three 15€ Amazon vouchers. We excluded one data set, as it was evident from the answers that the participant clicked through the tasks as quickly as possible. For data security and anonymity reasons, we only recorded age groups, as requested by the data security board of our local university. Most of the 42 participants (19 female, 23 male) were in the age groups of 20 to 23 (9 out of 42), 21 to 27 (18 out of 42), and 28 to 31 (9 out of 42), the remaining six were older than 31 (6 out of 42). All participants reported an academic background. Three participants indicated to have a red-green weakness.

### 3.3.3 Questions

The questions were supposed to tap into the individuals' ability to use and interpret information visualizations. They were created based on the low-level analysis task taxonomy of Amar et al.'s [AES05], who clustered and described different primitive tasks that readers of visualizations perform. Concretely, we decided to use the low-level tasks of *Filter*, *Determine Range*, and *Compute Derived Value*. Each question in our study combines two (see Tab. 3.1) and was presented in a multiple-choice format with six or seven answer options (see appendix Tab. A.2).

As we had five repetitions within each condition, we created a set of five task groups. Each question in a task group is based on the same structure and was only altered in their specific values of the respective data attribute (e.g., country names or year) to allow for a set of four specific instances of these questions usable across the conditions. Thus, we ensured that the questions only differed superficially between conditions. In Tab. 3.1 we present both, the low-level analysis tasks and an example question for each.

### 3.3.4 Design of Visualization Condition

We constrained our study to two Visualization Types (Bar Chart and Scatter Plot) to limit the overall study duration. As an adaptation strategy, we used the De-Emphasis approach presented by Carenini et al. [Car+14] in the *Adapted* condition. For the study, we created a total of 20 visualizations (see Fig. 3.3 and Fig. 3.4) with Tableau [@Tab]: ten for each Visualization Type (five *Adapted* and five *Non-Adapted*). Each of the *Adapted* visualizations was handcrafted based on their corresponding question. All 20 visualizations were based on the same data set generated from gapminder[2]. The data set contained general population information (e.g., child mortality, life expectancy) of 184 countries over 50 years. Fig. 3.3 shows the schematic representation of the visualizations, while Fig. 3.4 shows a concrete visualization instance.

### 3.3.5 Visualization Literacy Assessment

To assess the influence of VL on the task performance and user ratings, we recorded the individual VL with regard to the used Visualization Types. We, therefore, used

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[2] To be more precise, we used the data from the following gallery example: `https://public.tableau.com/en-us/gallery/how-has-world-changed-1962`

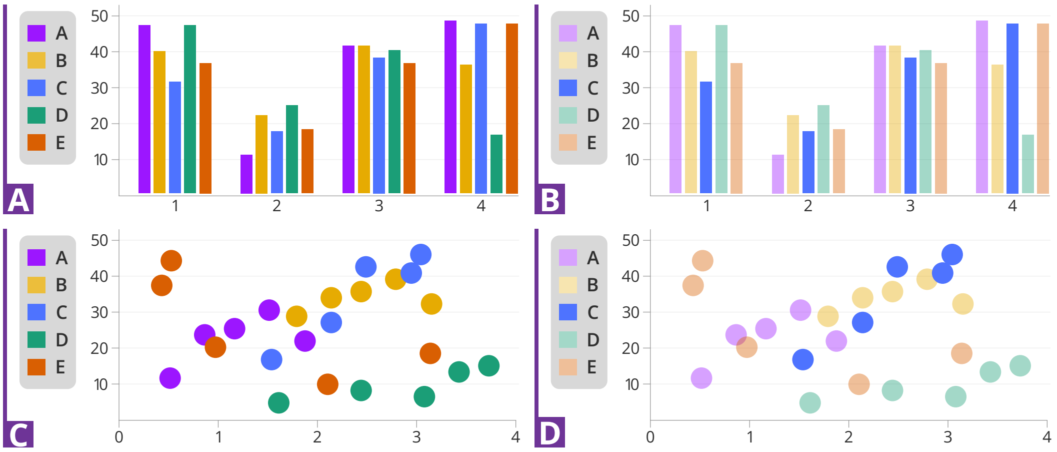

**Fig. 3.3.:** Schematic presentation of the used visualizations. **(A)** and **(B)** show a Bar Chart, while **(C)** and **(D)** depict a Scatter Plot. **(A)** and **(C)** show visualizations which are not adapted. On the other hand, **(B)** and **(D)** show adapted visualizations. In those, all other groupings that are not relevant for the task are de-emphasized (having a lower opacity and saturation) [Car+14]. A list of all visualizations can be seen in the appendix Fig. A.1.

the VL assessment of Boy et al. [Boy+14] to record the individual VL level of each participant. In the study, we redirected the participants to the provided online version of the test[3] (see Fig. 3.2). In general, the VL assessment allowed us to separately measure the VL scores for the two Visualization Types of Bar Chart and Scatter Plot as these are the types of visualizations we used for the tasks of this study. The test applies the Item Response Theory to assess VL using six tasks solved on twelve static visualizations [Boy+14] (see Sec. 3.2).

## 3.3.6 Task Performance Measures

The task performance was operationalized as the task completion time (TCT) and task accuracy (TA). For each task (combination of question and visualization), we recorded the TCT and the given answer. To reduce a potential effect from outliers on the TCT, each data point greater than $M + 2 * SD$ was defined as an outlier and was subsequently replaced by the exact value of this formula, as proposed by Field et al. [FMF12]. We replaced a total of $4.4\,\%$ values via this method. We used multiple-choice tests with up to seven options for the tasks, of which only one answer option was correct. Scoring for the TA was mapped to 1 if the answer was correct and 0 if the answer was incorrect.

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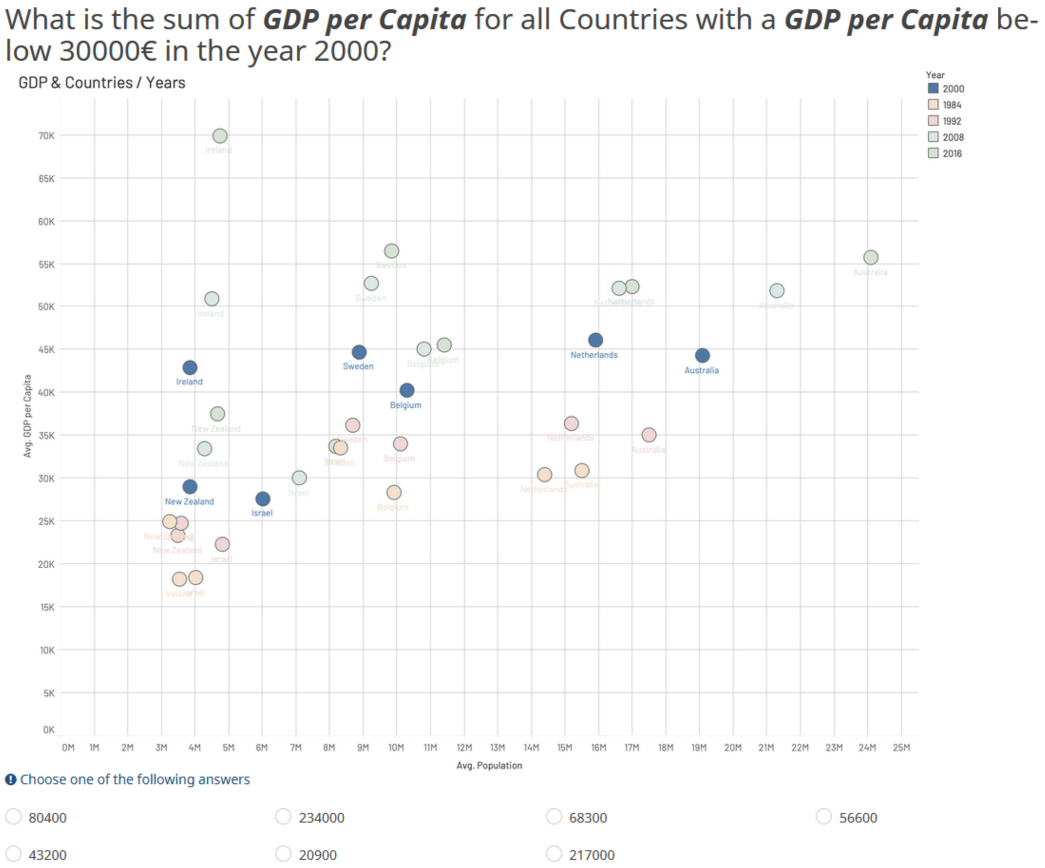
[3] The online version is no longer accessible. However, you can find the code in the GitHub repository: `https://github.com/INRIA/Visualization-Literacy-101`



What is the sum of ***GDP per Capita*** for all Countries with a ***GDP per Capita*** below 30000€ in the year 2000?

Choose one of the following answers

○ 80400 ○ 234000 ○ 68300 ○ 56600

○ 43200 ○ 20900 ○ 217000

**Fig. 3.4.:** A screenshot of one task from the online study, depicting an example of the *Adapted* Scatter Plot condition. The group of the year 2000 is highlighted by de-emphasizing irrelevant points.

### 3.3.7 User Experience Measures

To measure user experience, we chose the User Experience Questionnaire Plus (UEQ+)[4] [ST19; SHT17; LHS08]. Each scale within the questionnaire contains four questions on a seven-step Likert scale. As described by Laugwitz et al. [LHS08], we derived the score for each of the three UEQ+scales by computing the mean of the four corresponding questions. For our study, we made use of three scales. These scales assess whether users feel:

**Dependability:** if they are under the control of the generated data and can therefore trust them

**Usefulness:** if using the visualization provides an advantage for their personal productivity

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[4] English version of the questionnaire available here: `http://ueqplus.ueq-research.org/`

**Intuitive Use:** if they feel that they can use the visualization immediately and intuitively without any tutorial or on-boarding

Additionally, we asked the participants to state whether they preferred the *Adapted* or *Non-Adapted* version of both Visualization Types. Participants were asked to briefly explain their preferences by responding to the following questions: Why did you choose this answer? What did you perceive as frustrating during task solving? What did you like about the visualizations?

### 3.3.8 Setup & Procedure

We conducted the study as an online experiment implemented in LimeSurvey [@Lim]. The promotion was done via several mailing lists in our local university and over two survey websites[5]. The survey consisted of the following parts:

(1) A demographic questionnaire
(2) VL assessment [Boy+14] for Bar Chart, followed by Scatter Plot
(3) The *Non-Adapted* tasks
(4) The *Adapted* tasks
(5) A post-task questionnaire focused on user preferences and procedures.

We decided to present the task on *Non-Adapted* visualization (3) before the *Adapted* visualizations (4) were shown, to reduce the possibility of carry-over effects of the adaptations. Further, the order of the five visualization tasks within each task block (3 and 4) was randomized, thus reducing possible anchoring effects. As we redirected the participants to the online version of the VL assessment of Boy et al. [Boy+14], we asked them to report their received score after they completed the assessment, this way making the scores available to us. After each subphase in (3) and (4), the participants were asked to answer the user experience questionnaire [ST19]. The total duration of each session averaged to approximately $50\,\text{min}$ ($M = 50.26\,\text{min}, SD = 14.57\,\text{min}$) while approximately ($M = 12.24\,\text{min}, SD = 4.47\,\text{min}$) were needed for the Bar Chart and for the Scatter Plot VL assessment each.

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[5] To find additional study participants, we promoted our study via `https://surveyswap.io/` and `https://www.surveycircle.com`

## 3.4 Results

The following section will present the findings and results of our study. For that, we first present the descriptive data of the VL score before describing our data analysis approach and the related findings in detail.

### 3.4.1 Data Analysis

The following statistical tests were independently performed on the data sets for bar charts and scatter plots using JASP [@The]. For our analysis, we used multilevel modeling [FMF12; Win13; SK19], which allows for *"simultaneous study of relations among group-level and individual-level variables"* [Gre00]. We constructed linear mixed models for the dependent variable time and generalized linear mixed models (GLMM) [BDB08] for the dichotomous dependent variable accuracy. We followed the instructions from Singmann et al. [SK19] for constructing the models. In order to test the main effects and interaction effects of the fixed effect factors, we used the likelihood test ratio method to compare the crossed random effect models. In these models, we included the continuous value of VL as a fixed variable to test the main effect of VL score on the dependent variables. To address our question of how adaptation influences performance, we added the categorical value of Adaptation as a fixed effect variable in our models as well as the interaction of VL and Adaptation. The two experimental conditions, *Adapted* and *Non-Adapted*, were administered to all participants, i.e., as a within factor. Therefore, we ended up with several repeated measurements for each person. The measurements from the same person are likely more similar than two independent measurements from different people and are therefore correlated. In order to account for the correlated values of the repeated measures in the conditions *Adapted* and *Non-Adapted*, we used participants as a random effect grouping factor. The task groups (see Sec. 3.3.3) were also added as a random effect, as the answers for tasks of the same task group are likely to be more similar than answers for tasks of different task groups. With that, answers for the items from the same group will be correlated (not included for the user experience, as task groups cannot split those). An overview of the model fits can be found (on Page 38) in Tab. 3.2 and Tab. 3.3, while Tab. 3.4 and Tab. 3.5 present the fixed effects of the independent factors. Further, Fig. 3.6 and Fig. 3.7 visualize the mixed linear regressions of our data.

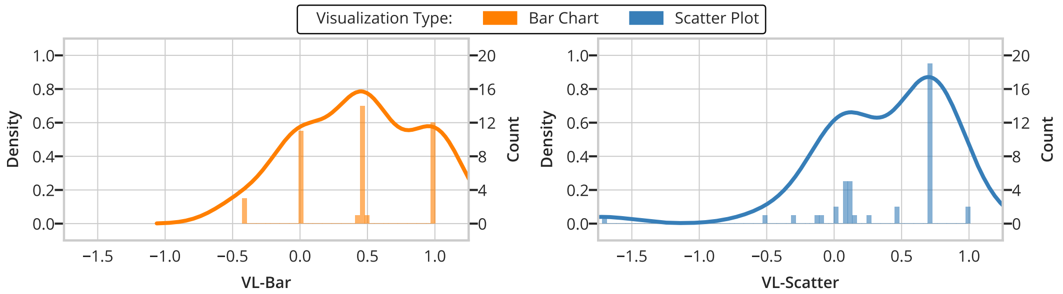

**Fig. 3.5.:** The kernel density estimation (KDE) plot of the VL scores for both Visualization Types.

### 3.4.2 Visualization Literacy Scores

Descriptive analyses of the distribution of the VL scores showed that it differed from the distributions reported by Boy et al. [Boy+14] for both visualization types. Participants in our sample showed a much higher mean VL score of $-0.43$ to $1$ ($M = 0.434$, 7 different scores) for Bar Chart and $-1.72$ to $1$ ($M = 0.363$, 14 different scores) for Scatter Plot, whereas Boy et al. reported a score of $-1.67$ to $0.99$ ($M = -0.39$, 21 different scores) for Bar Chart and $-1.72$ to $0.72$ ($M = -0.14$, 23 different scores) for Scatter Plot (see Fig. 3.5). A reason for this divergence could be the mostly academic background of our participants. Since visualizations play a vital role in academic teaching, thinking, and work, it may be that subjects in our study have had more practice than the average population resulting in higher levels of VL [MSH15]. The subjective ratings for different visualizations also confirm this. They show on a five-step rating scale medium to high familiarity ratings for bar charts ($M = 4.21, SD = 0.68$), scatter plots ($M = 3.05, SD = 1.45$), and for line charts ($M = 3.86, SD = 0.90$). In general, Wilcoxon signed-rank tests showed a significant difference between both visualization type familiarities ($W(41) = 399,\ p<.001,\ r = .966$), while we didn't find such a significance for the VL scores ($W(41) = 418.5,\ p=.18,\ r = .257$) themselves. Additionally, we couldn't find a correlation between the VL and familiarity for Bar Charts ($r_{Pearson} = .133, p<.399$) or Scatter Plots ($r_{Pearson} = .051, p<.749$).

### 3.4.3 Task Completion Time

For the TCT, we used a linear mixed model (see Fig. 3.6) without random slopes as it showed the best model fit. For Bar Chart, we found a relationship between the VL ($\chi^2(1) = 4.009, p<.05$), Adaptation ($\chi^2(1) = 20.432, p<.001$), and their interaction ($\chi^2(1) = 8.882, p<.01$) on the TCT across the participants and task groups (see

| Effect | Task Completion Time | | | Task Accuracy | | | Dependability | | | Usefulness | | | Intuitive Use | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | df | $\chi^2$ | p | df | $\chi^2$ | p | df | $\chi^2$ | p | df | $\chi^2$ | p | df | $\chi^2$ | p |
| VL | 1 | 4.009 | .045 | 1 | 0.746 | .388 | 1 | 1.731 | .188 | 1 | 0.785 | .376 | 1 | 3.391 | .066 |
| Adaptation | 1 | 20.43 | < .001 | 1 | 2.702 | .100 | 1 | 12.65 | < .001 | 1 | 5.429 | .020 | 1 | 6.160 | .013 |
| VL * Adaptation | 1 | 8.882 | .003 | 1 | 0.050 | .824 | 1 | 2.870 | .090 | 1 | 0.515 | .473 | 1 | 0.194 | .660 |
| BIC | | | 3527.682 | | | 393.081 | | | 287.674 | | | 309.694 | | | 291.323 |

**Tab. 3.2.:** ANOVAs for the **Bar Chart** tasks, comparing our models to the respecting reduced model in which the parameter corresponding to the effect is fixed to 0. BIC is the abbreviation for Schwarz's Bayesian Criterion. (🟩: $p < .05$, 🟩: $p < .01$, 🟩: $p < .001$)

| Effect | Task Completion Time | | | Task Accuracy | | | Dependability | | | Usefulness | | | Intuitive Use | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | df | $\chi^2$ | p | df | $\chi^2$ | p | df | $\chi^2$ | p | df | $\chi^2$ | p | df | $\chi^2$ | p |
| VL | 1 | 6.365 | .012 | 1 | 3.499 | .061 | 1 | 1.079 | .299 | 1 | 0.419 | .517 | 1 | 3.354 | .067 |
| Adaptation | 1 | 40.87 | < .001 | 1 | 16.74 | < .001 | 1 | 16.254 | < .001 | 1 | 7.576 | .006 | 1 | 14.832 | < .001 |
| VL * Adaptation | 1 | 1.304 | .254 | 1 | 0.059 | .808 | 1 | 2.483 | .115 | 1 | 0.142 | .706 | 1 | 1.948 | .163 |
| BIC | | | 3505.071 | | | 439.379 | | | 260.419 | | | 276.798 | | | 266.047 |

**Tab. 3.3.:** ANOVAs for the **Scatter Plot** tasks, comparing our models to the respecting reduced model in which the parameter corresponding to the effect is fixed to 0. BIC is the abbreviation for Schwarz's Bayesian Criterion. (🟩: $p < .05$, 🟩: $p < .01$, 🟩: $p < .001$)

| Term | Task Completion Time | | | Task Accuracy | | | Dependability | | | Usefulness | | | Intuitive Use | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | b | SE b | t | b | SE b | t | b | SE b | t | b | SE b | t | b | SE b | t |
| Baseline | 43.07 | 5.279 | 8.158 | 1.122 | .975 | 1.151 | .790 | .221 | 3.569 | 1.129 | .241 | 4.677 | .790 | .229 | 3.451 |
| VL | -7.046 | 3.343 | -2.052 | .346 | .452 | .765 | .476 | .358 | 1.329 | .348 | .390 | .980 | .696 | .370 | 1.879 |
| Adaptation | -4.430 | .967 | -4.583 | .747 | .390 | 1.914 | .535 | .139 | 3.842 | .399 | .166 | 2.407 | .362 | .141 | 2.576 |
| VL * Adaptation | 4.689 | 1.564 | 2.998 | -.084 | .322 | -.261 | -.388 | .225 | -1.723 | -.193 | .268 | -.720 | -.100 | .227 | -.441 |

**Tab. 3.4.:** An overview of all fixed effect estimations for each dependent variable in the **Bar Chart** tasks. (🟩: $p < .05$, 🟩: $p < .01$, 🟩: $p < .001$)

| Term | Task Completion Time | | | Task Accuracy | | | Dependability | | | Usefulness | | | Intuitive Use | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | b | SE b | t | b | SE b | t | b | SE b | t | b | SE b | t | b | SE b | t |
| Baseline | 38.91 | 3.892 | 9.997 | 1.354 | .420 | 3.225 | 1.040 | .205 | 5.081 | 1.344 | .204 | 6.594 | 1.000 | .199 | 5.025 |
| VL | -8.032 | 3.062 | -2.623 | .639 | .361 | 1.769 | .349 | .333 | 1.045 | .216 | .332 | .649 | .606 | .324 | 1.869 |
| Adaptation | -5.368 | .817 | -6.571 | .641 | .155 | 4.126 | .378 | .085 | 4.455 | .298 | .104 | 2.882 | .393 | .093 | 4.218 |
| VL * Adaptation | 1.521 | 1.331 | 1.143 | .157 | .243 | .646 | -.221 | .138 | -1.599 | .064 | .169 | .377 | -.215 | .152 | -1.412 |

**Tab. 3.5.:** An overview of all fixed effect estimations for each dependent variable in the **Scatter Plot** tasks. (🟩: $p < .05$, 🟩: $p < .01$, 🟩: $p < .001$)

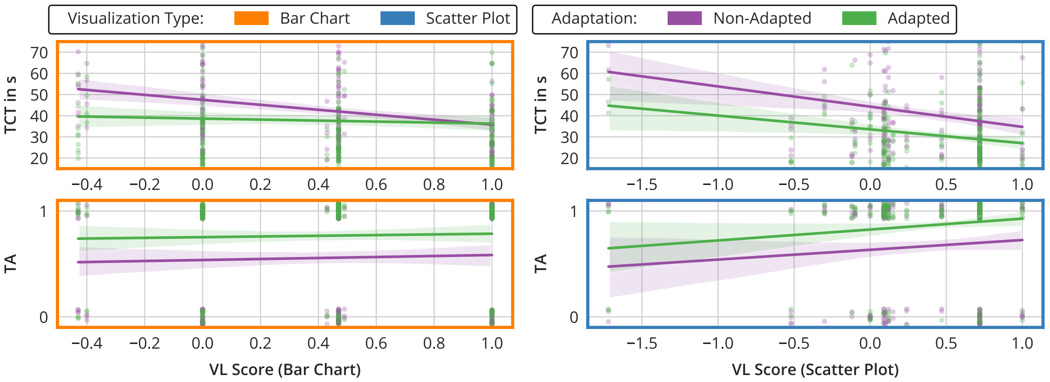

**Fig. 3.6.:** The linear regression for the task performance values over the VL split by Visualization Type (different plots) and Adaptation (different lines). The graphs in the left column present the data of the Bar Chart, while the graphs in the right column show the data of the Scatter Plot. Further, each line presents one of the two task performance values measured in our study, which are task completion time (TCT) and task accuracy (TA) respectively. The shadow behind the lines show the confidence interval of 95%, and the dots present each individual measurement. For the TA, a jitter on the y axis for the dichotomous value was introduced to reduce overplotting.

Tab. 3.2). This in turn shows that the TCT can be significantly predicted by the VL ($b = -7.046, t = -2.052, p<.05$), by the Adaptation ($b = -4.43, t = -4.583, p<.001$), and the interaction of both ($b = 4.689, t = 2.998, p<.01$) (see Tab. 3.4). In contrast, for the Scatter Plot, we found only a relationship between VL ($\chi^2(1) = 6.365, p<.05$) and Adaptation ($\chi^2(1) = 40.867, p<.001$) on the TCT, but no interaction effect (see Tab. 3.3). This in turn shows that the TCT can be significantly predicted by the VL ($b = -8.032, t = -2.623, p<.5$) and the Adaptation ($b = -5.368, t = -6.571, p<.001$) (see Tab. 3.5).

### 3.4.4 Task Accuracy

For the TA, we used a generalized linear mixed model (see Fig. 3.6) of the binomial family (logit link[6]) and a random slope for Adaptation. For Bar Chart, we did not find any relationship between the fixed effects and the TA (see Tab. 3.2). For the Scatter Plot, we found a relationship between the Adaptation ($\chi^2(1) = 12.774, p<.001$) and the TA (see Tab. 3.3). This in turn shows that the TA can be significantly predicted by the Adaptation ($b = 0.641, t = 4.126, p<.001$) (see Tab. 3.5).

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[6] With logit link, we transform a binary response into a continuous outcome space. In linear regression, we assume the error term to be normally distributed. In binary response and other models, we need to impose/assume a distribution on the error terms. The link function is the cumulative probability function that the error terms follow.

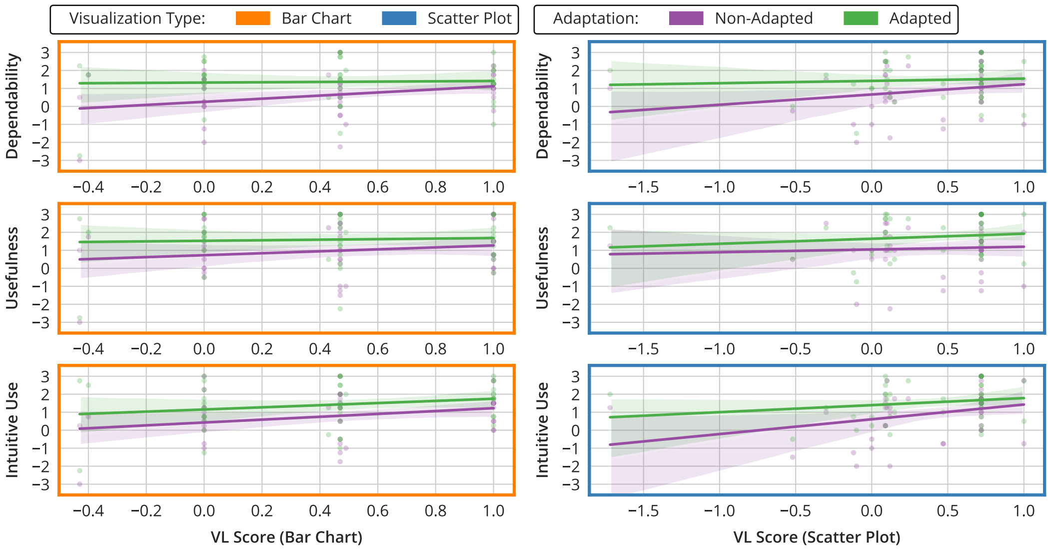

**Fig. 3.7.:** The linear regression for the user experience values over the VL split by Visualization Type (different plots) and Adaptation (different lines). The graphs in the left column presents the data of the Bar Chart, while the graphs in the right column show the data of the Scatter Plot. Further, each line presents one of the three user experience scales measured in our study, which are Dependability, Usefulness, and Intuitive Use respectively. The shaded band indicate the confidence interval of 95%, the dots represent individual measurements.

### 3.4.5 User Experience Ratings

For all three user experience scales we used a linear mixed model (see Fig. 3.7) without random slopes as they showed the best model fit. For Bar Chart, we found a relationship between the Adaptation and the Dependability ($\chi^2(1) = 12.65, p{<}.001$), Usefulness ($\chi^2(1) = 5.429, p{<}.05$), and Intuitive Use ($\chi^2(1) = 6.16, p{<}.05$) but no effects of Adaptation and no interaction effect (see Tab. 3.2). This in turn shows that the Adaptation can predict significantly the Dependability rating ($b = 0.535, t = 3.842, p{<}.001$), Usefulness rating ($b = 0.399, t = 2.407, p{<}.05$), and Intuitive Use rating ($b = .362, t = 2.576, p{<}.05$) (see Tab. 3.4). The same holds true for the Scatter Plot, where we found a relationship between the Adaptation and the Dependability ($\chi^2(1) = 16.254, p{<}.001$), Usefulness ($\chi^2(1) = 7.579, p{<}.01$), and Intuitive Use ($\chi^2(1) = 14.832, p{<}.001$) (see Tab. 3.3) showing that the Adaptation can predict significantly the Dependability rating ($b = 0.378, t = 4.455, p{<}.001$), Usefulness rating ($b = 0.298, t = 2.882, p{<}0.01$), and Intuitive Use rating ($b = 0.393, t = 4.218, p{<}.001$) (see Tab. 3.5). We found no effects for VL and no interaction effects.

### 3.4.6 Qualitative Data

Our data showed that the participants slightly preferred the *Adapted* visualizations over the *Non-Adapted* ones, for both the Bar Chart (23 out of 42) and the Scatter Plot (26 out of 42). This was further supported by participants' comments, stating that the Adaptation helped them to focus on the given task (20 out of 42). For example, one participant stated that *"already knowing what to focus on before fully reading the task description was rewarding, and [I] felt more confident"* (P8). In addition, some participants reported a beneficial effect of the color (16 out of 42) (e.g., *"different colors [helped] to differentiate [data points] better"* (P1)). Some participants also recognized the need to apply an adaptation, as they perceived the amount of information in the visualization as too high (10 out of 42). Specifically, one participant found *"graphs where too much data was presented simultaneously"* (P41) as frustrating. Some participants also highlighted that the tasks were challenging (7 out of 42). One participant stated that *"understanding the question and searching for the applicable bars/dots"* (P34) was also frustrating. In summary, the participants acknowledged the benefits of an adaptation concerning the presentation, data amount, and task. One participant concluded: *"[It is frustrating,] when colors are not immediately highlighted, which adds a couple of seconds - especially for scatter plot value points"* (P9).

### 3.4.7 Hypotheses Results

The principal findings of our study are the following. Firstly, we found a significant effect of VL on the TCT where higher levels of VL were associated with lower TCT for Bar Chart and Scatter Plot (see Fig. 3.6). However, for the performance indicator TA, we did not find a significant effect of VL. Therefore, **H1** that assumed better performance of participants with higher VL was only partly confirmed as only time was affected by VL level but not accuracy. For the user experience ratings, we also did not find any significant effects of VL level.

We manipulated whether participants received adaptations or not while working with visualizations. We found that adaptations had a positive effect on both the task performance and the user experience for all participants (see Fig. 3.7). Participants working with *Adapted* visualizations needed less time to answer the questions for Bar Chart and Scatter Plot. For Scatter Plot, we also found a significant positive effect of adaptations on the TA of the answers, which we did not see for Bar Charts. As we were particularly interested in exploring whether the effect of an adaptation is dependent on the level of VL, we also analyzed the interaction effect of VL and

Adaptation on the performance. We found an interaction effect on the TCT for Bar Chart (see Fig. 3.6), indicating that participants with lower VL benefited more from the adaptations than participants with higher VL. However, we did not find any interaction effects for accuracy in Bar Chart, nor for Scatter Plot. Hence, **H2** stating more considerable benefits of the adaptations for participants with low VL concerning the performance parameters was only partly confirmed.

Participants working with *Adapted* visualizations reported higher ratings in the three scales of user experience (Dependability, Usefulness, and Intuitive Use) for Bar Chart and Scatter Plot (see Fig. 3.7). However, we did not find any interaction effect of VL and Adaptation for any user experience ratings. Therefore, our results show that a low-level adaptation, such as the De-emphasis approach, appears to be beneficial for all participants regarding user experience rather than providing an additional beneficial effect for those with lower levels of VL as hypothesized in the first part of **H3**. Further, we did not find any detrimental effect of Adaptation for higher levels of VL as hypothesized in the second part of **H3**. Henceforth, we reject **H3**. We conjecture that one reason for the missing interaction effects may be that the type of adaptation used in this study reduces the amount of information presented to the users. Hence, it is likely that users across different VL scores would positively benefit from this type of adaptation.

## 3.5 Discussion

This study provided participants with two types of visualizations (Bar Chart, Scatter Plot) and manipulated their presentation (*Non-Adapted* vs. *Adapted* via De-Emphasis) in order to investigate how VL influences performance (TCT, TA) and user experiences (Dependability, Usefulness, Intuitive Use) if users have to work with these visualizations. Hence, the results add to the growing body of research on how to apply adaptive visualizations. In the following sections, we will first summarize and discuss our findings with regard to our three hypotheses (see Sec. 3.3.1), as well as addressing limitations and providing an outlook for future work.

### 3.5.1 Adaptation Strategies

Besides the interaction effect of adaptation and VL on TCT for Bar Charts, we did not find support for the notion that the effect of the adaptation varies for different levels of VL. However, it is conceivable that the pattern of results may change if the type of adaptation is replaced. For example, other types of adaptations could involve the presentation of additional visual elements, which are used as dynamic details on demand, overlays, tooltips, or highlights. While the introduced elements convey support as additional information, they may hinder more experienced users. For experts who already know the information that the additional details aim to convey, they might add unnecessary cognitive load because they need to be integrated into their existing knowledge structures [Kal07]. On the other hand, the additional information may facilitate understanding more complex visualizations for inexperienced users, i.e., users with lower VL. Another alternative to adapting a visualization is to replace a given visualization type with another. However, a change of the complete visualization type could adversely affect users with low VL, as they may be overwhelmed by the new visual representation of the data. At the same time, subjects with high VL may profit from a different representation format as it may make relationships within the data apparent that they did not recognize before. In that sense, a different representation may act similarly as a differently framed explanation (e.g., an analogy) for a complex set of facts [CL05].

From these considerations, it becomes apparent that the direction of expected interaction effects of adaptations and VL level will likely depend on the visualization type and the type of adaptation applied. Therefore, we believe that investigating how the VL level affects the benefit of specific adaption approaches is essential for designing and developing adaptive visualizations.

### 3.5.2 Visualization Types

In our study, we investigated the effects of VL and Adaptation on two simple visualization techniques: Bar Chart and Scatter Plot. Overall, participants rated to be more familiar with Bar Chart than with Scatter Plot (see Sec. 3.4.2). However, this was not reflected in the VL scores, i.e., we did not find any significant differences between individual VL scores for the different types (see Sec. 3.4.2). Instead, we found better performance in tasks with Bar Chart than in tasks with Scatter Plot on a descriptive level. Furthermore, the findings show that the effect of the Adaptation on the task performance and user experience for the Scatter Plots was greater than those for the Adaptation of the Bar Chart (see Tab. 3.4 and Tab. 3.5). Therefore, we suspect that Scatter Plot were perceived as more demanding and complex by our participants, thus increasing the potential benefit through the applied adaptation on a subjective level. On the other hand, we could find an interaction effect of both independent variables on the Bar Chart. This can be explained by the higher effectiveness of the De-Emphasis approach because bars make up a larger portion of the diagram than the points in a Scatter Plot. Furthermore, the general higher VL score for Bar Chart (see Fig. 3.5) shows that several participants were already quite familiar with this Visualization Type. Lastly, our used visualization types of Scatter Plots and Bar Chart are prevalent in our everyday life. In contrast, other types (e.g., parallel coordinate plots, tree maps) are less common, reducing the general experience with them. This may make the adaptation for less-used and known visualizations more valuable. Further, these results show that the quality and the layout of visual marks influence the effectiveness of a given adaptation. Since the results of this study are limited to Scatter Plots and Bar Charts, we see a need for future research to investigate other visualization types.

### 3.5.3 Visualization Literacy Assessment

With the assessment of the VL, we could derive an indicator that captures the individuals' competence to deal with a given visualization type. The overall VL level within our sample seemed to be above average (see Sec. 3.4.2). One reason for this could be the academic background of the participants in our sample [MSH15]. Since visualizations play a vital role in academic teaching and thinking, academics are likely more accustomed to and practiced at dealing with information visualizations resulting in high levels of VL. Therefore, we can only conclude the interplay of VL and adaptation for a limited range of VL scores. Notwithstanding, results may differ for users with lower levels of VL. Hence, it would be very interesting to recruit a less homogeneous sample in a subsequent study to get a broader picture of the effect of different VL levels. In order to substantiate the results and to gain a complete picture, it will be necessary to conduct a study with a greater sample size.

Through the use of the VL assessment of Boy et al. [Boy+14], we were able to collect separate VL scores for two different types of visualizations. We did not find a significant difference between individual VL scores for the two visualization types in a Wilcoxon signed-rank test (see Sec. 3.4.2). Nevertheless, the VL scores were correlated with the task performance indicator TCT, but not with TA. This can be explained by the conception of the tasks used in the VL assessment of Boy et al. It is based on the Item Responsive Theory, thus putting a particular focus on the speed of task completion. To be more precise, participants had only eleven seconds to answer tasks after an opportunity to familiarize themselves with the presented axis of a visualization (see Fig. 3.2). Furthermore, we were not able to find a correlation between the VL scores and the familiarity ratings of the participants (see Sec. 3.4.2). Since familiarity could also be related to how often participants encountered a given visualization type, we think pure familiarity cannot predict how well a participant performs.

Overall, we think the quality of the VL assessment should be improved by the following lines of research. Firstly, it should be investigated whether aggregated scores of VL, like the VLAT [LKK17] that does not differentiate between VL facets but provides an overall score for VL could give a better indicator. It may be that its results are more reliable but possibly less helpful to base adaptations upon because of their lack of specificity for particular visualization types. However, a drawback of aggregated tests is their longer assessment duration (in the case of VLAT [LKK17] 30 to 40 minutes on average), which in turn makes it less practical for a quick pre-testing of VL required for individualized adaptations. In our study, both visualization types were separately influenced by the adaptations, which lets us conjecture that it is beneficial to differentiate between visualization types. Therefore, the various visual marks of each type, such as bars, circles, or lines, likely require different sets of visual and cognitive processes.

Another vital step that will bring the tests of VL and their application forward (e.g., adaptive visualizations) is establishing reference-group-based rankings for the assessment tools. They will allow for an informed evaluation of test results concerning the expected score distribution in a reference group and hence discern whether results are average, bigger, or smaller. Up to now, the informed comparison has been impossible due to a lack of reference groups. Further, test results should be validated by comparing suitable external criteria such as performance or familiarity. We aimed to add to this by correlating VL scores with the familiarity ratings and performance values gathered in this study. Other studies have already shown that VL correlates with the need for cognition and numeracy [Lee+19]. We believe that validation of existing VL assessments and improvement of the same pose a necessary precondition for advancements in the VL-based visualization adaptations. In order to use VL scores effectively, the assessment tools need to measure reliably. Therefore, reliability scores of assessment tools need to be derived.

In our study, we concentrated on investigating how to support participants with concurrent support (i.e., just-in-time adaptations) while participants worked on the tasks. However, the issue of improving VL in the long run, for example, through adequate teaching techniques, is equally important [Sto+19]. Previous work developed programs that aim at improving VL in children and students [Huy+21; Alp+17] or through an onboarding procedure [Sto+19]. It is also conceivable that visualization adapted to meet a user's needs may be more enjoyable to work with. This can lead to more use and exposure to the visualizations and thus ultimately adding to a better understanding and improving VL in the long term. In conclusion, we can say that the research on how to use VL as a user characteristic for individualized visualization adaptations is still in the very beginning. Consequently, many exciting research questions emerge from our study results. We hope that we can spark interest in this important topic.

## 3.6 Chapter Conclusion

In this work, we investigated the effect of visualization strategies, i.e., De-Emphasis, on bar charts and scatter plots with regard to the user characteristic Visualization Literacy (VL). Our findings suggest that considering individual VL levels may be a promising way to create adaptations tailored to individual needs. Further research is required to substantiate the effect of other visualizations and adaptations as seen for treemaps [FDL20] and histograms and boxplots [DGO05]. We hope our work can be used as a stepping stone in future research on adaptive visualizations based on VL.

At the beginning of this chapter, I described that VL is independent of the output medium of AR. However, it is not less critical since AR can be used for visual data analysis, as seen with IA. In general, AR demands an extended set of visual literacy of the users as described by Hurley [Hur22]. In the case of HMDs, this also extends to the general capability of depth and stereoscopic perception. With this, it is possible to natively show 3D visualization in AR, which are already partly used on common 2D output mediums, like seen with time-oriented data [@TA23; Aig+11]. Looking back at possible VL assessments, none incorporate 3D visualizations. Additionally, as being in the same space as the data promotes spatial movement and understanding of the users, general spatial abilities also become essential to consider [Dre+23]. Lastly, AR visualizations not only need their own set of VL but can also be used in the education domain [Wu+13] to foster and train literacy in general [YT20].

All in all, while I investigated the effect of VL separate from AR, it is clear that the general capability to work with visualizations also transfers to the IA application domain. In the following, I first want to understand how placing visualizations in an immersive environment affects their usage before further investigations of VL in AR should be conducted. Specifically, I want to look next into another fundamental user characteristic – visual perception.

# 4

# Influence of Real-World Backgrounds on the Perception of AR Visualizations

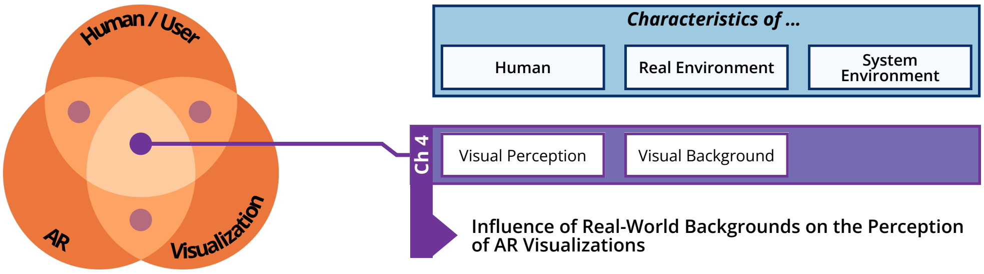

**Fig. 4.1.:** This research project (Ch. 4) is situated in the Augmented Reality (AR), Visualization, and Human/User cross-section. Within this project, I focus on human visual perception and the influence of the visual background always present in the environment.

AR lets users experience an environment that does not exist in the physical world by imitating and arousing different senses of humans. Compared to VR, AR is not meant to completely shut off and separate the user from the existing real world. On the contrary, AR aimed to combine sensory information from the virtual and real world, as seen in the research focused on embedded [WJD17] or situated [Bre+22] data representation. However, a combination of both can also negatively affect the presentation quality of content as virtual content overlays the real world. This can cause, e.g., an alteration of the presented colors or distorting patterns and textures. Furthermore, even the presence of other visual stimuli beside and around a virtual content element can make it harder to visually differentiate, understand, and interpret them. With this, the visual background is not only an real-world environmental characteristic but also influences the user's characteristics of visual perception (see Fig. 4.1). Henceforth, with the here presented research project we[1] will explore the influence of real-world visual backgrounds on the perception of 2D data visualizations. To achieve this, we contribute the following:

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[1] "We" in this chapter relates to the author Marc Satkowski, as well as Raimund Dachselt as co-contributor to this research.

- A detailed motivation for this research project (Sec. 4.1), including related background (Sec. 4.2) revolving around the visual perception in AR and the measurement and definition of visual clutter.
- One study (Sec. 4.3) focused on the influence of the visual background and the visual complexity of visualizations on performance and user experience.
- A second study (Sec. 4.4) investigating the influence of the visual background and a dual task design.
- A discussion (Sec. 4.5) of our findings and the limitations of our approach.

Parts of the research presented in this chapter have previously appeared in:

**Marc Satkowski** and Raimund Dachselt. "Investigating the Impact of Real-World Environments on the Perception of 2D Visualizations in Augmented Reality". In Proceedings of: *ACM Conference on Human Factors in Computing Systems (CHI)*. Yokohama, Japan, May 8–13, 2021. [SD21]

*Own Contribution:* I was the major contributor to the complete project, which includes the study design, conducting the study, analyzing the data, and discussing the results.
*Applied Changes:* This chapter does not differ heavily from the published article. In general, the related work was split up and only partly presented in this chapter, while visualizations were partly recreated and also added from the supplemental material of this corresponding publication.

## 4.1 Motivation

In the past, AR research often focused on displaying additional 3D objects or simple visual elements like text [SH16]. In comparison, we can observe a rising interest in effectively integrating more complex and even abstract information into real-world scenes. This is exemplified by trends such as situated, embedded [WJD17; SH16; ESL13], and immersive analytics [Mar+18] as new areas of data visualization. While the immersive visualization research community is quite active with regard to these topics [FP19; Kim+18], it was still unsure how the environment that those visualizations are used in or even embedded in influences how visualizations are perceived in the first place. Such an understanding can help us to make informed decisions on how and where information can be presented in AR. This is especially necessary to elevate AR technology to a tool used in casual everyday situations and productive scenarios, like modern production plants. For such a tool, it is essential to present information with simple visual representations (e.g., text) and in a more advanced and complex presentation style, as commonly seen for data visualizations.

Information visualizations (e.g., line charts or scatter plots) show abstract and often complex data by combining different relatively simple visual elements (e.g., text, lines, bars). The perception of such elements has already been studied, and design recommendations were presented as well [Gat+15a; Fio+13]. However, to our knowledge, a deeper understanding of how more complex visualizations are perceived in AR is lacking. This gap is especially crucial to be closed for immersive analytics [Mar+18] applications that use AR to generate insights often directly linked to real-world objects. However, other application domains would also benefit from findings in this research area. Traditional use cases for AR range from instructions over manuals to training (an overview can be found in [WON16]). Tourism [KKZ12], education [Wu+13], and even grocery shopping [BMD18; Alb+15] are further possible scenarios. All those differ regarding their real-world environments, including the background, noise, or lighting. Some use cases are more demanding and challenging than others. While use cases like tourism often focus on more casual interaction, AR applications for industrial scenarios clearly aim to use AR as a productive tool. When operators have to observe complex data (e.g., trend charts) augmented to several machines, they also face complex visual backgrounds besides concentrating on their primary task. Inspired by the wish for productive tools in the challenging industrial context of AR visualizations, but not limited to this domain, we want to better understand the influence of the background scene in the perception of AR visualizations.

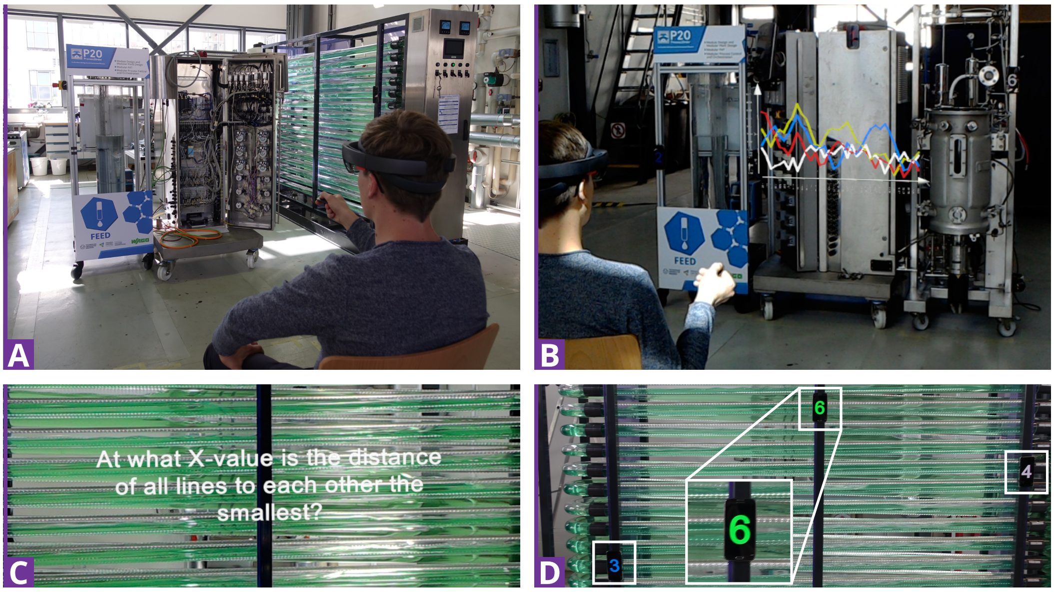

**Fig. 4.2.:** Different aspects of the design of our user studies: **(A)** and **(B)** show a subject sitting in front of two background configurations. **(B)** illustrates subjects solving a task on the shown visualization in front of background *BG4*, while **(C)** depicts a question on *BG3*. **(D)** shows three additional displays (indicated by white squares) with different signal colors and numbers that simulate a secondary observation task for the second study.

We investigate the influence of the visual background while working with AR visualization through two user studies. The studies were conducted in an experimental production plant which allowed us to create different background configurations (see Fig. 4.2). We manipulated the number of shown data points in our first study. However, this does not fully reflect a real-world use case since operators often have to interact with the presented AR content and the machines in front of them. For this reason, we added a secondary observation task coupled with the background for the second study to simulate such a scenario. Most current research investigating AR takes place in strictly controlled laboratory environments and often uses 2D pictures of 3D scenes as visual backgrounds (as seen in [Lu+14a; Lu+14b]). Instead, we focused on one real-world scenario for our studies: industrial production plants. However, we enabled the generalization of our findings to other settings and domains by using a generally applicable measurement of the visual background texture. The results of our studies show an unexpected result: real-world backgrounds have far less influence on the measured performance than expected. Having said that, the subjective reports of our participants reveal that the perceived influence differs from the measured one. We understand our work as part of a research agenda to make Augmented Reality - and AR visualizations in particular - truly usable as a productive tool in real-world contexts.

## 4.2 Background: Perception & Visual Clutter

The current AR research landscape lacks investigations of the visual perception of augmented content like information visualizations [Eri+20; KSF10; Kim+18]. The existing research papers mainly examined fundamental topics, such as depth perception and handling of occlusion [FAD02], color perception [Liv+13], and automatic color correction [Dav+14]. Lu et al. [Lu+14a; Lu+14b] looked more profoundly into how attention can be controlled through subtle cues in AR scenes. In general, perceptual experiments primarily investigated those effects on *pictures* of 3D scenes. Lu et al. [Lu+14a] recommended conducting perceptual experiments with OST devices and, therefore, in real-world scenes. A more applied view on perception in AR can be seen in different research projects focusing on basic visual elements, like text. Thereby the style of text and background [Kru+18; Gat+15a; Deb+14; Gat+15b; Fio+13; GS08] or the placement of text labels [Mad+16; PAE08; AF03] were often investigated. There is also work attempting to automatically determine the legibility of text in correlation to the background it is placed on [LT04]. Research shows that white text on a blue background is the best choice. Still, it is unclear how the findings can be transferred to different and more complex visual objects like information visualizations. Further, the placement of labels only focused on connections between the real-world environment and the digital data. Information visualizations often contain a combination of text and additional visual elements and use visual variables like color as a property to represent or highlight data.

More complex content types, like information visualization, consisting of several basic content elements, were rarely the focus of perceptual studies. One such example is the work of Büschel et al. [BVD19], who compare different types of edges for graph visualization on performance for graph analysis tasks. Their goal was not to understand how the visual background could influence their findings. Still, the participants mentioned that the environment did not influence them while solving the task. Another recent research project from Whitlock et al. [WSA20] investigated how users interpret data visualizations. The authors compared various display types, including a VST AR display, with which the study participants had to solve multiple tasks for 2D and 3D scatterplots and bar charts. With their experiments, Whitlock et al. presented that a navigation task in AR performed better than the other display types. They also state that color was harder to distinguish due to the color of the real-world objects in the surrounding.

To reiterate, Lu et al. [Lu+14a] advocated for conducting studies in real-world scenes. In their experiment, they made use of the Feature Congestion (FC) [Ros+05] as a measurement of how cluttered a visual background is. Clutter itself can be described as *"the state in which excess items, or their representation or organization, lead to a degradation of performance at some task"* [RLN07]. On the other hand, the FC measures how congested and exhausted a given feature is. The specific value is calculated by considering the feature spaces of color, luminance, and orientation of a given image and, therefore, how easy it is to use a given feature to draw attention to an area in the given image. Our two subsequent studies will use the FC value.

## 4.3 Study 1: Influence of Background on the Performance

AR applications will always exhibit various real-world backgrounds as seen in industrial scenarios. It is necessary to investigate the influence of those backgrounds to allow AR visualizations and applications to reach and even surpass currently used productive tools in performance and user-friendliness. However, we believe that the understanding of this influence can also be transferred to different use cases. Every AR visualization is and will be placed in different real-world environments and therefore has to be fitted to the respective backgrounds.

The concept of visual perceptual load, which describes *"that perception has a limited capacity, which automatically proceeds until exhausted"* [MFD13] is also relevant for this project. It could influence the primary visual tasks presented in AR since *"task-irrelevant stimuli are still processed to an extent that enables them to affect performance in a primary task"* [PMK20]. With this problem in mind, we created the first study.

### 4.3.1 Design & Hypotheses

Since we aimed to answer whether the background in AR applications influences the perception of information visualizations, we focused on two independent variables. Those are the *background* (*BG1*, *BG2*, and *BG3* as seen in Fig. 4.3) and the visualization *complexity* (presented by the number of data points in each visualization: 40, 50, 60a, 60b, and 70). The different *background* configurations were motivated by the wish to understand better the influence of dynamic and real-world backgrounds [Eri+20; Kim+18; Lu+14a]. We used those as a between-subject variable. The visualization *complexity* was altered within each session, motivated by the visual complexity that can increase the overall visual load [MHB08; Oli+04].

We measured the following dependent variables: task completion time (TCT), error rate (ER) values, and questionnaire data. The ER will be split in absolute error (EA) and percentage error (EP). Lastly, we distinguished between different analysis tasks based on the low-level analysis tasks presented by Amar et al. [AES05].

We generated four hypotheses to guide our research:

**H1** Solving tasks on *backgrounds* with more complex elements (employing visual clutter) performs worse. A more distracting *background* will interfere with the overall perception of the shown visualizations.

**H2** Solving tasks on visualizations with higher *complexity* perform worse. With more data points to analyze, the subjects will take longer and eventually give more incorrect answers.

**H3** The negative effect of the *background* will be more visible while the subjects solve tasks on visualizations with higher *complexity* due to the overall increase of visual complexity.

**H4** Subjects perceive the *backgrounds* with more clutter as more distracting.

### 4.3.2 Participants

We recruited 21 unpaid participants per word-of-mouth for our study. We had to exclude three runs due to headaches of one subject and problems with the state of one of the study environments for the other two. The remaining 18 participants (11 female, 7 male) were students from our local university's media informatics, media research, and computer science study courses. The average age was 21 years ($M = 20.89$ years, $SD = 2.11$ years) and the self-reported height ranged from 162 cm to 198 cm ($M = 173.05$ cm, $SD = 9.38$ cm). No specific knowledge was required to participate in this study. All participants had normal or corrected-to-normal vision and had no color vision defect or spatial perception difficulties. On a five-step scale, all participants had less experience with AR in general ($M = 2.17, SD = 0.92$), no experience with AR via head-mounted displays ($M = 1.17, SD = 0.38$), no experience with Virtual Reality ($M = 1.61, SD = 0.70$) and some experience with the use of visualizations ($M = 2.72, SD = 0.89$) in general.

### 4.3.3 Setup & Apparatus

The study was conducted in an experimental production hall with a real-life modular chemical plant inside. We created our backgrounds (see Fig. 4.3) based on the

**Fig. 4.3.:** All background configurations used in both studies. ***BG1***, ***BG2*** and ***BG3*** were used in the first study. ***BG3*** and ***BG4*** were used in the second study. ***BG4*** also shows the placement of the additional displays (indicated by white squares). The placement is similar to ***BG3*** (see Fig. 4.2D). The displayed FC values are the mean of all images taken from the Microsoft HoloLens v1 in each session for each study (S1 for Study 1, S2 for Study 2).

Feature Congestion (FC) value [RLN07] and some visual characteristics. The FC is a single value that is computed through a combination of the color, luminance, and orientation map of a given image (for this, we used the Piranhas Toolkit [DAE16]). The smaller the value, the less clutter is present in the image. We did not rely solely on the FC value to define our backgrounds. Still, we also used our human judgment based on different characteristics, like motion, uniformity, or overall color. After we tested several background configurations in the industrial production hall, we chose two sufficiently different backgrounds (*BG2*, *BG3*), while the third (*BG1*) was added as a baseline. *BG3* shows moving green water, additional LED stripes, and an overall uniform design with slightly angled pipes. On the other hand, *BG2* has two different sections. The left side is relatively uniform, while the right side is cluttered with cables. The FC values for the *backgrounds*, calculated as an average out of all images taken in the session for each participant, are: $FC(BG1) = 2.06$, $FC(BG2) = 2.90$, and $FC(BG3) = 5.36$ Fig. 4.3. As typical for many real-world scenarios (outside a clean, controlled laboratory), the noise of the environment and machines, the temperature in the production hall, the lighting, and the presence of other people were hard to control. To minimize disturbances in our study sessions, we took some precautions, like informing the staff and blocking the specific area in the hall. However, the module used in *BG3* created a constant noise, and some people occasionally worked at the same time the experiments were conducted.

For our study, we built two applications: an AR client application used by the subjects and a server application controlled by the investigator. The AR application was developed for the Microsoft HoloLens v1, which has good image quality but a rather small field of view of approximately 30 degrees diagonally. The client application was implemented using the Unity 3D engine and the IATK framework [Cor+19], which we modified to fit our needs better. To interact with the application, the participants used a Microsoft Clicker. We chose the Clicker to minimize gesture recognition problems, arm fatigue, and the subjects' learning procedure. While the participants were seated at a distance of approximately 2.5 m in front of the backgrounds (see Fig. 4.2A), the application showed questions (see Fig. 4.2C) and the visualization (see Fig. 4.2B) at the height of 1.15 m above the floor. Additionally, the visualizations almost filled the field of view of the HoloLens. The server application was implemented in C# with WPF and helped the investigator control the experiments. This application allows monitoring the current state of the AR application and the subjects' interaction. Further, it logged all interactions and information the participants generated in the experiment.

### 4.3.4 Procedure

Each session consisted of the following phases:

(1) A short introduction to the production hall and to modular industrial factories
(2) A questionnaire and a declaration of consent
(3) An explanation of the study tasks and interaction vocabulary
(4) The calibration of the HoloLens to the subject and a short training (four tasks)
(5) The conduction of the experiment
(6) The final questionnaire regarding the experiment and the perceived influence of the background

One investigator in the production hall but seated outside the field of view of the participants led the experiment. He only interacted with the participants during the experiment if they had any questions, wanted to answer an analysis task, or some technical problem occurred (e.g., with the input device).

Each click with the Clicker advanced the session to a different state. A hold of 1 s allowed the subject to orally answer the previously shown analysis task. We chose an

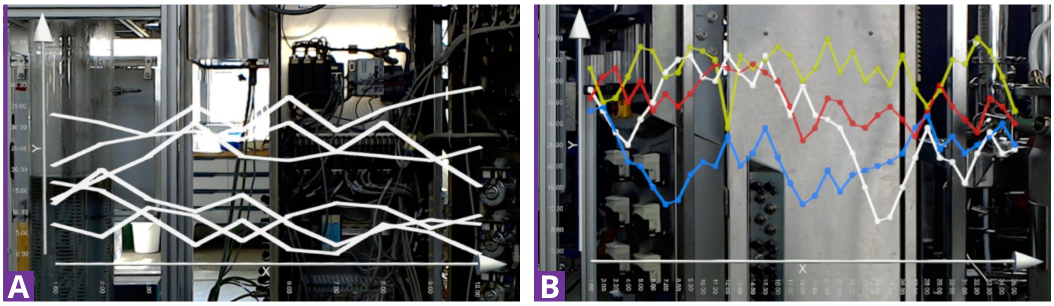

**Fig. 4.4.:** Line charts in front of the background from both studies. **(A)** was used in the first study (*complexity* of 60 data points with 10 x-values and 6 lines), while **(B)** was used in the second one (with a static amount of 35 x-values and 4 lines). Further, **(A)** shows *BG2* and **(B)** *BG4*.

| Low-Level-Analysis Task | # of Questions S1 | S2 | Example Question |
|---|---|---|---|
| Retrieve Value | 4 | 3 | What is the Y-value at the given X-value? |
| Filter | 3 | 1 | How many lines have a Y-value **higher** than **45**? |
| Compute Derived Value | 3 | 2 | What is the average Y-value for all Y-values of those lines? |
| Find Extremum | 3 | 1 | At what X-value is the **highest** Y-value of the selected lines? |
| Sort | | 1 | What is the descending order of all lines according to their **highest** Y-value? |
| Determine Range | 1 | 1 | What is the Y-value range for those lines? |
| Find Anomalies | 1 | | At what X-value lies an outlier point? |
| Cluster | | 1 | At what X-value is the distance of all lines to each other the **smallest**? |
| Compare | | 2 | Does the mentioned Y-value lie **below** the average Y-value of all lines? |

**Tab. 4.1.:** All used analysis tasks (based on the work of Amar et al. [AES05]) in our study. The numbers in the middle columns show how many of the questions in each repetition were mapped to those analysis tasks. Lastly, the bold words in the example questions were altered between different repetitions (e.g., higher to smaller). A list of all tasks can be found in the appendix: Tab. B.1 and B.2.

oral answer method to reduce the number of needed interaction devices and vocabulary. After the investigator entered the given answer, the session advanced to the next analysis task or question block. Altogether, each session lasted approximately 51 min ($M = 51.38$ min, $SD = 8.03$ min), of which 25 min ($M = 25.07$ min, $SD = 5.40$ min) were needed for phase (5) of the study.

### 4.3.5 Tasks

The participants of our study had to solve analysis tasks on line charts (see Fig. 4.4A). We chose 2D line charts since they are widely established (as considered a basic visualization by Saket et al. [SED19]) and often used as trend charts in industrial factories. This decision allowed us to reduce the complexity of our experiment. The mentioned analysis tasks the subjects had to solve were based on Amar et al.'s [AES05] low-level analysis tasks. They describe that those tasks *"largely capture people's* *activities while employing information visualization tools for understanding data"*. We chose a subset of six primitive tasks to generate a more natural set of questions. Those are: *Retrieve Value*, *Filter*, *Compute Derived Value*, *Find Extremum*, *Determine Range*, and *Find Anomalies*.

To generate a set of questions, we created four block types. Of those, three types contained four, while the last contained only three analysis tasks. The questions in one block are built on the preceding analysis task answers to allow a more complex analysis. Each block was repeated five times, based on the *complexity*. In each repetition, we altered small details, like the highest or smallest value for a *Find Extremum* task (see Tab. 4.2). Each line chart was created based on one *complexity* level that defines the number of shown data points in increments of 10, altered through the number of data points per line and the number of lines. We chose this approach since the *"Visual complexity is mainly represented by the perceptual dimensions of quantity of objects [and] clutter"* [MHB08; Oli+04]. The y-value range remained constant between 0 and 50 for each *complexity*. In total, we created five *complexity* levels: 40 (5 lines with 8 x-values); 50 (5 lines with 10 x-values); 60a (5 lines with 12 x-values); 60b (6 lines with 10 x-values); 70 (7 lines with 10 x-values). The data used in those charts were generated through a Python script. Altogether, each participant had to solve 75 analysis tasks (5 repetitions, each with 15 tasks).

We minimized the possible bias through training effects by counterbalancing the order in which each participant had to solve all 20 blocks (5 *complexity* x 4 block types). We used a latin-square for both factors separately. Therefore, each participant had to solve one block type with the five possible *complexities* before the next block type was presented. Lastly, each participant was randomly assigned to only one of the three *backgrounds*. In total, each value of the independent variable *background* was tested by six different subjects.

### 4.3.6 Measurements & Derived Data

As part of our study applications, we logged timestamps (e.g., the start of a block, toggle between visualization and question), different events, and each participant's given answers. With the timestamps, we could calculate the time spent completing one analysis task (in the following mentioned as TCT). This time was measured from first seeing the visualization (after a new question) to when the subject's answer was entered into the system. On the other hand, the answers allowed us to calculate the error rate (ER). Here we differ between absolute error (EA) for tasks with the numerical outcome (e.g., *Retrieve Value*) and percentage error (EP) for answers that could only be correct or not (e.g., *Filter*). In the following, we will refer to both ERs and the TCT as performance. Each session was video recorded while the investigator observed the participants and took notes.

The questionnaires contained a total of 40 questions. 13 questions focused on demographic data, and 19 were closed questions (see appendix Sec. B.1.1) based on a rating scale. The last eight were open questions. In general, we were guided in creating the post-study questionnaire by three main questions we would like to answer: (1) Does the task-solving process influence the user's physical state? (2) How does the user perceive the background? (3) How were the visualizations and their associated tasks perceived? The closed questions are about the physical state (fatigue, concentration, motivation, headache, dry and irritated eyes) before and after the study, the overall recognition of the lines and axes, as well as the perception of the visualization and the background (see Fig. 4.7 and 4.8). A NASA TLX was also performed and is assigned to this category. Among the open questions were the following: *"Which particular areas of the background caused problems to you?"*, *"To what extent did you notice the background when solving the tasks?"*, and *"Were there any other influences that distracted you in the study?"*.

### 4.3.7 Data Analysis

Before we started to analyze our data, we checked for outliers and replaced those with the following formula: $M + 2 * SD$ (as proposed by Field et al. [FMF12]). A total of 7.5 % data points for EA and 2.7 % for TCT were replaced. Afterward, our preliminary test showed that our data is not normally distributed (Shapiro-Wilk). Additionally, we checked the equality of variance (Levene) for the *backgrounds* while we calculated the sphericity (Mauchly) on the *complexities*. All tests showed that the data has no violation of the equality and one violation on the sphericity for *complexity* on EA. Following, we used one-way ANOVAs on the *background* (grouped over all questions per block) and one-way repeated measurements ANOVAs for the *complexity* with a Greenhouse-Geisser correction for the violation of sphericity. Furthermore, we used two-way mixed ANOVAs for the interaction of *background* and *complexity* and Kruskal-Wallis H test for the questionnaire answers on a rating scale. If we found any significance, we calculated either pairwise t-tests or Mann-Whitney U test with Benjamini/Hochberg FDR correction.

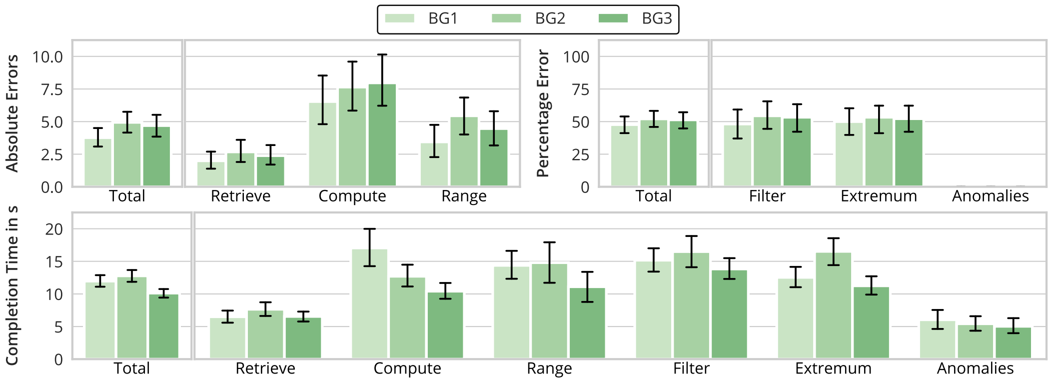

**Fig. 4.5.:** Result analysis visualizations for the first study with regard to the *backgrounds*. The EA, EP (first row) and TCT (second row) grouped by each analysis task and *background* are presented. The visualizations display the mean value and a 95% confidence interval with the whiskers.

## 4.3.8 Results

This section will present the results grouped by the generated hypotheses, followed by additional findings concerning subjective experiences. The results of our study are depicted in several diagrams of our measured data (see Fig. 4.5 and 4.6) and questionnaire data (see Fig. 4.7, 4.8, and 4.10).

### H1 (clutter on performance)

The statistic tests reveal no significant influence on the performance, as seen by EA ($F(2,50) = 0.281$, $p$=0.7561, $\eta_p^2 = 0.011$), EP ($F(2,51) = 0.086$, $p$=0.9175, -$\eta_p^2 = 0.003$), and TCT ($F(2,104) = 2.408$, $p$=0.0950, $\eta_p^2 = 0.044$). Additionally, Fig. 4.5 shows that tasks solved in our baseline condition *BG1* (lowest FC value) have the fewest EA. Overall, solved tasks on *BG3* (dynamic background with highest FC value) were the fastest, while the second fastest condition varies for different analysis tasks. In summary, *no significant influence of background clutter on the overall performance was found.*

### H2 (complexity on performance)

The statistic tests show a significant effect on the performance, as seen by EA ($F(4,68) = 3.901$, $p$<0.05, $\eta_p^2 = 0.187$) and EP ($F(4,68) = 6.362$, $p$<0.001, $\eta_p^2 = 0.272$), while TCT ($F(4,68) = 1.144$, $p$=0.3426, $\eta_p^2 = 0.063$) did not. The t-tests for EA, visualized in Fig. 4.6, show that both *complexities* with 60 data points have the least error rates. For percentage errors, the t-tests present different significant combinations (see Fig. 4.6). In summary, *our data displays that the complexity has an influence on the ER but not on the TCT.*

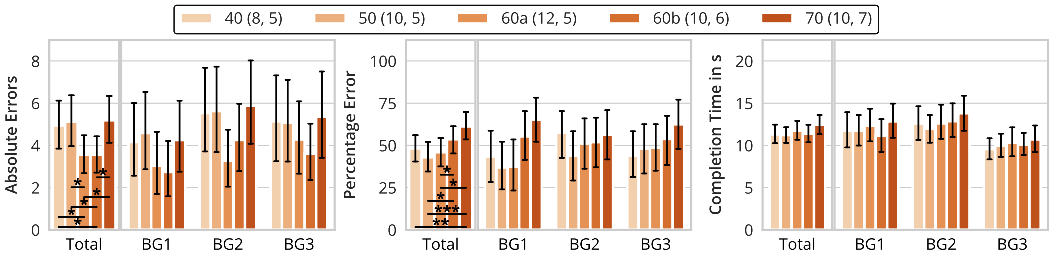

**Fig. 4.6.:** Result analysis visualizations for the first study with regard to the *complexities*. The EA, EP (first row) and TCT (second row) for the different *complexities* and *backgrounds* are shown. The visualizations display the mean value and a 95% confidence interval with the whiskers. (***: $p<0.001$, **: $p<0.01$, *: $p<0.05$ for pairwise t-tests)

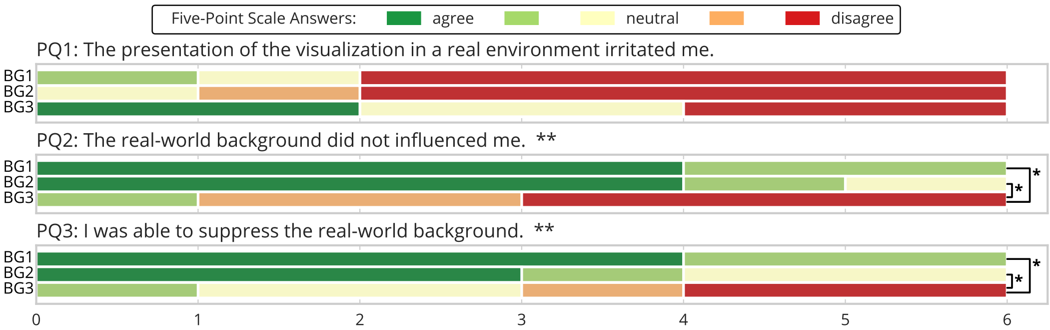

**Fig. 4.7.:** Survey results of questions scored on a five-point scale regarding the general perception (*PQ* = perception question) for Study 1. The x-axis presents the number of participants that voted for each answer respectively. (**: $p<0.01$, *: $p<0.05$)

### H3 (complexity & clutter on performance)

The statistic tests demonstrate no significant interaction between *background* and *complexity* on EA ($F(8,60) = 0.398$, $p$=0.9171, $\eta_p^2 = 0.05$), EP ($F(8,60) = 1.518$, -$p$=0.1702, $\eta_p^2 = 0.168$), and TCT ($F(8,60) = 0.202$, $p$=0.9895, $\eta_p^2 = 0.026$). Fig. 4.6 shows again that *BG1* has the least amount of error rates. In summary, *the combination of background and complexity shows no significant interaction and therefore no significant effect.*

### H4 (clutter on perceived distraction)

The questions focused on the perceived distraction and performance (see Fig. 4.7 and Fig. 4.8, *PQ* = perception questions) show that the *background* has a significant effect on the perceived influence (*PQ2* and *PQ3*) and how well the visualizations could be read (*PQ5*, *PQ6*, *PQ7*). All these questions signify that *BG1* is the *background* with the least influence and distraction. The additional open question *"To what extent did you notice the background during the tasks?"* also supports this. Subjects on *BG1* mentioned that the *background* was not noticeable (5 out of 6), while *BG2*

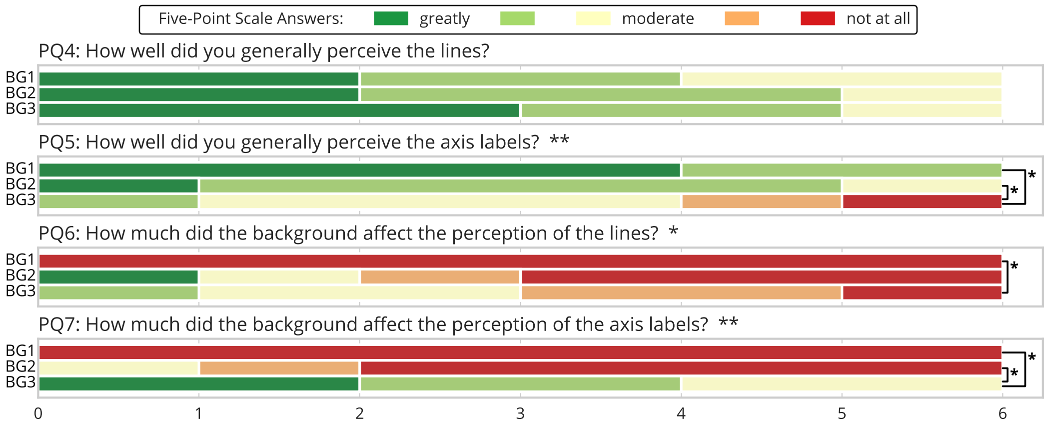

**Fig. 4.8.:** Survey results of questions scored on a five-point scale regarding the perception of the visualizations (*PQ* = perception question) for Study 1. The x-axis presents the number of participant that voted for each answer respectively. (**: $p<0.01$, *: $p<0.05$)

was perceived as partly noticeable (3 out of 6). The participants on *BG3* rated the *background* as quite difficult (6 out of 6). The open question *"What areas of the visual background caused the most difficulties?"* shows that the reflection, the lighting and the cables (1 out of 6 for each) of *BG2* were recognized. For *BG3* the light stripes (2 out of 6) and the movement (2 out of 6) made it hard to read the visualizations correctly (2 out of 6). This also caused the visual merging of lines and the *background* (2 out of 6). We can conclude *that participants perceive the background conditions with a higher FC value as more distracting.*

### Further findings

Additionally, we analyzed the NASA TLX and the change in the physical state throughout the study. The first showed no significance, while only the question regarding dry and irritated eyes showed that the background has a significant influence ($H(2) = 8.675,\ p = <0.05$) with a possible effect between *BG1* and *BG3* ($U = 7.5,\ p{=}0.0814$) and a significant effect between *BG1* and *BG2* ($U = 2.5$, - $p<0.05$). Lastly, a few subjects gave negative comments on the field of view of the HoloLens (4 out of 18), while some perceived the constant noise produced by *BG3* as distracting (5 out of 18).

## 4.3.9 Discussion

Overall, our results show that the *background* does not influence the measured performance (**H1**). However, we can see interesting differences in each measured value separately. *BG1*, the *background* with the least clutter, shows the best results

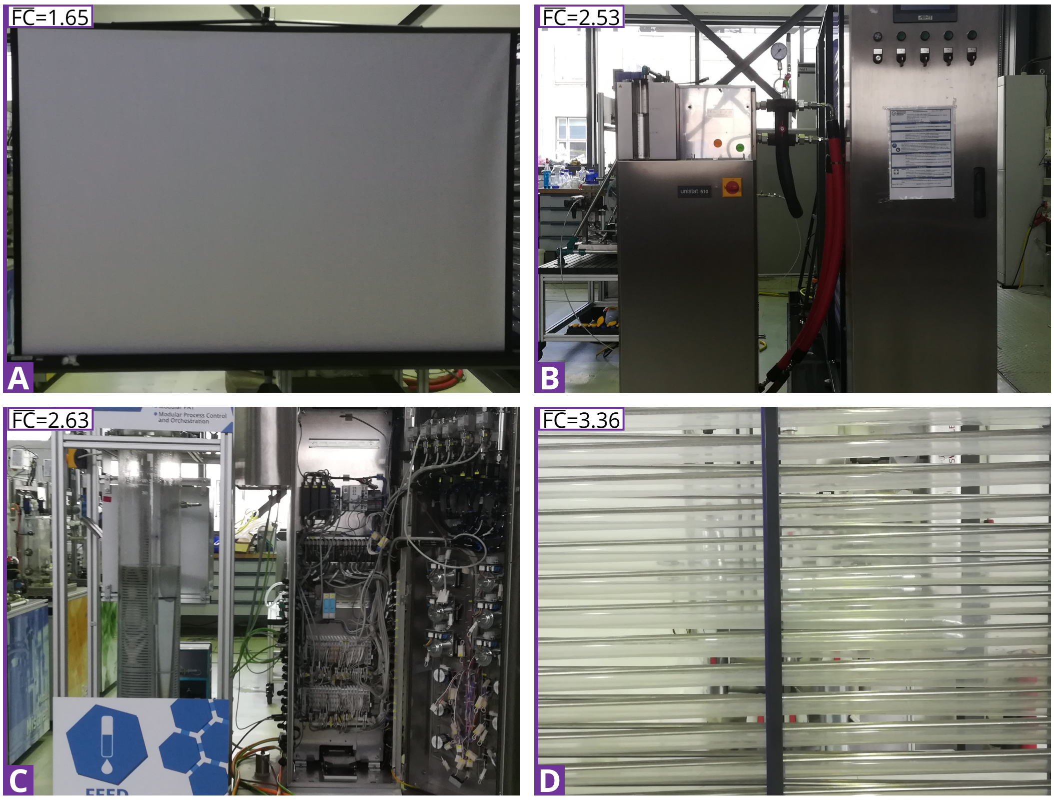

**Fig. 4.9.:** The backgrounds used in the questionnaire of the first study. All four backgrounds show different configurations with different values of FC. The rating results can be seen in Fig. 4.10.

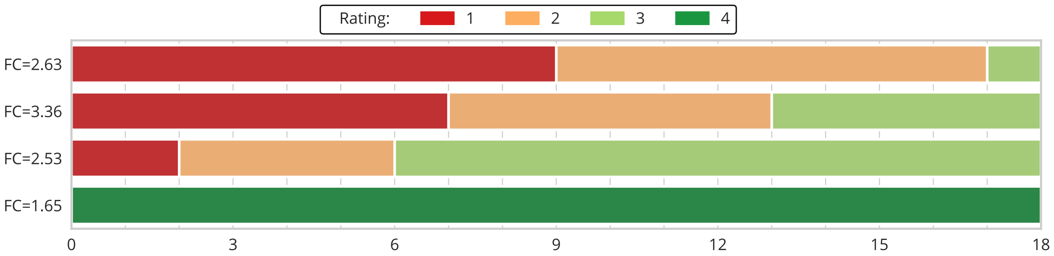

**Fig. 4.10.:** The order the subjects chose for four additional images presenting different background configurations. Each image has its own FC values and can be seen in Fig. 4.9. The rating 1 represents the image with the highest perceived distraction level.

in EA and EP, while the other two backgrounds are pretty close to each other. Interestingly, the background with the highest clutter, *BG3*, has the fastest completion time. One explanation could be that the subjects did not invest the same effort in solving the tasks on this *background* since they perceived the distraction and their performance on this background as rather bad. Also 3 out of 6 subjects reported slight dizziness on *BG3*. This could also explain why they wanted to finish the experiment on this *background* quickly. The performance values for the different *complexities* also reveal an interesting result. While the TCT increases steadily, but not significantly, the error rates show a significant effect for the *complexities* (**H2** and **H3**). Especially the *complexities* with 60 data points have the lowest number of errors. However, we cannot explain why this number of data points performed better than those with fewer data points (40 and 50). In general, the influence seen through the measured values differs from the perceived influence of the participants (**H4**). The subjects found it difficult to read values on the axes for *BG3* due to the light stripes, water movement, and the contrast difference in the scene. However, the measured ER reveal no such effect while those even performed the fastest. Overall, we have seen that the subjects perceived backgrounds with a higher FC value as more distracting while the measured data show no support for this.

Lastly, we wanted to get a feeling of how well the Feature Congestions (FC) can represent the perceived clutter of an image. Therefore, we presented the subjects with four images of background configurations with fixed FC values which were partly not used in the study (see Fig. 4.9). The subjects had to rate those based on how distracting the shown backgrounds would be to work on (see Fig. 4.10). The background with the highest distraction level should be placed in the first place. The ratings reveal that the FC values do not always match the perceived most distracting background. This can be seen by the images with close FC values of $FC = 2.63$ and $FC = 2.53$. While the $FC = 2.63$ is in the first place $M = 1.56$, $FC = 2.53$ is in the third place $M = 2.56$. We think that not only the specific FC value of each image defines how distracting subjects perceive a background. Also the specific characteristics, like the light stripes (2 out of 6), moving water (2 out of 6) or the cables (1 out of 6) are quite important.

## 4.4 Study 2: Influence of Secondary Task and Background on Performance

In our first study, the background was decoupled from the AR visualization and was only used as a visual distraction. In most real-world environments, this would not be the case. Especially immersive and embedded visualizations [Ska+19; Mar+18; WJD17; SH16; ESL13] try to connect the shown virtual information with the real world, as is also the case with research focusing on AR assisted assembly tasks [WON16; PR15]. Additionally, machines in real-life production plants often already possess displays to show important information [SJ18]. Therefore, users often alter their focus between the background and the virtual information. Overall, the second study aims to deepen the understanding of the influence of the background on information visualization while considering the forced attention switch between the background and the AR content caused by introducing a secondary task.

### 4.4.1 Design & Hypotheses

To understand the additional influence of a secondary task, we designed a user study that was also conducted in a real experimental production plant. We used the following two independent variables: the *background* (*BG3* and *BG4* as seen in Fig. 4.3) and focus type (*single focus* and *split focus*). The goal of the focus type was to increase the attention the participants had to pay to the background, which should increase the overall influence of the background itself. Both variables were used in a within-subject design and allowed us to measure the following dependent variables: task completion time, ER (as EA and EP), and questionnaire data. Further, we used a different subset of analysis tasks than in S1.

We focused on the following hypotheses:

**H5** The clutter of the *background* has no influence on the performance of the subjects (inverted **H1** from S1).

**H6** The performance of solving the primary task gets worse when it is performed in the *split focus* condition.

**H7** Solving tasks on a *background* with more clutter in the *split focus* condition decreases the performance.

**H8** When the secondary task is introduced, the *background* is more noticeable for subjects.

**H9** Subjects perceive the *background* with more clutter as more distracting (the same as **H4** from S1).

### 4.4.2 Participants

We recruited 18 participants through e-mail and word-of-mouth for this study. They did not participate in S1 and were not compensated. The gathered data from only 16 volunteers could be used for our data analysis. One session had to be aborted due to external interruptions in the production hall, while the second subject showed major difficulties in understanding the presented tasks. The remaining 16 volunteers (11 male, 5 female) were students or post-graduates with an engineering background.

The average age of the participants was 24 year ($M = 23.81$ year, $SD = 3.08$ year) and the self-reported height ranged from 162 cm to 198 cm ($M = 178.81$ cm, -$SD = 11.65$ cm). Again, no specific knowledge was required to participate in this study. All participants had normal or corrected-to-normal vision and no spatial perception difficulties. We adjusted the colors for one subject due to red-green weakness. On a five-step scale, all participants generally had some experience with AR ($M = 2.44, SD = 0.89$), little experience with AR via head-mounted display ($M = 2.00, SD = 1.03$), no experience with VR ($M = 1.75, SD = 0.77$) and were generally quite experienced at working with visualizations ($M = 3.88, SD = 0.72$). The volunteers also had to solve a small introductory question on how well they could define elements in a line chart with a total score of eight points (see appendix Fig. B.1). Only one subject had one error (mixed up the keywords "x-value" and "x-axis"), while the participant with the comprehension problems had four errors.

### 4.4.3 Setup & Apparatus

Overall, this study has the same setup as S1 but changed and altered the used backgrounds. To enable our secondary task design, we added three 6 inch smartphones (two Huawei Honer 9 and one Samsung Galaxy S4) as simulated displays of real-life modules to our backgrounds. We therefore used the following backgrounds with their respective FC values: $FC(BG3) = 5.65$ and $FC(BG4) = 2.75$. We removed *BG1* to reduce the complexity of the study and enable a within-subject design. We transformed *BG2* to *BG4* to create a wider background for a uniform smartphone placement between both backgrounds. This also allowed us to increase the difference between *BG4* and *BG3*, since *BG4* is more uniform by reducing the open cables of *BG2*. The height at which the additional smartphones were attached to the backgrounds differs between positions, with approximately 95 cm on the left, 170 cm on the center, and 140 cm on the right (see Fig. 4.3D).

Our AR application is the same as in S1, while the server application, in addition, handles the events of the smartphones. The smartphone application was also implemented in Unity and only displayed a different number for each device to allow the simulation of a secondary observation task. Those ranged from 0 to 9 and could be colored in yellow, white, blue, or red, while green was used as a signal color (white and green were swapped for the subject with red-green weakness) (see Fig. 4.2D). The number changed in an interval of 5 s to 10 s for each display while the signal color appeared with the next network message to any device after a period of 90 s.

| Low-Level-Analysis Task | # of Questions S1 | S2 | Example Question |
|---|---|---|---|
| Retrieve Value | 4 | 3 | What is the Y-value at the given X-value? |
| Filter | 3 | 1 | How many lines have a Y-value **higher** than **45**? |
| Compute Derived Value | 3 | 2 | What is the average Y-value for all Y-values of those lines? |
| Find Extremum | 3 | 1 | At what X-value is the **highest** Y-value of the selected lines? |
| Sort | | 1 | What is the descending order of all lines according to their **highest** Y-value? |
| Determine Range | 1 | 1 | What is the Y-value range for those lines? |
| Find Anomalies | 1 | | At what X-value lies an outlier point? |
| Cluster | | 1 | At what X-value is the distance of all lines to each other the **smallest**? |
| Compare | | 2 | Does the mentioned Y-value lie **below** the average Y-value of all lines? |

**Tab. 4.2.:** All used analysis tasks (based on the work of Amar et al.[AES05]) in our study. The numbers in the middle columns show how many of the questions in each repetition were mapped to those analysis tasks. Lastly, the bold words in the example questions were altered between different repetitions (e.g., higher to smaller). A list of all tasks can be found in the appendix: Tab. B.1 and B.2.

We tried to control possible disturbing factors in our setup. However, *BG3* still created a constant background noise, in addition to some people working in the production hall simultaneously.

### 4.4.4 Procedure

Each session followed the following phases:

(1) A small introduction to the experimental environment
(2) A declaration of consent and a first questionnaire
(3) An explanation of the analysis tasks, the interaction and both focus types
(4) Short training with six questions and a preceded calibration of the HoloLens
(5) The first half of the experiment on the first *background*
(6) A short break with a second questionnaire regarding the first *background*
(7) The second half of the experiment with the second *background*
(8) A final and third questionnaire with questions connected to the second *background* as well as overall questions

The experiment was led by one investigator who was in the production hall and was seated partly inside the field of view of the participants.

The subjects had to interact with the system as described in S1. Additionally, the subjects had to raise their hand and speak aloud the value when they saw a green number on one of the displays in the *split focus* condition. Each session lasted on average 78 min ($M = 77.98$ min, $SD = 10.63$ min), whereby 39 min ($M = 39.35$ min, $SD = 8.57$ min) were needed for phases (5) and (7).

### 4.4.5 Tasks

The subjects of the study had to solve analysis tasks on line charts, like in S1. Our set of task types consisted of seven primitive low-level analysis tasks [AES05]. Those were *Retrieve Value*, *Filter*, *Compute Derived Value*, *Find Extremum*, *Sort*, *Determine Range*, and *Cluster*. Additionally, we added *Compare* as a higher-level task which often uses different low-level analysis tasks (see Tab. 4.2). As in S1, we created three blocks containing four questions each. Furthermore, the questions are built upon the answers to the preceding questions in the same block. We introduced the focus type to simulate a secondary observation task. The focus type had two different states: *single focus* and *split focus*. In *single focus*, the participants only had to focus on solving the primary task presented for the visualization (as in S1), while in *split focus* they also had to observe the background as a secondary task. The subjects had to recognize and orally confirm the value of a green number (out of 5 different colors) on one of three displays placed inside the background configuration. The state of the focus type was switched after half of the tasks (six blocks) in phases (5) and (7) were solved.

Like in S1, we used line charts as our visualization type of choice. However, all charts were created with the same parameters: four colored lines (red, blue, yellow, white), x-value range of 0 to 35, and y-value range of 0 to 50. The colors made the lines more distinguishable (see Fig. 4.4B). We created two different visualizations for each combination of *background*, focus type, and block. In total, subjects had to solve 96 tasks (2 *backgrounds* x 2 focus types x 2 visualization x 3 blocks x 4 analysis tasks).

We again minimized a possible bias through training effects by counterbalancing the tasks. For each subject we ordered the four conditions created from the *backgrounds* and the focus type, finishing one *background* before switching to the second one (for example the order of: *BG3 single focus*, *BG3 split focus*, *BG4 single focus*, *BG4 split focus*). We cycled through all eight possible order combinations. Lastly, we ordered the 12 task blocks through a latin-square, split them into groups of three, and assigned each group to each condition, while keeping the order of analysis tasks in each task block.

### 4.4.6 Measurements & Derived Data

As in S1, we collected each participant's answers and timestamps. Additionally, we logged the events connected to the smartphone (value updates and answers for the *split focus*). The derived data are also the same with EA, EP, and TCT. Each session was again video recorded while the investigator took notes accordingly.

The three questionnaires contained a total of 57 questions (see appendix Sec. B.1.2). 14 were assigned to demographic data, 31 were questions based on a rating scale, and 12 were open questions. As in S1, we used the same guiding questions. However, compared to S1, we added questions regarding the *split focus*. At the same time, we repeated the questions for the physical state, the recognition of visual elements, and the perception of the background after each individual *background*. Lastly, we added five closed questions for the focus type regarding the influence on the main task (see Fig. 4.14).

## 4.4.7 Data Analysis

As in our first study, we checked and replaced outliers (2.5 % for EA, 4.3 % for TCT) in our data with the following formula: $M + 2 * SD$ (as proposed by Field et al. [FMF12]). We checked our data with preliminary tests before we analyzed them further. For this, we tested for normal distribution (Shapiro-Wilk), which was never the case, and sphericity (Mauchly), which was never violated, for the *background* and focus type separately. We used one-way ANOVAs on the *background* and focus type while calculating two-way repeated measurements ANOVAs on the combination of *background* and focus type. Further, we use a Friedman F test for the questionnaire answers on a rating scale. In general, if we found any significance, we calculated pairwise t-tests or Wilcoxon W tests.

## 4.4.8 Results

This section reveals the results of our second study, ordered by the presented hypotheses. They are depicted in visualizations of our measured data (see Fig. 4.11, Fig. 4.12, and Fig. 4.13) and questionnaire data (see Fig. 4.15, Fig. 4.16, and Fig. 4.14).

### H5 (clutter on performance)

The statistic tests show no significance effect on EA ($F(1,15) = 0.418,\ p{=}0.528,$ - $\eta_p^2 = 0.027$) and EP ($F(1,15) = 0.850,\ p{=}0.371,\ \eta_p^2 = 0.054$) while a significant influence can be seen for TCT ($F(1,15) = 5.407,\ p{<}0.05,\ \eta_p^2 = 0.265$). Further, Fig. 4.11 shows that *BG3* has always less EA than *BG4*, while this order changes

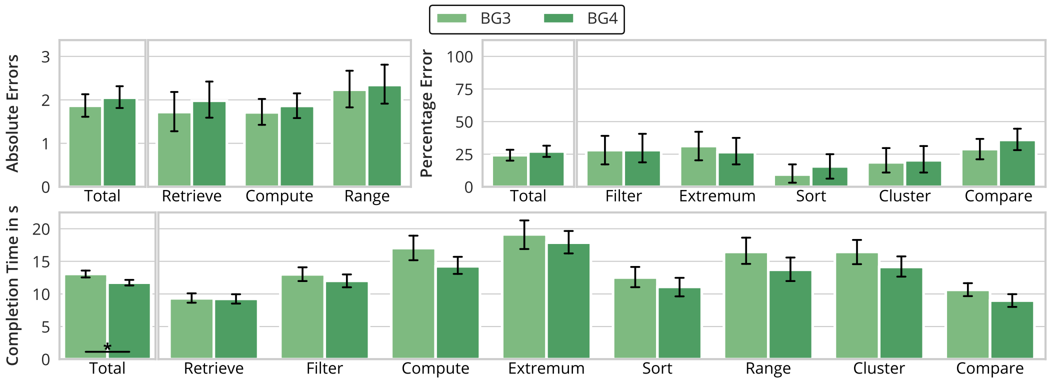

**Fig. 4.11.:** Result analysis visualizations for the second study with regard to the *backgrounds*. The EA, EP (first row) and TCT (second row) grouped by each analysis task and *background* are presented. The visualizations display the mean value and a 95% confidence interval with the whiskers. (*: $p$<0.05)

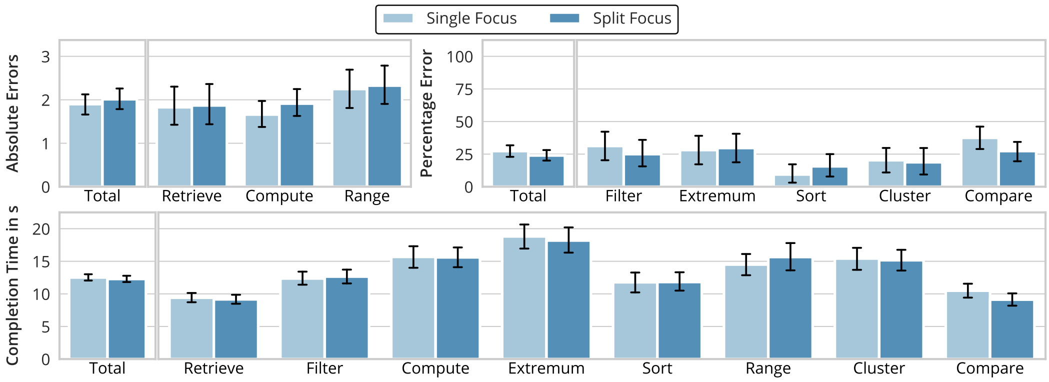

**Fig. 4.12.:** Result analysis visualizations for the second study with regard to the focus type. The EA, EP (first row) and TCT (second row) for different analysis task and focus type are shown. The visualizations display the mean value and a 95% confidence interval with the whiskers.

for EP with different analysis tasks. In summary, *the performance is only partly influenced by the background clutter.*

### H6 (focus condition on performance)

The statistic tests display no significant effect on the performance values EA ($F(1,15) = 0.514$, $p$=0.484, $\eta_p^2 = 0.033$), EP ($F(1,15) = 1.338$, $p$=0.266, $\eta_p^2 = 0.082$), and TCT ($F(1,15) = 0.298$, $p$=0.593, $\eta_p^2 = 0.019$). However, Fig. 4.12 depicts that less absolute errors appear in the *single focus*, while this changes between different analysis tasks for the EP. In summary, *the focus type shows no significant influence on the subjects' performance.*

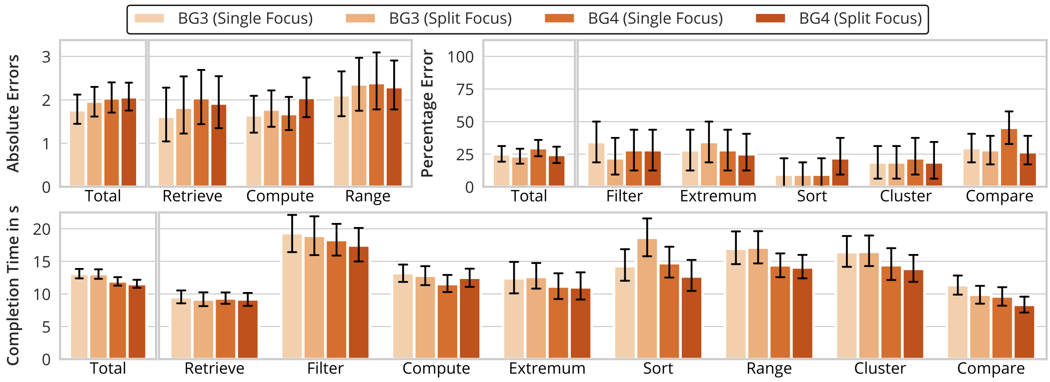

**Fig. 4.13.:** Different data analysis visualizations for the second study with regard to the combination of *background* and focus type. The EA, EP and TCT grouped by each analysis task and the combination of *background* and focus type are displayed. The visualizations display the mean value and a 95% confidence interval with the whiskers.

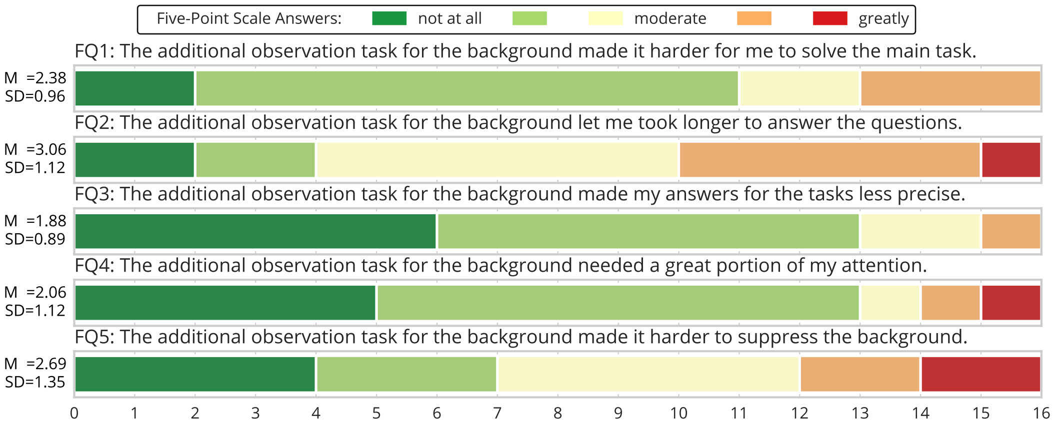

**Fig. 4.14.:** Survey results of questions scored on a five-point agreement scale regarding the *split focus* condition (focus type = focus questions). Left to each question's bar, we also present the mean score (M) and standard deviation (SD). The x-axis presents the number of participants that voted for each answer respectively.

### H7 (clutter & focus type on performance)

The statistic tests reveals no significant interaction between *background* and focus type on EA ($F(1,15) = 0.022$, $p$=0.6454, $\eta_p^2 = 0.014$), EP ($F(1,15) = 0.657$, $p$=0.430, $\eta_p^2 = 0.042$), and TCT ($F(1,15) = 0.305$, $p$=0.589, $\eta_p^2 = 0.020$). Fig. 4.13 shows that the analysis tasks perform differently in *split focus* than in *single focus*. Interestingly, how the secondary task influenced the analysis tasks differs. Some increased the error and needed more time, while others reduced both. In summary, *there is no significant interaction between the background and the focus type regarding the subjects' performance.*

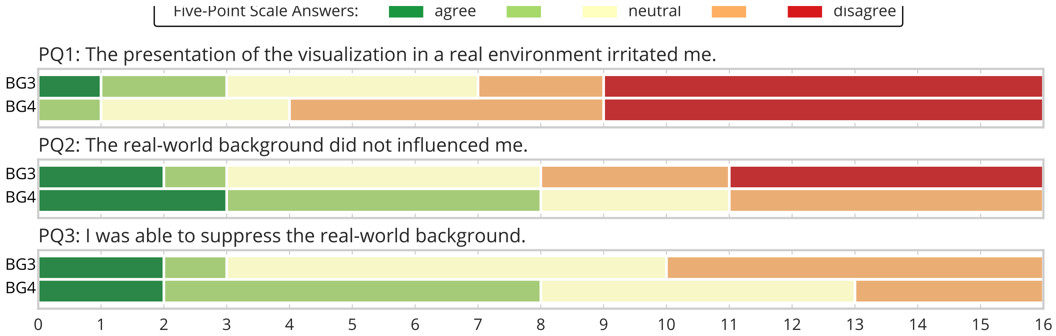

**Fig. 4.15.:** Survey results of questions scored on a five-point scale regarding the general perception (*PQ* = perception question) for Study 2. The x-axis presents the number of participant that voted for each answer respectively.

### H8 (focus type on perceived distraction)

The questionnaire contained five questions regarding the additional focus type (*FQ* = focus question), as seen in Fig. 4.14. Overall, the subjects perceived that the *split focus* condition made it more challenging to solve the main task (*FQ1*: $M = 2.38, SD = 0.96$) as it needed some additional attention (*FQ4*: $M = 2.69, SD = 1.12$). The secondary task increased the perceived TCT (*FQ2*: $M = 3.06, SD = 1.12$), while the given answers were only slightly influenced (*FQ3*: $M = 1.88, SD = 0.89$). We can conclude *that the split focus condition increased the awareness and the influence of the background for the subjects.*

### H9 (clutter on perceived distraction)

Our collected questionnaire data regarding the perception (*PQ*) of the *background* (see Fig. 4.15 and Fig. 4.16) shows no significant influence on the perceived distraction or performance. However, a small difference between both *backgrounds* exists. *BG4* is overall perceived less distracting than *BG3*, the background with dynamic elements and additional light. This is especially true for *PQ2* ($Q(1) = 3.267,\ p$=0.0707), *PQ3* ($Q(1) = 1.923,\ p$=0.1655), and *PQ7* ($Q(1) = 2.571,\ p$=0.1088). We asked the participants which of the *backgrounds* was more challenging to work in. 13 out of 16 participants chose *BG3*. The light stripes (4 out of 16), the pipes (4 out of 16), the water movement (6 out of 16), and green color (4 out of 16) were stated as the main reasons for this. On the other hand, *BG4* was perceived as only slightly distracting (6 out of 16), which changed with the introduction of the *split focus* (3 out of 16). The sunlight through a window in the background (5 out of 16) and the reflection on the smartphones (2 out of 16) were the most distracting factors. We conclude *that the background clutter has no significant influence on the perception. However, the open questions and comments depict a strong tendency that BG3 was perceived as more distracting.*

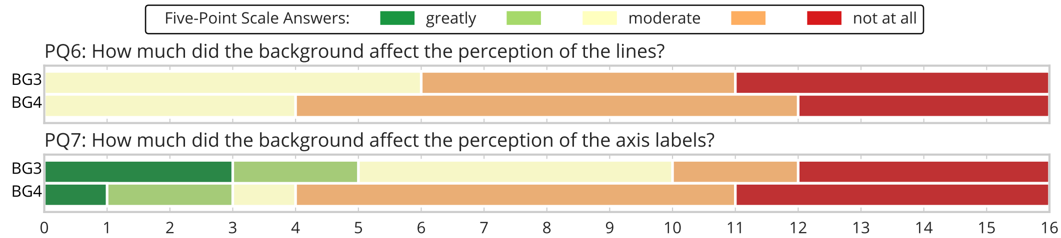

**Fig. 4.16.:** Survey results of questions scored on a five-point scale regarding the perception of the visualizations (*PQ* = perception question) for Study 2. The x-axis presents the number of participant that voted for each answer respectively.

### Further findings

Additionally, we analyzed the NASA TLX and the change in the physical state between each *background* as we did in S1. This time, we could not find any significant influence regarding the different questions. We also looked at the number of times the participants reported a number with the correct signal color in the *split focus* condition. Here we can see that the subjects recognized the numbers less often on *BG3* ($M = 75.42\ \%,\ SD = 22.22\ \%$) than on *BG4* ($M = 83.10\ \%,\ SD = 20.09\ \%$). Some participants gave us negative comments about the field of view of the HoloLens v1 (6 out of 16) and some mentioned that they could not suppress the constant noise of *BG3* (8 out of 16). Lastly, a few participants wished for more support through the visualizations with a grid, ticks on the axis, and better overlap handling of the lines (2 out of 16 for each).

## 4.4.9 Discussion

Our results reveal that the *background* affects the TCT, while the error rates are not affected (**H5**). Tasks that were solved on more cluttered *backgrounds*, like *BG3*, took longer to solve than on a *background* with less clutter. Interestingly, with longer TCTs the subjects gave less error-prone answers. This allows us to assume that harder-to-suppress backgrounds increase users' duration to find the correct answer. However, the answers themselves seem not to be influenced by the backgrounds. The collected subjective questionnaire answers also support that backgrounds with a higher FC value are perceived as more distracting and cluttered (**H9**). Further, in the questionnaire regarding *BG3*, some subjects found it hard to read values on the axes (4 out of 16). However, the answers given for tasks on this *background* were slightly better than for *BG4* (see absolute errors in Fig. 4.11). Following, we think that users are quite capable to overcome the faced perceptual issues.

As we investigated our second independent variable, the focus type, we could not find any significance in the measured performance (**H6**). This is especially interesting since we believed that the increased task load through the *split focus* (**H8**) would also decrease the overall performance (**H7**). The participants also perceived the introduced focus type as more demanding. The questionnaire answers (see Fig. 4.14) show that the participants perceived a higher task load and increased TCT. Overall, the *split focus* setup successfully increased the awareness of the *background* for the participants (*FQ5*: $M = 2.69, SD = 1.35$), which was also stated directly from some of the subjects (3 out of 16). Again, we can verify that our subjects' perceived and measured performance greatly differs. Lastly, the difference of the recognition rate for the *split focus* condition on both backgrounds can be explained through the change blindness [Jen+11], as the signal color was the same as the color of the moving water in *BG3*.

## 4.5 Overall Discussion and Limitations

This section will discuss the results of our two studies in combination. For this, we will first look at the limitations of the studies and then present an overall discussion.

### 4.5.1 Limitations

With our presented user studies, we created a mixture of controlled lab and in-the-wild studies. Those allowed us to investigate the influence of real-world backgrounds on the perception of AR visualizations. However, our overall design decisions also introduced several limitations we want to discuss.

We deliberately chose only one specific visualization type for our investigation: line charts. Other visualization techniques and small changes in visual parameters, like, e.g., bar charts or scatter plots might produce different results. This could be particularly true for 3D visualizations. In addition, our chosen visualizations only show static data. However, dynamic data sets, which are more common in industrial scenarios, can also change the overall perception and the outcome of studies. The tasks performed on the shown visualization were cognitively challenging, as demonstrated by our NASA TLX on mental demand ($M = 6.09, SD = 1.73$). Less demanding tasks could also change how strong the influence of the background is perceived.

Our studies used the Microsoft HoloLens v1 to present AR content to the participants. Using a head-mounted display is more practicable since it frees the hands for interaction but also has drawbacks. Especially the field of view is a limiting factor in how big visualizations can be and how much information can be perceived simultaneously. In our studies, 10 out of 34 participants mentioned a small field of view. The HoloLens was also perceived as quite uncomfortable (12 out of 34). The participants reported pressure (5 out of 34) or pain (5 out of 34) on the nasal bridge. However, we think that manufacturers will address those limitations, as already seen with the HoloLens 2.

Our user studies were placed in a real-world experimental production plant that introduced many possible uncontrollable factors like the temperature, the presence of other people, or noises. Our findings could slightly differ in an environment with varying influencing factors and background configurations. The backgrounds we created use case specific and contained static and dynamic elements. Different backgrounds with more distinct properties, like color gradients, stronger movement, or additional and more extensive information displays, could change the overall perception. The Feature Congestion (FC), in combination with other environmental characteristics, was used to create our background configurations. However, the FC value is calculated on static images and only takes into account three different image properties [RLN07]. Those properties make it difficult to fully represent the complete background and environment AR applications could be used in. A different way of defining the disturbance and clutter could enhance our study design and improve future research projects focusing on backgrounds.

Our overall setup was quite restricting. The experiment's duration was relatively short, and the participants were instructed to sit for the whole period. However, in a real scenario, users will move around, interact with the environment, and change their posture and viewing angle. All those factors might change a user's perception with regard to the environment and the presented visualizations.

We are aware of the relatively small sample size of both studies. However, our studies already show first essential insights into how the background of a real-world scene could have or have not influenced on the perception of visualizations. Lastly, the participants of our studies only reflect a small spectrum of the relevant population, as visible through the age distribution and the background the participants were coming from. This is generally a problem if we want to analyze how perception is influenced in an industrial scenario.

### 4.5.2 Discussion

This discussion is split into four topics that we believe are the most important outcomes of our research.

#### The background has only marginal influence on the perception of visualizations shown in AR.

Both our studies reveal that the background does not influence the answers given to the presented tasks (**H1** and **H5**). However, the TCT was influenced in S2, while it was not affected in S1. Overall, participants could ignore the influence of the presented background configurations. This makes us believe that AR visualizations can be used in many real-life scenarios without significantly affecting users' performance. This can also be seen by the percentage of how often participants recognized the signaled number in the *split focus* condition in S2 since the higher cluttered background (*BG3*) had a lower recognition value in comparison. However, this also shows that important information placed in such a background should be more prominent and recognizable. Additionally, we believe that users may compensate for the increased difficulty by increasing their TCT, as seen in S2. However, we cannot see this compensation in S1 as well. In comparison, the TCT in S1 was the fastest on *BG3*. This, as well as the relatively high ER rate in S1, could be explained by the different demographics of our study participants, the overall task difficulty (visualizations in S2 contained more data points), or the diversevisual representation of the visualization (only white lines in S1). Overall, we do not consider it advisable to prioritize adjustments to the real environment, as the decrease in performance based on more distracting environments is minimal for short-term tasks. Notwithstanding, as performance is dependent on working with both virtual foreground and real background, this need can shift.

#### There is more than visual clutter that defines background and its influence on perception.

We used the Feature Congestion (FC) [RLN07] as guidance while we created background configurations for our studies. In general, the FC value can create a rather good definition of how cluttered or distracting a background scene is. However, it only uses images and therefore loses specific characteristics of a real-world scene (**H4** and **H9**). Such characteristics, as stated by the participants, can include the overall lighting (11 out of 34), reflections (3 out of 34), movement (8 out of 34), particular areas like the pipes and their attachments (4 out of 34), or the cables of *BG2* (1 out of 34). The perception of those characteristics can further change if users also interact with objects in the background (**H8**). We think a purely automatic calculation of visual clutter and distraction based on images (e.g., Feature Congestion) regarding real-life environments is insufficient since it does not consider specific background characteristics. Possible extensions of the FC algorithm should consider crowding [BCR09], depth perception [Eri+20] of real-world scenes, or the dynamics of the background [Eri+20]. Lastly, a learned classifier working with human-labeled and rated images could also be beneficial.

#### Users perceive a visually cluttered background as more distracting than it actually affects their overall performance.

Participants reported that the background (**H4** and **H9**), as well as the secondary task of S2 (**H8**) influenced their performance. The participants felt they took longer and were less precise in their given answers while working on a background with a higher FC value. They also felt a higher task load or had a more challenging time reading the values of the visualizations, like the axes. However, this perceived influence was not visible in their measured performance values. This perception can also influence actual performance in more extended working scenarios than simulated in our experiments. Additionally, since the perception is coupled with the user, overall user satisfaction should also be considered. This is because higher satisfaction could compensate for the loss in performance. Overall, the *backgrounds* increased cognitive load, while the answers were unaffected. This could change with longer working sessions or even over several sessions. Further, the safety of the user and the real-world environment should also be a concern since the participants in our experiments were able to suppress the background rather well. This can be especially dangerous if they ignore warning signs in the background as simulated with the focus type in S2. In summary, we can see a difference between the measured and perceived performance of the users. This makes us believe that a greater focus on user experience could help in the design phase of user interfaces or visualizations for such AR applications. Lastly, a more user-centric design could help users to perceive their work as more correct and productive.

#### Various task or visualization parameters could influence the real and perceived performance.

In both studies, we investigated an additional secondary independent variable, the *complexity* of the visualization in S1 and an additional secondary task in S2. The *complexity* showed a significant effect on the performance, while the interaction with the *background* had no such effect (**H2** and **H3**). The focus type of S2 reveals no significance, either individually or in interaction with the *background* (**H6** and **H7**). However, the secondary task increased the awareness of the background for the users

(**H8**). In general, we believe that other parameters of visualizations or the presented tasks could have different effects on the user. Using various visual parameters (e.g, visualizations types, visual marks) or another secondary task, like changing the parameters of a running production machine, could enhance or decrease the influence of the environment such an AR application is used in. Lastly, it seems advisable not to prioritize an adaptation to a relatively simple secondary task.

## 4.6 Chapter Conclusion

In this project, we presented the results of our investigations on how real-world environments can influence the perception of visualizations in AR based on different background configurations created in an experimental production plant. In addition, we also investigated the complexity of visualizations and the introduction of a secondary parallel task in combination with the created background scenes. Both studies showed that the background has only a marginal influence on the measured task performance, while the perceived performance was affected by the real-world backgrounds. We discussed the results of the studies and their limitations and provided insights and recommendations. Overall, we hope our work can be used to make informed design and development decisions and bring AR a step closer to becoming a productive tool in real-life working scenarios.

As I described at the beginning of this chapter, I investigated user and environmental characteristics, namely visual perception and background or clutter. I could demonstrate that visual perception and cognition can generally handle the challenges created through a higher visual load caused by the visual background. This is the case if the virtual and real worlds are conceptual or task-wise separated. However, for settings where users have to observe and interact with both realities simultaneously, the user experience and performance are equally affected. My next step will lead me to explore another environmental parameter to counter such effects – the AR content placement areas in the real world.

# 5

# Understanding AR Content Placement on Ceiling and Floor

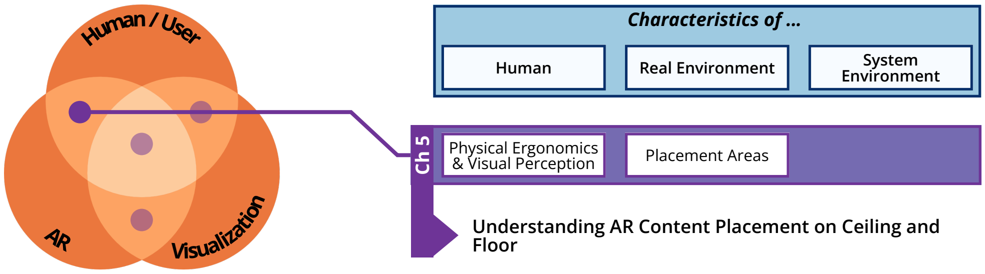

**Fig. 5.1.:** This research project (Ch. 5) is situated in the Augmented Reality (AR) and Human/User cross-section. Within this project, I focus on human visual perception and physical ergonomics (i.e., head movement) in combination with the placement of virtual content on the ceiling and floor in the environment.

AR interfaces support users by providing access to digital content within real-world environments. The virtually shown content can be placed everywhere in the environment but is most prominently placed directly at the users' eye level. While this is generally the most comfortable position, it can lead to the occlusion of the real world. Since it is impossible for every potential future AR application to display content directly in front of the user, other ways to manage content in AR must be investigated. Therefore, exploring two specific alternative placement areas for AR content, namely the ceiling and floor, appears promising. While placing content on either area frees up space on the eye level, it leads to a need for up- or downwards movement of the head, which could inflict additional physical strain on the users. With this, the decision on what placement area to use is not only the real-world environmental characteristic but also influences the user's characteristics of physical ergonomics and visual perception (see Fig. 5.1). Henceforth, with the presented research project we[1] will explore the feasibility of the ceiling and floor as alternative AR content placement and its influence on human ergonomics. To achieve this, we contribute the following:

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[1] "We" in this chapter relates to the author Marc Satkowski, as well as Rufat Rzayev, Eva Gobel, and Raimund Dachselt as co-contributors to this research.

- ➤ A detailed motivation for this research project (Sec. 5.1), including a small-scale survey for existing systems and designs which make use of the ceiling and floor in AR (Sec. 5.2).
- ➤ A design space describing the different available parameters for content placement on ceiling and floor (Sec. 5.3), motivated by two additional scenarios.
- ➤ One study (Sec. 5.4) focused on the feasibility and usefulness of both areas.
- ➤ A second study (Sec. 5.5) for defining the specific instances of the proposed placement parameters.
- ➤ A discussion (Sec. 5.6) of our findings and their limitations which result in a list of design recommendations for the future use of the ceiling and floor in AR.

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Parts of the research presented in this chapter have previously appeared in:

**Marc Satkowski**, Rufat Rzayev, Eva Goebel, and Raimund Dachselt. “ABOVE & BELOW: Investigating Ceiling and Floor for Augmented Reality Content Placement”. In Proceddings of: *21st IEEE International Symposium on Mixed and Augmented Reality (ISMAR)*. Singapore, October 17-21, 2022. [Sat+22b]

*Own Contribution:* I was the major contributor to the complete project, which included the study design, the placement design space, the scenarios, and the data analysis. Most of the different work packages within this work were created in discussion with my co-authors. The general idea of this topic arose at the beginning of my Ph.D. project. Later, this idea was further advanced via extensive discussion with the co-authors, which resulted in the two presented studies, the design space of placement and perceptual parameters, but also scenarios that were previously not part of the publication.
*Applied Changes:* The publication related to this chapter consists of the article and an additional appendix file which I integrated into this chapter. Additionally, a new section focusing on the before-mentioned scenarios was added.

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**Fig. 5.2.:** Envisioning a future AR application displaying content on the ceiling and the floor. The image illustrates a small grocery shopping scenario. The arrows on the floor help navigate the supermarket, while the content on the ceiling shows a notification, part of a shopping list connected to a recipe, and supply chain information for a product.

## 5.1 Motivation

Enhanced availability of digital information combined with AR user interfaces opens up new possibilities for displaying and interacting with digital information [Azu+01]. As AR enables the simultaneous presence of reality and digital content by embedding virtual information into real-world scenes, it is possible to support primary real-world tasks. For example, digital labels can enrich a shopping experience [BMD18], navigational aids can help to orientate in unknown buildings [MSS11], or in-situ content can be used to find and refer to new information in museums [Sch+18]. Fundamentally, displaying AR information requires well-grounded placement strategies and view management [BFH01]. Extending the current placement options beyond the eye level is necessary to avoid obscuring essential real-world information with AR content in front of the user.

As more AR research and systems exist, more and more of the available display space in the users' eye level will be filled up with various types of content. Therefore, it becomes essential to explore alternative placement areas. For that, we systematically investigate displaying virtual content on the *ceiling* above and the *floor* below the user as promising placement areas beyond conventional eye level in indoor AR environments. More precisely, our initial exploration will focus on 2D virtual content that can provide valuable information in everyday life situations. With this, we aim to understand better whether and how the ceiling and floor in indoor environments can be used to place 2D virtual content using AR applications, which are not meant to replace but extend and support the existing content placed on the eye level. The ubiquity of both areas, also motivated by other research (e.g., [Tom08; Dan+15]), opens up new possibilities for displaying digital content, but also for possible interactions between the eye-level and the presented areas. As both areas are easily accessible through a simple head or eye movement, content placement is also interesting for the research direction of glanceable interfaces [Lu+20]. For example, the ceiling and the floor in a supermarket (see Fig. 5.2) can be used for the presentation of additional information, like displaying information about particular vegetables, showing a grocery list, helping a user navigate through the building, or displaying notifications.

While previous research has used these areas for content placement (e.g., [RP20; TP20]), a more profound and systematic treatment of the design dimensions considering AR content placement is still lacking. To fill this research gap, we comprehensively investigated AR content placement on the ceiling and the floor in indoor environments via two user studies. In the first study, we focused on a qualitative analysis of how the placement of 2D AR content on the ceiling and the floor is perceived. For the second study, we investigated optimal placement parameters in these areas. To ground both studies, we created a shared systematic on how the placement in both areas can be defined. Additionally, this design space helps us describe and highlight why the placement of AR content on the ceiling and floor differs from each other and the generic eye level.

## 5.2 Background: Properties of Ceiling & Floor

Our work is mainly related to previous research on ubiquitous content placement using AR, especially ceiling and floor as the virtual content location we discuss in the following.

### 5.2.1 Properties of Floor and Ceiling

Several properties of ceiling and floor make them promising areas in indoor environments for displaying information.

### Floor

The floor always provides humans and objects a solid foundation and ground to stand on while being an essential element for conveying information, regulating the use, and being decorative or aesthetic [Pet+05]. In general, the floor fulfills guiding functions by either the nature or texture of the floor in combination with multisensory information [Law+09], changing elevation levels, like separating pedestrian paths by borders, the placement of objects, or additionally placed signs, e.g., boundaries of bus stop areas. Humans are rather familiar with looking downward to verify their next steps or current position. Typically, the ground around people is visible [FMR20], which gives them safety that the following steps are not hindered by any objects, furniture, or other people, which is quite common [Wim+13]. In cases where the elevation changes drastically, like stairs or irregular outdoor surfaces [Dan+15], it is essential to keep an eye on the ground.

### Ceiling

Like the floor, the ceiling is always present [TG07] as long as we are inside a building. In general, the ceiling is always visible [TG07; Wim+13; TGM07], mostly planar, and remains free and featureless [Tom+08; Baz+13] with only a few exceptions [LTM11] (further properties can be found in [Tom08]). Such exceptions are mainly due to a light source [Wim+13; Oh+12], object attachments [Wim+13] (e.g., banner, curtains, or fans), or communication surfaces [LTM11] (e.g., signage).

### General

Considering these properties of the ceiling and the floor, both areas provide easy and effortless access, which makes them suitable for presenting glanceable interfaces [Lu+20; Mat07]. However, several constraints should be considered while displaying information on the ceiling or the floor. First, while designing applications enabling information presentation on the ceiling and the floor, users' posture, such as standing, sitting, kneeling, lying, or even cycling [Sch+15; VÜD15] should be taken into account as it affects how easily the ceiling and floor are perceived. Second, people are not regularly paying attention to the ceiling [HT19] since it is relatively unobtrusive [TG07]. Additionally, it can be tiring for people to look at the ceiling for an extended amount of time [Tom08]. Another important attribute of the ceiling is its height, which can significantly differ from building to building or even be perceived as infinite outside. Therefore, applications should notify users about the content on the ceiling if needed and not require their attention for a long time. Finally, available space should be considered while placing content on the ceiling or the floor. There could be static objects, such as a chandelier or available space, that might dynamically change due to other people or moveable objects

| **Technology** | **Ceiling** | **Floor** |
|---|---|---|
| **UbiComp Solutions** | | |
| ▷ Monitor System | [MHG07] [TGM07] [Tom+08] | [Sch+15] [Ver+15] [Mat+20]<br>[Ott+20] |
| ▷ Stationary Projector | [TGM07] [TG07] [Tom+08]<br>[Oh+12] [Baz+13] [Wim+13]<br>[Per+16] [Sch+18] [HT19] | [Pet+05] [Law+09] [Aug+10]<br>[Brä+13] [Fuj+13] [GC16]<br>[MM18] [AMR20] [FMR20] |
| **Personal Augmentation** | | |
| ▷ Mobile Projector | [LTM11] | [Ota+10] [Cau+12] [Win+14]<br>[Dan+15] [VÜD15] [Sat+16]<br>[Sak+17] [Kni+18] |
| ▷ Head-mounted Display | [Sog+08] [Rei+20] | [Ana+18] [Mül+19] [RP20]<br>[TP20] |

Tab. 5.1.: Overview of 38 papers considering the content placement on the *ceiling* and the *floor*.

in the environment. Thus, tracking might be required in the case of a dynamic environment.

### 5.2.2 Displaying Virtual Content on Floor and Ceiling

Displaying content above on the ceiling and below on the floor were already explored in several use cases, such asa visit to public spaces (e.g., museum) [Sch+18; RP20], indoor guidance [Mat+20; AMR20; RP20], outdoor guidance [Ana+18; Win+14], office work [Wim+13; Baz+13], smart living spaces [HT19; Oh+12; Sch+15; Brä+13], gaming [FMR20], industrial applications [Ott+20], and for awareness and ambient displays [Tom+08; TGM07; Per+16; MM18; Fuj+13; Law+09; LTM11]. To display content in these areas, monitor systems, stationary and wearable projectors, and HMDs were mainly used in previous works. We can group these works into *UbiComp solutions* and *personal augmentation* considering the used display technologies (see Tab. 5.1).

The majority of related work can be classified as *UbiComp solutions* using one of two display technologies:

- Monitor systems with single or multiple displays on the ceiling [TGM07; Tom+08] or on the floor [Mat+20; Sch+15], as well as low resolution displays consisting of individual LED units [Ver+15].
- Projector setups, either with rear projection on the ceiling [Wim+13] and floor [Aug+10] to avoid shadowing, or front projection on the ceiling [Oh+12] and floor [FMR20].

As both display technologies are stationary and mostly directly embedded into the environment, it is possible to optimize the presentation of the virtual content to the environment. Furthermore, by using additional hardware (e.g., Kinect), it is possible to track the user to enable, e.g., foot or touch interaction [Aug+10; Brä+13; Sch+15] or record position, posture, or gestures [FMR20; Fuj+13; GC16; MM18; Ver+15; Oh+12]. However, the augmentation is limited to the predefined local area in these works. Through the global nature of such installations, presented content is always visible to all persons in this environment. Furthermore, areas of display or projection can be occluded by persons or objects.

A smaller group of the related literature could be classified as *personal augmentation* using the following two display technologies:

- Pico-projectors worn, e.g., in a handbag [LTM11], around the neck [Sak+17], or at the waist of the user [Dan+15], as well as other mobile projectors, such as a projector-quadcopter [Kni+18].
- Head-mounted displays [RP20; TP20].

These technologies allow a mobile and dynamic augmentation of the environment since they are directly bound to the user by, e.g., wearing such devices. In general, body-bound devices allow the presentation of additional virtual information in any given environment, which is also visible in the number of use cases focused on navigational tasks (e.g., [VÜD15; Rei+20; TP20]). However, optimizing the display of these devices for the real-world environment is more challenging than using stationary setups embedded in the environment. Wearable projectors allow to augment a specific area on either the ceiling or the floor and are limited to the displayable area. In comparison, despite the low resolution of current OST HMDs, they enable to augment both the ceiling and the floor and other areas of the environment simultaneously while not being limited to the field of view (FoV) of these devices. However, to our knowledge, no previous studies have systematically investigated content placement on the ceiling and the floor using OST HMDs.

While investigating foot-tap interaction with an interface that was displayed on the floor, Müller et al. [Mül+19] found that this kind of interface should be used for short-term and fine-grained interactions. Renner and Pfeiffer [RP20] showed that interfaces requiring the user to permanently look at the floor for the navigation task are not optimal considering the ergonomics. However, while comparing map locations for a simulated AR pedestrian navigation interface in a fully immersive virtual environment, Tran and Parker [TP20] found that participants prefer the display location on the floor in front of them compared to on their hands or as a floating display. In their study, Reiner et al. [Rei+20] compared displaying a 2D map

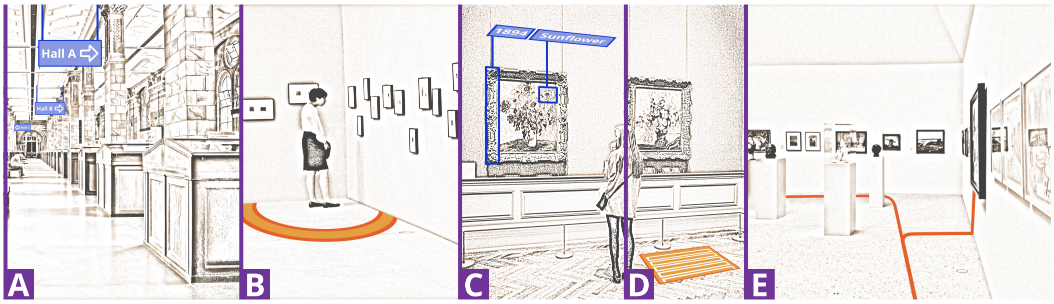

**Fig. 5.3.:** A small scenario illustrating a possible use of the *ceiling* and the *floor* in a museum use case. This is further described in Sec. 5.3.1.

in front of the user and a topographic layout of the terrain in the upper visual field in a route confirmation task. While simulating the task in a fully immersive virtual environment, they found that participants with prior virtual reality experience were more accurate during the task with the presentation in the upper visual field.

## 5.3 Content Placement on Ceiling and Floor

For efficient content placement on the *ceiling* and *floor*, it is essential to understand the parameters and constraints affecting the placement. Therefore, we first describe scenarios that help us demonstrate both areas' usability (Sec. 5.3.1). With those, we motivate and describe the general placement parameters and strategies on both *ceiling* and *floor* (Sec. 5.3.2). Afterward, we describe potential perceptual issues related to the content placement on the *ceiling* and the *floor* and introduce the angular size as an essential placement measurement (Sec. 5.3.3).

### 5.3.1 Scenario

We will describe two scenarios illustrating the use of *ceiling* and *floor* in a museum and production plant use case, respectively.

#### Museum Visit

In this first scenario, Mia visits a museum in another country (see Fig. 5.3). After entering the museum, she first wants to stroll through various departments before visiting specific exhibition pieces. **(A)**: Unfortunately, the signs on the ceiling are useless for her as they are in a foreign language and not present at every interesting location. However, using an app on her AR HMD, it is possible to show additional

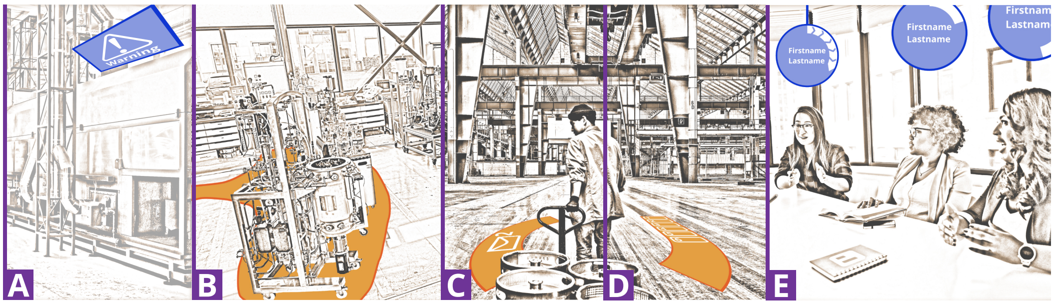

**Fig. 5.4.:** A small scenario illustrating a possible use of the *ceiling* and the *floor* in a industrial use case. This is further described in Sec. 5.3.1.

virtual signs adapted to Mia's native language, which can overlay, replace, or complement the existing signage. The attached virtual connection lines on the AR signs further increase their immersive perception, so they do not seem to float in the air. **(B)**: While Mia is walking through the museum, she meets other visitors to whom she wants to keep a recommended distance of at least 1.5 m due to a still ongoing pandemic. Since it is not always possible to correctly estimate the distance or keep this rule in mind, a virtual circle around other visitors can visualize the areas to avoid while navigating the museum. As she approaches another person, this circle increases its height and imitates a 3D obstacle on the floor. **(C)**: Next, Mia stands in front of an intriguing painting. Triggered by her proximity to the painting and a longer dwell time, certain areas in the image are slightly highlighted in AR and connected to additional information panels placed on the virtual ceiling. **(D)**: Mia decides to read the short description of the art styles of the painting in one of the panels. As she is interested in a particular style and its corresponding painters, she saves the relevant virtual information in her personal storage area, which is presented on the floor. **(E)**: Additionally, Mia wants to find more exhibits from the same painter and confirms the already suggested painter's name in the AR application. The application displays links on the floor to connect the matching paintings.

#### Production Plant Maintenance

In our second scenario, we follow Jake through a work day in a production hall of a cyber-physical production plant (see Fig. 5.4). First, Jake monitors different machines in preparation for his report in a meeting later that day. **(A)**: On his way to the next machine, he sees a notification above a nearby machine informing him about problems that require intervention. To react to the error, Jake moves closer to the machine. As he approaches, the notification tilts for a more pleasant viewing angle, and the content changes to a detailed error log. **(B)**: Jake finds that another machine causes the problem in this production chain. To help find it, an additional

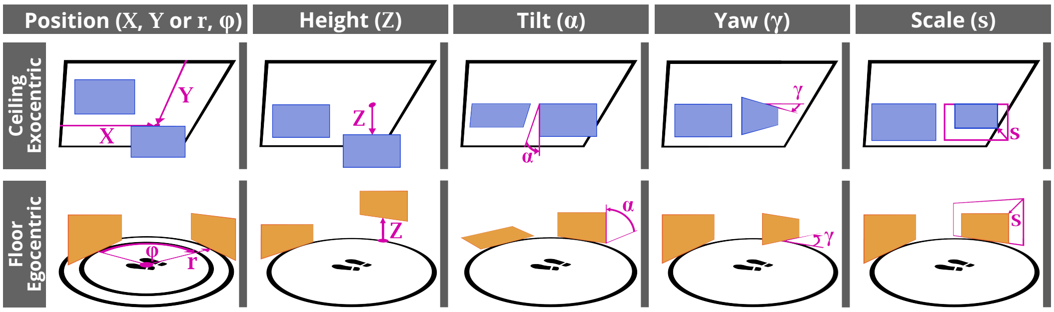

**Fig. 5.5.:** The placement parameters usable on *ceiling* and *floor*. Roll ($\beta$) is not included since it is not useful for a good placement. While the first row shows an *exocentric* placement on the *ceiling*, the second shows an *egocentric* placement on the *floor*. However, the opposite is also possible, which means to place content egocentrically on the *ceiling* or exocentrically on the *floor*.

group visualization can be shown on the floor, highlighting and encompassing the entire production line. **(C)**: While Jake walks to the other machine, he receives an e-mail. The corresponding notification is placed on the floor in his personal space. To scan the e-mail content, he looks down at the symbol, triggering an enlargement of the content containing the sender and subject of the message. **(D)**: As Jake is too busy to solve the email task immediately, he decides to store it as a new item in his personal ToDo list on the floor. **(E)**: After Jake has finished the maintenance work, he starts the meeting on the current state of the production plant. As the meeting host, he needs to manage the presentation and speaking times of the participants. For this, he sees the corresponding speaking time above each participant as additional information diagrams.

### 5.3.2 Content Placement and Constrains

A placement in AR can be done in relation to the environment, like in Immersive Analytics [Mar+18; Ska+19] or as situated and embedded visualizations [WJD17; ESL13]. Moreover, AR applications can also display virtual content about a user. Considering those two options, two reference frames for the content placement can be defined: the *exocentric* and *egocentric* reference frames [EHI14].

To define the placement using the *exocentric* reference frame, we use a Cartesian coordinate system with translation (X, Y, Z) and rotation ($\alpha$, $\beta$, $\gamma$) parameters. For the *egocentric* reference frame, we propose using a cylindrical coordinate system with the user's position as its point of origin, a translation combined from the radius (r), azimuth ($\phi$) and height (Z), and the rotation ($\alpha$, $\beta$, $\gamma$) parameters, accordingly. For both, $\alpha$ referes to pitch, $\beta$ to roll, and $\gamma$ to yaw.

Those coordinate systems can be applied to both areas, which splits the coordinate system into *floor* and *ceiling* variants that are mirrored to each other (see Fig. 5.5). This split and the need to keep the virtual content visible lead to constraints on the general usability of the coordinate systems parameters. First, as both variants are mirrored, the height (Z) and pitch ($\alpha$) are also mirrored. Second, the pitch ($\alpha$) is limited to the range of $0°$ to $90°$. Hence, an angle of $90°$ means that the content is perpendicular to both areas, while at $0°$, the content lies flat on either area and faces inwards. Third, the roll ($\beta$) should be blocked and perpendicular to either area to prevent the content from pervading the physical areas. Finally, the pivot point for the virtual content differs between both areas to ensure that content is always connected to the corresponding plane regardless of its orientation as long as the height (Z) is 0. This pivot point is at the top and bottom center for virtual content on the *ceiling* and the *floor*, respectively.

### 5.3.3 Visual Perception and Ergonomics

Considering the previously described scenarios (see Sec. 5.3.1) viewing AR content on the *ceiling* or *floor* (e.g., Fig. 5.2) can be affected by perceptual factors, like the distance perception [CV95] as content could be out-of-view. Therefore, it is necessary to make users aware of such content by notifying or guiding them to it with the help of visual aids (e.g., [BR03; PMN17; Gru+17]) or change the distance (d) to the content to support its visibility. Other perceptual factors, such as text perception [Gat+15b], color perception [Liv+13], or visual attention [Lu+14b], can be of importance as well.

#### Angular Size

The apparent or angular size ($\delta$) changes depending on the placement parameters, resulting in hard-to-read content due to the perceived size or higher occlusion of the real-world environment. In general, the angular size ($\delta$) can be calculated at the eye level as follows: $\delta = \arctan(s/2d)$ (see Fig. 5.6A). However, as soon as we move the content up or down to align it to the *ceiling* or the *floor*, the angular size ($\delta$) changes (see Fig. 5.6B). To set up an optimal apparent size ($\delta$) as seen with the distance-independent millimeter [DKO18], it is possible to manipulate the three placement parameters of distance (d), size (s), and pitch ($\alpha$) in different ways (see Fig. 5.6C). To calculate the angular size ($\delta$) of any given content on the *ceiling* or *floor*, the following formula can be used: $\delta = \arccos((a^2 + b^2 - s^2)/2ab)$. Here, $a$ is the distance to the edge of the content connected to either area, and $b$ is the distance

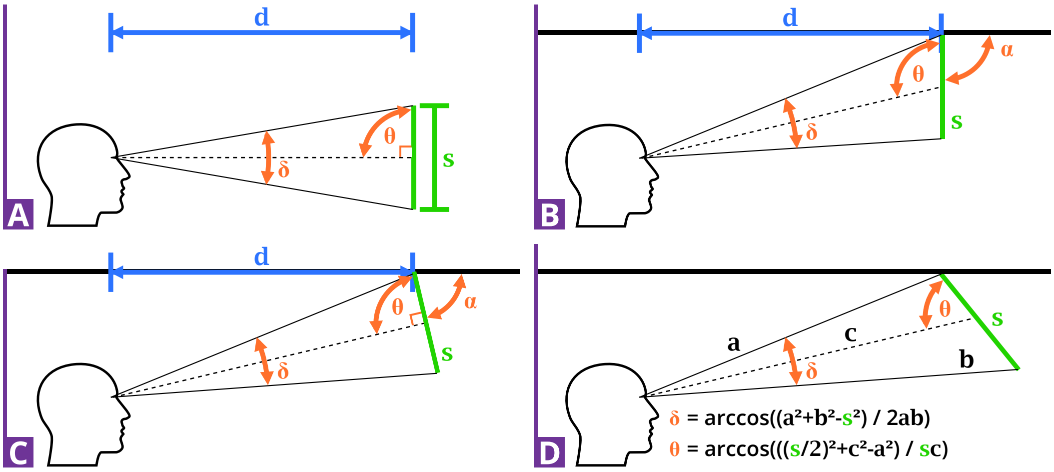

**Fig. 5.6.:** Calculation of the angular size ($\delta$) and viewing angle ($\theta$). **(A)** The angular size ($\delta$) can be calculated by distance (d) and size (s) of the object, while the viewing angle ($\theta$) is orthogonal to the content. **(B)** As the content is placed on the *ceiling* (or *floor*), the viewing angle ($\theta$) is no longer orthogonal. **(C)** The pitch ($\alpha$) can be changed to achieve an orthogonal viewing angle ($\theta$). **(D)** To calculate the angular size ($\delta$) and the viewing angle ($\theta$), the distances from the eyes can be used. For content on the *floor*, a and b are swapped and thus, the viewing angle ($\theta$) is mirrored.

to the other edge of the content (see Fig. 5.6D). This calculation is the same for the *ceiling* and the *floor*.

### Viewing Angle

While moving content from the eye level of a user to the *ceiling* or the *floor*, the viewing angle ($\theta$) of the content also changes (see Fig. 5.6A and B). This causes virtual content to appear distorted and makes it harder to read and understand the presented information. To increase the visibility and set up an optimal viewing angle ($\theta$), it is again possible to manipulate the three placement parameters of distance (d), size (s), and pitch ($\alpha$) in different ways (see Fig. 5.6C). To calculate the viewing angle ($\theta$) of any given content on the *ceiling* or *floor*, the following formula can be used: $\theta = \arccos\left(((s/2)^2 + c^2 - a^2)/sc\right)$. Here, $a$ is the distance to the edge of the content connected to either area, and $c$ is the distance to the center of the content (see Fig. 5.6D). For the *ceiling*, the viewing angle ($\theta$) is linked to the upper half of the content (see Fig. 5.6B), while for the *floor*, this angle is on the lower half.

### Differences Ceiling and Floor

Mentioned perceptual issues can differ between content placed on the *ceiling* or the *floor*. In most cases, the *ceiling* is closer to the head of a user than the *floor* (see Fig. 5.7A), which alters the general viewing direction, as well as the tilt of the neck

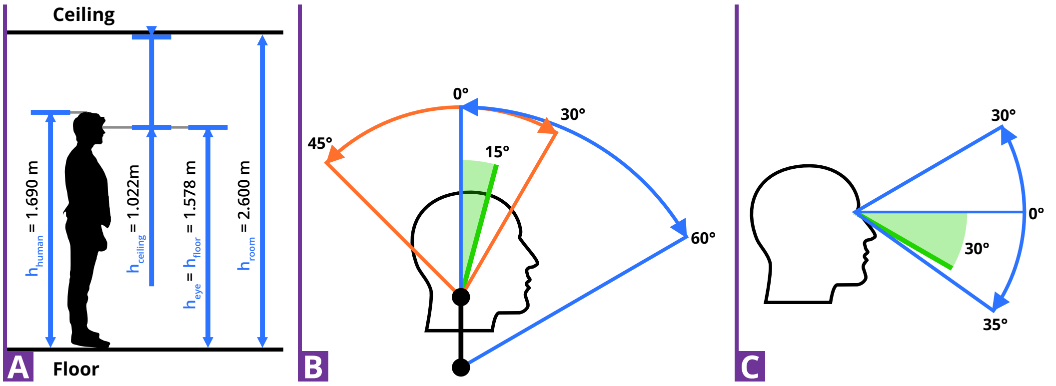

**Fig. 5.7.:** Information about the human ergonomics and the measurements of typical environments. **(A)** An exemplary height (h) from the eye to a typical *ceiling* and *floor* are displayed [Til02]. **(B)** The neck tilt angle ranges forwards (blue) and backwards (orange) with the optimal movement range (green) [Til02]. **(C)** The eye movement and vertical FoV range (blue) with the optimal movement range (green) [Til02].

and eyes. In general, it is easier for humans to look downwards [Til02], as the ranges for the neck tilt (see Fig. 5.7B) and eye tilt (see Fig. 5.7C) downwards are more extensive as compared to upwards. Further, the comfort zones for both neck and eye tilts are also in the downward direction.

### 5.3.4 Study Plans

Following this section, we describe two user studies we conducted to address the previously defined research gaps while considering possible content placement challenges in either area. While the first study focuses on generating a general understanding of if and how *ceiling* and *floor* can be used in future AR applications, the second study concentrates on verifying the optimal values for the angular size ($\delta$) and viewing angle ($\theta$).

For the rest of the section, we will use the term *secondary* content, which we define as content or information that is not urgent or not prioritized. Still, such content can be helpful for the user's current primary task or support a secondary task. Additionally, we will also use the term *visual complexity* (VC). It is related to information density, as it is *"mainly represented by the perceptual dimensions of quantity of objects [and] clutter"* [HMS09], but also *"depends on the amount of perceptual grouping an observer perceives in the scene"* [Oli+04]. Further, VC can also be related to readability, especially concerning the proposed placement parameters, as those alter the perceived size and can introduce distortions.

## 5.4 Study 1: Explorative User Study

To gain an understanding of the usability of *ceiling* and *floor* as placement areas for AR content, we first conducted an exploratory user study. As our goal was to study how users perceive AR content displayed on both areas in indoor environments, we did not compare these placement areas with the one on users' eye level.

### 5.4.1 Design and Methodology

We conducted a semi-structured interview in combination with a think-aloud method using an AR prototype. The interview was split into six blocks consisting of two to five sub-questions (see appendix Sec. C.1.1). Those blocks focused on:

(1) The relationship between the distance (d) and content concerning the visual complexity (see Sec. 5.3.4) and placement area.
(2) The relationship of the distance (d) to the perception of public and personal content.
(3) Other properties for public and personal content, such as billboarding.
(4) The relationship of posture to the general perception and usability of the placement areas.
(5) The interaction with the content placed on the *ceiling* or *floor*.
(6) Questions that focused on the possible use of *ceiling* and *floor*, scenarios, functionalities, ergonomics, and other issues.

The experimenter generally kept a protocol of participants' answers, complemented by the recorded audio.

For the study, we described to the participants a grocery shopping scenario (see Fig. 5.2) to let them envision possible future use cases for AR in their everyday life. Further, this scenario also guided us in creating virtual content, which varies in VC (see appendix Fig. C.1). Beginning with the lowest VC, those are a music app symbol, mail notification symbol with text, grocery shopping list, floor plan for the supermarket, fitness data overview with diagram and text, and a cooking recipe.

### 5.4.2 Participants

We recruited eight unpaid participants (3 female, 5 male) for our exploratory study. Seven worked as scientific employees at TUD Dresden University of Technology,

**Fig. 5.8.:** Scenes 1 and 2 of our first study where a participant controls the content with the tablet **(A)**, and several content elements at *ceiling* and *floor* of which some orient themselves to the participant **(B)**.

while one worked as a technician. The age ranged from 25 to 56 years ($M = 36.25$ years, $SD = 9.45$ years), and the self-reported height ranged from 155 to 198 cm ($M = 176.75$ cm, $SD = 9.45$ cm). All participants had normal or corrected-to-normal vision and no color vision defects. One participant reported slight difficulties with spatial perception in the past, which were corrected by training and experience. On a five-point rating scale, all participants had some experience with AR in general ($M = 2.5, SD = 1.07$), HMD-based AR ($M = 2.63, SD = 1.19$), and VR ($M = 2.13, SD = 0.99$). The study required no specific previous experience from participants.

### 5.4.3 Setup and Apparatus

We conducted the study in a laboratory room of 5.1 m x 8.5 m and a ceiling height of 2.6 m. During the study, participants could either sit on a chair (see Fig. 5.8A) or move freely through the room, which let them explore the full range of possible postures AR can be used in. As an apparatus, we used a Microsoft *HoloLens 2* worn by the participants, a tablet (Microsoft *Surface Go*) that allowed the participants to manipulate the AR content, and a desktop computer running a server for network communication of the devices and an application to control the study and log relevant data. We used the Mixed Reality Toolkit (MRTK), Unity 3D, and C# to implement the HoloLens application. To align the virtual content with the real-world study environment, we used a QR code[2] scanned at the beginning of the study session. We implemented a web application via JavaScript to remotely control the shown content by placing content on either placement area, changing the displayed

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[2] Microsoft provided functionality to scan and spatially locate QR codes via `https://www.nuget.org/Packages/Microsoft.MixedReality.QR`

**Fig. 5.9.:** Scene 3 of our first study. **(A-C)** illustrates the proximity-based interaction, while they also show show the point of view of the participants.

content element, and placing the content based on the available parameters (see Fig. 5.5).

For the HoloLens application, we implemented three scenes, each connected to a set of interview blocks. In **Scene 1** (related to first two interview blocks), a content element was displayed either on the *ceiling* or *floor* at a pitch of $45°$. The participants could manipulate the content using the tablet (see Fig. 5.8A) by altering the placement areas (e.g., pitch), the content elements, or changing the distance to the content between 0 m and 6 m measured from their chair. We used 6 m as the maximum distance to virtual contents considering the vergence-accommodation conflict [@Micb]. In **Scene 2** (related to third and fourth interview block), we presented all six content elements directly on both placement areas with a pitch between $45°$ and $90°$ (see Fig. 5.8B). Additionally, billboarding for the yaw ($\gamma$) was activated for half of them on either plane. In **Scene 3** (related to fifth interview block), we presented two interaction techniques similar to a semantic zooming approach [LBC04; HD08]. Both techniques changed the detail of the presented content (see Fig. 5.9). Only a mail icon or meal images are visible in the default state. Triggered by either gaze (dwell time) or proximity (less than 1.5 m), the shown content changed its pitch from $0°$ to $90°$ while exchanging the content to another view, containing the subject and first two lines of the mail or a user rating. Lastly, the complete mail or recipe could be accessed by an air-tap on the content, which brought it to the usual eye level.

### 5.4.4 Procedure

After getting acquainted with the purpose of the study, participants signed the consent form and filled out a questionnaire about demographic data and technology familiarity (see appendix Sec. C.1.2). Afterward, the experimenter presented the grocery shopping scenario, guided the participants to wear a HoloLens 2 and perform an eye calibration for a better viewing experience. Next, participants were asked to scan a QR code placed on a table in the room to fix the exocentric coordinate system. The participants then started the web application on the tablet while the experimenter started the server and the study control application. During the main part of the study, participants experienced all three scenes in ascending order. The participants were instructed to think aloud while exploring the scenes and answering the interview questions. The latter was also used to guide the participants through the application. The participants were encouraged to sit on a chair, stand, or walk inside the study environment throughout the session. At the beginning of the experiment, participants were sitting. The main part of the study lasted approximately 59 min ($M = 59:26$ min, $SD = 6:51$ min).

### 5.4.5 Study Results

We analyzed 484 notes collected from participants (P) through an affinity diagramming [HH15] approach. We created four overarching thematic groups focusing on placement areas, content types and their placement, interaction and functionalities, ergonomics and postures.

#### Placement Areas

In general, the *ceiling* and the *floor* were perceived to be suitable exclusively as a secondary information display (P1, P2, P4, P5, P7, P8), i.e., for easily and quickly digestible content that does not take up the user's primary attention. While four participants preferred displaying AR content on the *floor* (P3, P6-8), one favored the *ceiling* (P5). Participants highlighted that content placed on the *floor* could be perceived as obstacles (P1, P3-5, P7) that can limit movement (P5). However, placing a content flat on the ground ($pitch = 0°$) might be perceived as a *"sticker"* (P5) and reduce the *"respect"* for this content (P5, P7). Some participants were also concerned that the virtual content might occlude physical objects in the environment, such as signs on the *floor* (P2, P5, P7, P8). Furthermore, participants indicated that by getting familiar with the *ceiling* and some training, possible out-of-view problems could be resolved (P1, P3, P6, P7). Moreover, it was also mentioned that a quick look at the *ceiling* to check secondary content such as a notification is a *"reduction of movement"* (P7) compared to taking a smartphone in hand and unlocking it.

#### Content Types and their Placement

As participants spoke about their preferred content types, six participants (P1-4, P7, P8) favored abstract and less complex information on the *ceiling*. In comparison, five participants (P2-4, P7, P8) preferred detailed and, therefore, more complex information on the *floor*. Three participants (P6, P7, P8) stated that the content on the *floor* should be displayed close to the user. This is also the case for content with more information, as mentioned by seven participants (P1-5, P7, P8). Lastly, five participants (P1, P2, P6-8) preferred content on the *ceiling* to be displayed farther away, which shows the overall wish to reduce the uncommon upward head movements.

#### Interactions and Functionalities

A simple head movement up or down allows the users to access the content on either content area. This was deemed enough for two participants (P2, P8), while two others (P5, P6) stated a need for additional interaction techniques. In the second scene, participants commented that the billboarding effect was an *"attention catcher"* (P4, P5, P7), which distracted some participants (P2, P5, P8). For the third scene, both used interaction techniques were rated as beneficial (Gaze: P1, P3-6, P8; Proximity: P1-6). Lastly, all participants liked the possibility of bringing virtual content to their eye level on demand.

#### Posture and Ergonomics

In our study, we encouraged the participants to sit, stand, and walk while exploring the HoloLens application. Three participants (P1, P2, P7) stated that they prefer standing as it promotes physical navigation. Additionally, two participants (P4, P6) mentioned that while standing, the *floor* was more uncomfortable since it had become farther away, while the *ceiling* was better to use for more distant content (P4). Regarding ergonomics, four participants (P1, P3, P6, P7) found looking at the *ceiling* for an extended time exhausting. In contrast, one participant found the weight of the *HoloLens 2* exhausting for looking at the *floor*. Five participants (P1, P4, P6-8) did not see any problem with ergonomics as long as the areas were mainly used for secondary content presentation.

### 5.4.6 Discussion

While our results showed that *ceiling* and *floor* are promising placement areas, users might miss content due to out-of-eye-level placement. Participants reported they could easily access this content with a short head movement. Moreover, our results

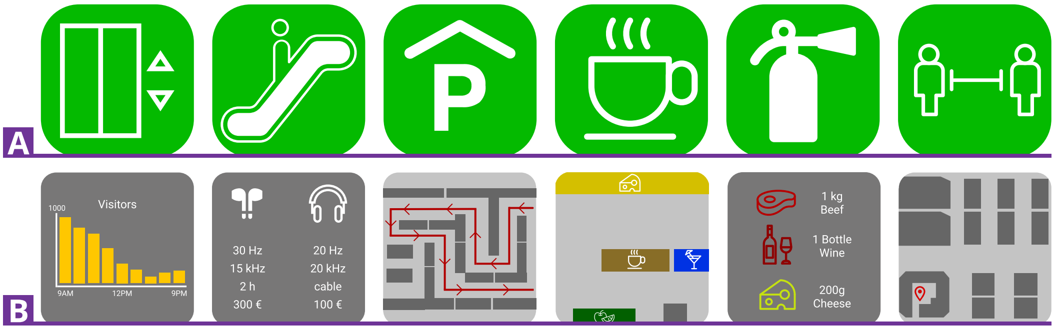

**Fig. 5.10.:** Twelve examples of the total 40 content elements (see appendix Fig. C.2) used in our study. Those content elements have either *low* **(A)** or *medium* **(B)** visual complexity (VC).

suggest that content on the *ceiling* should be abstract and displayed further away, and more detailed content should be placed closer to the *floor*. This can be explained by the need to reduce long uncommon upward head movements. Participants were also concerned with occlusion and less visible content placement issues on the *ceiling* and *floor*. These issues can be resolved by changing the distance (d) to the user or altering the virtual content's pitch ($\alpha$) in these areas. However, the preferable parameters of virtual content placement above on the *ceiling* and below on the *floor* remain unclear.

## 5.5 Study 2: Qualitative User Study for Placement Parameters

Our early exploratory user study results show that the *ceiling* and *floor* are promising secondary content placement areas. As participants preferred different amounts of information, we conducted a second study to investigate preferred placement of varying content types in either area. In this study, we asked participants to adjust the placement parameters of distance (d), pitch ($\alpha$), and content size (s). Through the study, we aimed to address the following research questions:

**RQ1** Is it preferred to have a viewing angle ($\theta$) of $90°$ perpendicular to the viewing direction?

**RQ2** Are there any differences in the choice of placement parameters in the placement process depending on visual complexity levels?

**RQ3** Are there any differences regarding *ceiling* and *floor* regarding the user-defined content placement?

| Parameter | Fixed Values | | | | |
|---|---|---|---|---|---|
| Distance (d) | 1 m | 2.25 m | 3.5 m | 4.75 m | 6 m |
| Pitch ($\alpha$) | $0°$ | $22.5°$ | $45°$ | $67.5°$ | $90°$ |
| Size (s) | 0.2 m | 0.425 m | 0.65 m | 0.875 m | 1.1 m |

**Tab. 5.2.:** Overview of the fixed parameters for Study 2.

### 5.5.1 Design and Methodology

We conducted a within-subject user study with two independent variables: placement area (*ceiling* and *floor*) and VC (*low* and *medium*). While for *low* VC, we used content with an iconic representation that can be very quickly perceived, for *medium* VC, we presented combinations of several icons, shapes, or texts. This decision is in line with the results of our first study, as it suggests the use of content that does not require immediate attention. Further, we did not include high VC content (e.g., a recipe), as such content appears to not be fit for either area, due to an extended duration to perceive it and could hinder users from their primary task [TP20]. Motivated by the grocery shopping scenario, we created a set of 20 different instances of each VC level. Those include, e.g., arrow and elevator signs as *low* VC and location plan and product comparison as *medium* VC contents (see Fig. 5.10B and Fig. 5.11B).

Our five dependent variables were the distance (d) from content to the user, pitch ($\alpha$) of the content, content size (s), as well as the angular size ($\delta$) and viewing angle ($\theta$) as compound values formed from the previous three parameters (see Sec. 5.3.3). Each participant performed 120 trials in this study, wherein two placement parameters could be freely controlled within a predefined range. At the same time, the third one was selected from a set of five predefined instances for every trial. Similar to the previous work [DKO18], we fixed the third parameter since the parameters were related (see Tab. 5.2). Considering the design guidelines for a comfortable content **distance (d)** range of 1.25 m to 5 m [@Micb], we selected a range of 1 m to 6 m, in combination with five instances of the distance as 1 m, 2.25 m, 3.5 m, 4.75 m, and 6 m. Regarding the **pitch ($\alpha$)**, we used a range from $0°$ to $90°$ (see Sec. 5.3.2). Again, we additionally selected five fixed instances of the pitch by splitting the range into equal pieces: $0°$, $22.5°$, $45°$, $67.5°$, and $90°$. Lastly, we conducted a small experiment with six participants to define a square content element's **size (s)**. Here, participants used a HoloLens 2 to define the biggest and smallest sizes of visible test content displayed at the distance of 1 m and 6 m on their eye level. This generated an average range from 0.2 m to 1.1 m. Using this range, we defined the instances for the size as 0.2 m, 0.425 m, 0.65 m, 0.875 m, and 1.1 m.

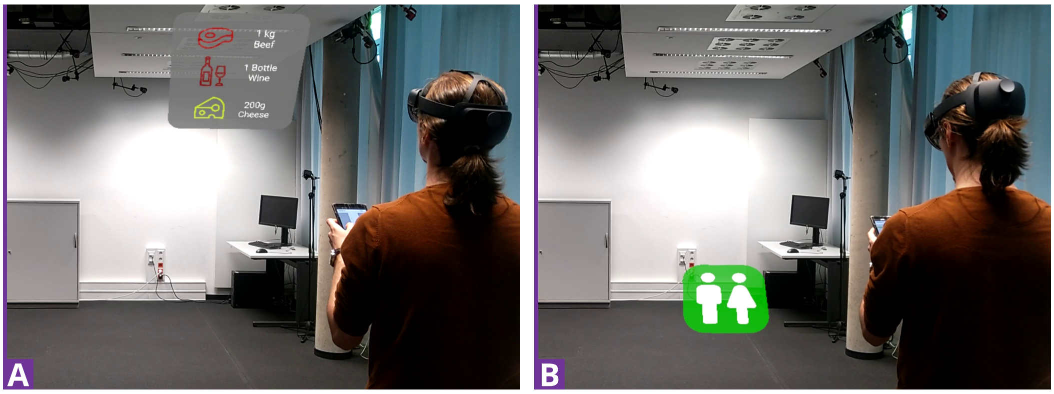

**Fig. 5.11.:** Images of the second study setup. Both images show a participant looking at content on either **(A)** *ceiling* or **(B)** *floor*.

For each study session, we logged the preferred placement parameters to calculate the angular size ($\delta$) and viewing angle ($\theta$) (see Sec. 5.3.3). We also used questionnaires to collect demographic data and information about participants' height, their health state before and after the study, their strategies for adjusting the available placement parameters (e.g., "Did you have a special procedure for setting the parameters?"), and their placement preferences (e.g., "Which parameter was most important for you?").

## 5.5.2 Participants

We recruited 26 participants (7 female, 19 male) who were compensated with 10€. All participants had a technical background and were either studying or working at TUD Dresden University of Technology. The age ranged from 20 to 42 years ($M = 26.04$ years, $SD = 4.82$ years), and the self-reported height ranged from 155 to 198 cm ($M = 176.19$ cm, $SD = 10.08$ cm). All participants had normal or corrected-to-normal vision. Two participants indicated color deficiency, while one had slight spatial perception problems. On a five-point rating scale, all participants had some experience with AR in general ($M = 2.54, SD = 1.21$), HMD-based AR ($M = 2.07, SD = 1.09$), and VR ($M = 2.07, SD = 1.09$). As in the first study, no specific experience was required for participation.

## 5.5.3 Setup and Apparatus

For this study, we used the same prototype, apparatus, and room as described in our first study (see Sec. 5.4.3). However, we made several changes to fit the study design.

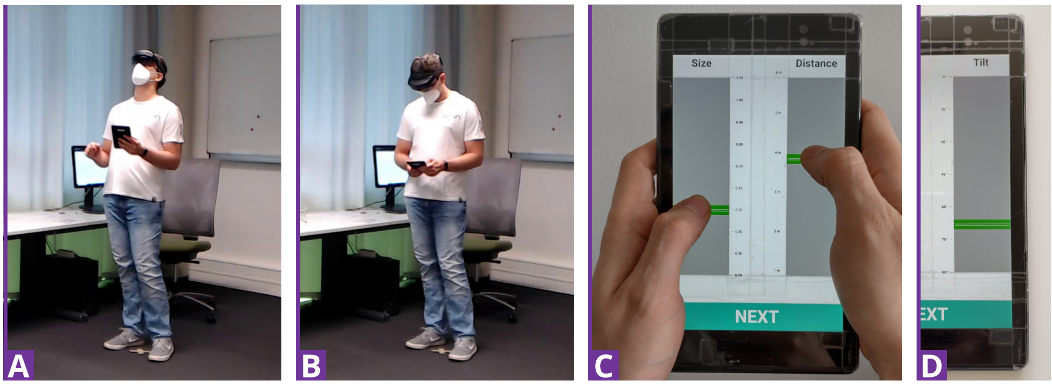

**Fig. 5.12.:** Images of the second study setup. **(A)** and **(B)** shows a participant looking down- and upwards respectively for content displayed at the *ceiling* and *floor* at a distance of $d = 1\ m$ in the third study part. **(C)** and **(D)** shows the tablet the participants used in the study, on which we put transparent tape to create a haptic feedback for an eyes-free interaction. The participants were only able to manipulate two parameters at the same time.

During the study, participants stood at a predefined position in the room while using a HoloLens 2 application (see Fig. 5.12A and B). The application displayed virtual content on either placement area and participants could manipulate it using sliders on the tablet (see Fig. 5.12C and D). We also changed the UI of the web app to allow controlling two parameters via sliders on the tablet (Asus Nexus 7) and advancing to the subsequent trial with a “Next” button on the bottom of the screen. Further, we taped the tablet to help participants easily find the locations of the sliders and the button on the screen without looking at the tablet (see Fig. 5.12C and D). To present the questionnaires, we used LimeSurvey.

### 5.5.4 Task

The presented task was formulated as: “Place the visible content with the available parameters so that they are optimal and best perceivable for you”. The participants should focus on their subjective perception and placement strategies within the task, which we later gathered via the questionnaires. We created three parts, in which the participants could only control two of the three placement parameters (see Fig. 5.12C and D). In **Part 1**, the distance (d) and pitch ($\alpha$), in **Part 2**, the distance (d) and size (s) (see Fig. 5.12C), and in **Part 3**, the pitch ($\alpha$) and size (s) were controllable within their ranges, while we used one of the five fixed instances in each trial for the remaining parameter. This allowed us to collect data for all values on our predefined range and verify the relation between different values of the same parameter. Overall, each participant had to solve 40 trials per part (2

| **Condition** | Angular Size ($\delta$) | | | Viewing Angle ($\theta$) | | |
|---|---|---|---|---|---|---|
| | $\mathbf{F}_{1,25}$ | **p** | $\eta_p^2$ | $\mathbf{F}_{1,25}$ | **p** | $\eta_p^2$ |
| Area | 0.896 | 0.353 | 0.035 | 1.691 | 0.205 | 0.063 |
| VC | 124.185 | $< 0.0001$ | 0.832 | 26.610 | $< 0.0001$ | 0.519 |
| Area x VC | 0.004 | 0.945 | 0.000 | 9.073 | $< 0.01$ | 0.266 |

Tab. 5.3.: ANOVA main effects and interactions for the angular size ($\delta$) and viewing angle ($\theta$). Statistically significant effects ($p < 0.05$) are highlighted in green.

placement areas × 2 VC × 5 fixed-parameter instances × 2 repetitions), resulting in 120 trials per participant. We altered the used placement area after every ten trials to reduce a potential neck strain. To reduce the possible effects of the order of parts and trials, we randomized the order of the parts via a Latin square. Furthermore, the order of trials (fixed-parameter instances × VC) and the start values for the two controllable parameters in each trial were completely randomized.

### 5.5.5 Procedure

After the participants filled out a consent form and a questionnaire about demographics and technology familiarity, they were introduced to the grocery shopping scenario. Next, participants stood in the predefined location in the room. We helped them to wear the HoloLens 2, perform an eye calibration on the device, and start the mobile study application on the tablet. Afterward, we asked participants to scan a QR code placed on a table in the room to fix the exocentric coordinate system, which was repeated in each study part. After a short training session, the main body of the study started, and participants performed the task in three parts, as mentioned above. After each part, participants filled out a questionnaire to indicate their content placement strategy. While completing the questionnaire, participants put down the HoloLens 2 to recover from possible neck strains. At the end of the study, the participants indicated their preferences regarding the placement areas and provided general feedback. The main part of the study, without filling out the questionnaires, lasted approximately 23 min ($M = 23:25$ min, $SD = 6:08$ min).

### 5.5.6 Study Results

We collected data from 3120 trials. We removed 37 trials (1.18%) due to technical reasons (i.e., unintentional double click on the “Next” button on the tablet), which were detected by comparing start and end time and start and submitted value of the

| Condition | | d in m | | $\alpha$ in ° | | s in m | | $\delta$ in ° | | $\theta$ in ° | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Area | VC | M | SD | M | SD | M | SD | M | SD | M | SD |
| C | L | 4.46 | 1.34 | 68.4 | 19.5 | 0.47 | 0.20 | 6.63 | 3.96 | 73.1 | 24.5 |
| C | M | 3.46 | 1.37 | 68.0 | 17.5 | 0.74 | 0.22 | 10.2 | 4.23 | 73.6 | 22.2 |
| F | L | 4.06 | 1.44 | 49.4 | 29.5 | 0.48 | 0.19 | 6.46 | 3.57 | 71.5 | 26.2 |
| F | M | 3.09 | 1.33 | 55.8 | 21.9 | 0.71 | 0.20 | 10.01 | 3.9 | 78.2 | 20.4 |
| C | | 3.96 | 1.47 | 68.2 | 18.5 | 0.60 | 0.25 | 8.42 | 4.47 | 73.3 | 23.4 |
| F | | 3.57 | 1.47 | 52.6 | 26.1 | 0.60 | 0.23 | 8.21 | 4.16 | 74.9 | 23.7 |
| | L | 4.26 | 1.43 | 58.9 | 26.7 | 0.48 | 0.20 | 6.54 | 3.77 | 72.3 | 25.4 |
| | M | 3.27 | 1.36 | 61.8 | 20.7 | 0.72 | 0.21 | 10.1 | 4.09 | 75.9 | 21.4 |

**Tab. 5.4.:** Mean (M) and standard deviation (SD) values of each placement and the derived parameters. For each placement parameter, we removed the trials with fixed values. With F = *floor*, C = *ceiling*, VC = visual complexity level, L = *low*, and M = *medium*.

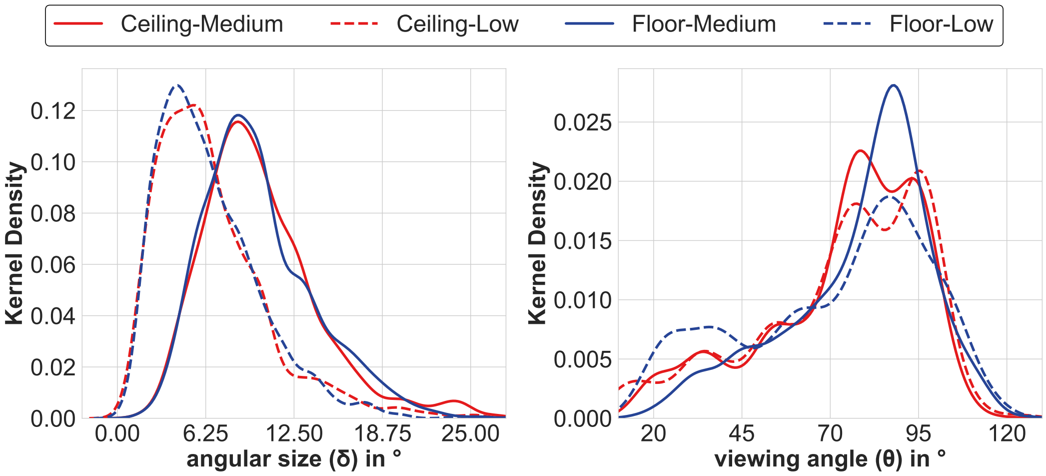

**Fig. 5.13.:** A kernel density estimation plot for both the angular size ($\delta$) and viewing angle ($\theta$).

trial. We calculated the angular size ($\delta$) and viewing angle ($\theta$) using the formulas presented in Fig. 5.6D. Moreover, we subtracted 11.2 cm from the participants' body height to calculate the distance from the ground to the participant's eyes, as suggested by Tiley [Til02]. Additional to the quantitative logged data of the trials, the questionnaires provided us with 304 comments, which we sorted by affinity diagramming [HH15].

### Angular Size and Viewing Angle

We performed two-way repeated-measures ANOVAs (see Tab. 5.3) on angular size ($\delta$) and viewing angle ($\theta$), which show that VC statistically significantly affects both values. Moreover, there was an interaction effect between the placement area and VC for the viewing angle, also visible in Tab. 5.4 and in Fig. 5.13. In general, the contents with *low* VC were set to a lower angular size ($\delta$) $(M = 6.5^\circ,\ SD = 3.8^\circ)$

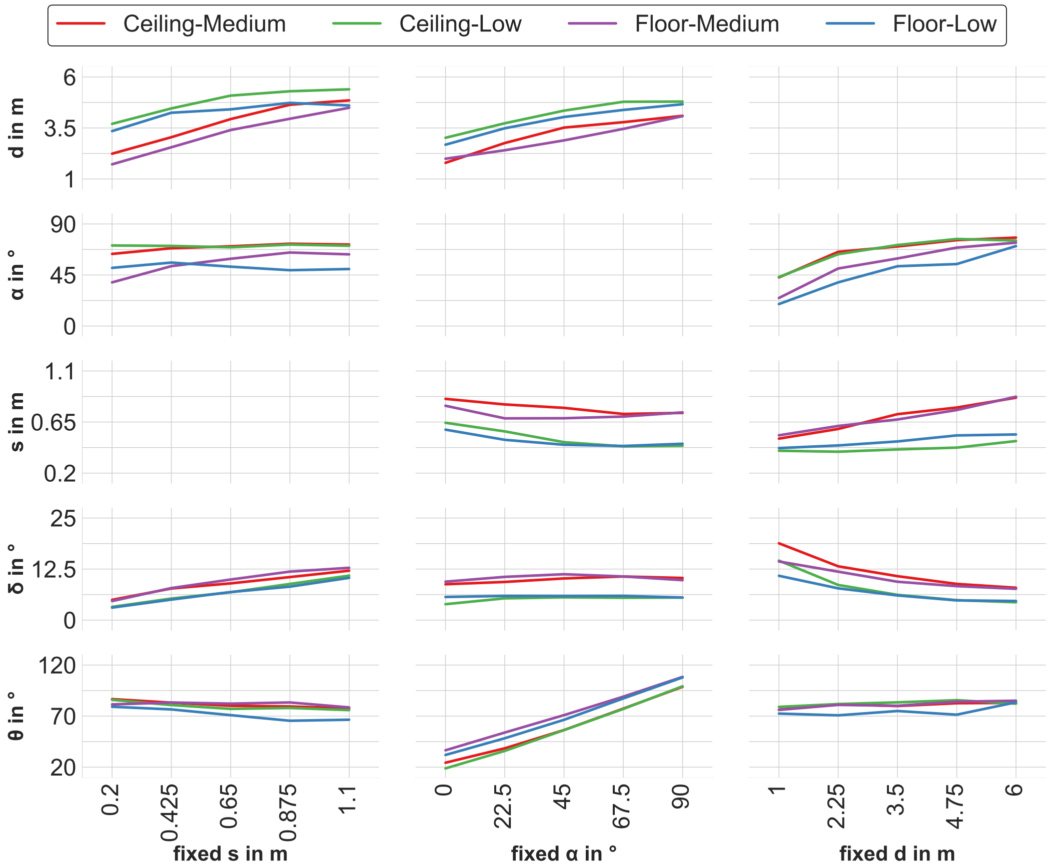

**Fig. 5.14.:** Overview how the dependent parameters of distance (d), tilt ($\alpha$), size (s), angular size ($\delta$), and viewing angle ($\theta$) changed with regard to the fixed parameters instances (five per x axis). All visualizations are split by both condition parameters of area (*ceiling* and *floor*) and Visual Complexity (VC) levels (*low* and *medium*).

than those with *medium* VC ($M = 10.1°,\ SD = 4.1°$). This shows that with a growing amount of information on a content element, this content's apparent size ($\delta$) should also increase. Additionally, the viewing angle ($\theta$) for content with *low* VC was smaller ($M = 72.3°,\ SD = 25.4°$) than for this with *medium* VC ($M = 75.9°,\ SD = 21.4°$). The bigger standard deviation for *low* VC content in combination with the wider distribution of the viewing angle ($\theta$) in Fig. 5.13 (a plateau for floor content at around $30°$ for trials with *low* VC content) shows that the viewing angle ($\theta$) for *low* VC is usable in a more flexible manner. Furthermore, 5 participants stated that they are far more tolerant towards imperfect viewing angles on the *floor* compared to the ones on the *ceiling*.

### Placement Parameters

With our study design, participants had to compensate for a non-adjustable parameter to achieve optimal angular size ($\delta$) or viewing angle ($\theta$). 14 participants also reflected on this behavior in the questionnaire. While pitch ($\alpha$) had the most considerable influence on the viewing angle ($\theta$) (Fig. 5.14, middle column), the differences between *low* and *medium* VC content in Part 3 (Fig. 5.14, right column) increased faster over the fixed distances (d) to achieve a bigger angular size ($\delta$).

Descriptive statistics (see Tab. 5.4) show the following behavior partly supported by participants' comments. Participants placed content on the *ceiling* farther away ($M = 3.96\,m, SD = 1.47\,m$) than the content on the *floor* ($M = 3.57\,m, SD = 1.47\,m$) which was supported by participants comments (5 out of 26). Content with *low* VC was also placed farther away ($M = 4.26\,m, SD = 1.43\,m$) while having a smaller size ($M = 0.48\,m, SD = 0.2\,m$), compared to the *medium* VC content, which was closer ($M = 3.27\,m, SD = 1.36\,m$) and bigger in size (s) ($M = 0.72\,m, SD = 0.21\,m$). The behavior regarding the content with *low* VC was confirmed by 10 participants. Lastly, the content on the *ceiling* had a bigger pitch ($\alpha$) ($M = 68.2°,\ SD = 18.5°$) than the content on the *floor* ($M = 52.6°,\ SD = 26.1°$). Participants also commented on placement parameter values. While 10 participants stated that content on the *ceiling* should have a $90°$ pitch ($\alpha$), 6 participants reported that the content on the *floor* should be at $0°$ pitch ($\alpha$). Furthermore, participants mentioned that smaller content should be displayed closer (7 out of 26) and bigger content farther away (7 out of 26) from the user. Lastly, 12 participants described a relation between the pitch ($\alpha$) and the distance (d) parameters by stating that a smaller pitch ($\alpha$) led to closer content and vice versa. Similarly, for 6 participants, a bigger pitch ($\alpha$) led to further away content.

### Participants' Goal and Preferences

To the question of which parameter was most important for the placement, 11 voted for distance (d), 10 preferred pitch ($\alpha$), and 5 indicated size (s). 24 participants stated they aimed to achieve the most readable and visible content. This includes participants' wish to see the content as straight and undistorted as possible (14 out of 26) while not completely filling up their and the HoloLens' FoV (9 out of 26). Furthermore, most participants tried to minimize the neck strain while optimizing the ergonomics of the placed content (21 out of 26). 10 participants also stated that it is more pleasant to look at content on the *floor* than on the *ceiling*, which is related to the bending range of the neck and the eyes (see Fig. 5.7B and C).

Furthermore, placement preferences were influenced based on the real-world environment (9 out of 26) or the meaning and context of the presented content (8 out of 26) (e.g., arrow for direction, maps for orientation). For example, to simulate signage hanging from the *ceiling* in the real world, 10 participants placed the content with a $90°$ pitch ($\alpha$). On the other hand, 6 participants placed the content on the *floor* with a $0°$ pitch ($\alpha$) to simulate guiding arrow on the streets. However, 5 participants stated that they would rather keep the *floor* as free as possible as they would perceive its content as an obstacle.

## 5.5.7 Discussion

Following, we discuss the results of our second study by addressing our three research questions (see Sec. 5.5.1).

### RQ1: Is a viewing angle ($\theta$) of $90°$ preferred?

RQ1 was not confirmed as the results showed that the mean values (see Tab. 5.4) for the viewing angle ($\theta$) were lower than $90°$. This can be explained by the fact that trials with fixed pitch ($\alpha$), which has the most significant influence on the viewing angle ($\theta$) (see Fig. 5.6C and Fig. 5.14 middle column), are considered for the mean values. Overall, the participants strived for $90°$ of viewing angle ($\theta$) on both areas. However, due to preferences, this is not always achieved. For examples they placed content on the *floor* flat ($\alpha = 0°$), which reduced the viewing angle ($\theta$), or content hanging from the *ceiling* like signage ($\alpha = 90°$), which increased the viewing angle ($\theta$) above $90°$ (see Fig. 5.13).

### RQ2: Are there differences in content placement regarding visual complexities?

Our results show a difference in the preferred angular size ($\delta$) and viewing angle ($\theta$) for the content on the *ceiling* and *floor* (see Tab. 5.3 and Fig. 5.13). Participants preferred a bigger angular size ($\delta$) and viewing angle ($\theta$) for medium VC content than low VC.

### RQ3: Are there differences in content placement regarding both areas?

Our data show several differences with regard to the content placement on the *ceiling* and *floor* (see Tab. 5.4). Participants manipulated the placement parameters differently to achieve a similar angular size ($\delta$) in both areas. However, while viewing angles ($\theta$) were similar for contents on the *ceiling*, participants set a bigger viewing angle ($\theta$) for the medium VC content than the low one on the *floor*.

## 5.6 Overall Discussion

The findings of our two user studies showed how the *ceiling* and the *floor* can be used for AR content placement in indoor environments. Following, we discuss the findings of both studies while presenting design guidelines and future research directions in combination with the limitations of our approach.

### 5.6.1 Result Discussion

With Study 2 (S2), we showed that content placement on the *ceiling* and *floor* is governed by the wish for an optimal viewing angle ($\theta$) and angular size ($\delta$). Through Study 1 (S1), we showed that visual complexity (VC) should be considered while placing content in these areas. We found that secondary content (e.g., non-urgent short text notes, icons) was deemed suitable for both areas. In contrast, primary content (e.g., compelling text-heavy content) should be avoided (S1: 6 participants). Both findings can further be motivated by the two goals the participants described: the ergonomics of finding and reading the content (S1: 6, S2: 21) and the readability of the content itself (S2: 24). The trial duration in S2 differentiated between both VC levels ($F(1, 25) = 23.95,\ p<0.001,\ \eta_p^2 = 0.489$), whereof trials with *low* VC content ($M = 10.78\ sec, SD = 7.07\ sec$) were faster than those with *medium* VC content ($M = 12.24\ sec, SD = 7.80\ sec$). This shows that low VC content was easier to place, which can be explained by the decreasing complexity, increased readability, and even the higher tolerance for low VC content.

Another factor that influences readability and ergonomics is the area of content placement. Based on a seven-point rating scale (-3 to 3) in S2, we found that participants prefer *low* VC content to be placed on the *ceiling* ($M = -0.0653, SD = 1.648$) and *medium* VC content on the *floor* ($M = 0.577, SD = 1.858$). Through the comments in S1, this preference of placing *low* VC content on the *ceiling* (S1: 6) and *medium* VC content on the *floor* (S1: 5) can be further strengthened. In general, the *floor* (S1: 5) is more preferable for content placement than the *ceiling* (S1: 1), as it is more comfortable to look downwards (S2: 10) than upwards (S2: 2). However, the longer, continuous, and more focused use of both areas, as presented in S2, showed a small negative effect on the users. This is visible by comparing the 5-point rating scale answers for the question "How strained is your neck?" ($t(25) = -5.52, p<0.0001, d = 0.87$) before ($M = 1.462, SD = 0.582$) and after ($M = 2.231, SD = 1.107$) the study.

### 5.6.2 Design Recommendations

Through our findings, we can present an initial set of recommendations (DR) to help future developers and researchers design user interfaces displaying 2D AR content on the *ceiling* and *floor*.

**DR1** As the ceiling and floor are unobtrusive locations, these areas should be only used to display secondary information.

**DR2** Both placement areas should be used for different types of content. The *ceiling* is mainly for *low* VC content. In contrast, the *floor* can be used for *medium* VC content, which can be explained by the high neck strain while locking upwards and the more comfortable downwards movement range.

**DR3** Content on the *floor* can be perceived as obstacles, which could hinder the general movement of users. Therefore, we recommend minimizing the use of pitch ($\alpha$) and distance from the *floor* (height (Z), see Fig. 5.5), which can be perceived as 3D content.

**DR4** It is possible to achieve an optimal placement in environments where the present real-world objects would constrain the availability of specific placement parameters. This adjustment of the angular size ($\delta$) and the viewing angle ($\theta$) can be made by utilizing the other available placement parameters (see Fig. 5.6).

**DR5** Any given virtual content's angular size ($\delta$) should be defined in relation to its VC. We recommend the following angular size for content with *low* VC: $\delta \approx 6.5°$; and for content with *medium* VC: $\delta \approx 10°$.

**DR6** Content should be undistorted (viewing angle $\theta = 90°$). However, specific user preferences should be considered first, like the placement of flat stickers on the *floor* ($\alpha = 0°$) or signage hanging from the *ceiling* ($\alpha = 90°$).

### 5.6.3 Future Work and Limitations

Our findings suggest that future AR systems could automatically adjust the content placed on the *ceiling* or *floor*. However, it is unclear how users of such applications would perceive dynamically changing virtual objects. Future research is needed to investigate if this adaptation would distract users while interacting with the real world or other virtual content placed in the environment. The static setup in our second study (standing participants) helped us to reduce possible confounding factors while setting optimal placement parameters. However, dynamic environments or even participants' movements can cause a difference in the observed preferences, which shows the need for future research. Furthermore, this can also be extended to altering *ceiling* heights and the heights of the person, which can already differ for each user individually as they change their posture from, e.g., standing to sitting. Additionally, although our grouping of the virtual content via visual complexity was loosely defined on information density and readability, we already found statistically significant effects. We assume that using a content element with higher visual complexity would amplify this effect. Further, a more in-depth understanding of different content aspects will benefit future systems.

The environment can also heavily influence how users perceive virtual and real-world content. While our participants considered virtual content occluding real-world signage on the *floor* as an issue (S1: 4, S2: 5), they also mentioned that the same virtual content, if not flat on the *floor* ($\alpha = 0°$), could be perceived as an obstacle (S1: 5). Therefore, we suggest researchers investigate how content placed in both areas changes the user behavior and the perception of the real-world environment. As the environment can also affect the placement of the content (S2: 9), it is necessary to investigate the effect of *ceiling* and *floor* textures, environmental factors, contexts, or use cases. Those can also be extended to not only indoor but also outdoor scenarios. Lastly, we believe that our findings for the *exocentric* placement can be translated to *egocentric* reference frames. However, this should be verified in the future.

To conduct the studies, we used the Mircosoft HoloLens 2 as a state-of-the-art AR HMD. However, the current technology is still relatively limited, especially concerning the resolution and FoV. Therefore, we expect some specific findings to change slightly if the same experiments were repeated on more advanced hardware. The same content can be perceivable through a higher resolution on even greater distances (d) than 6 m. At the same time, a bigger FoV allows easier access to content as the required head movement can be reduced. However, we would still assume that users would aim for a constant angular size ($\delta$) and viewing angle ($\theta$), as shown in our results, which would affect the placement parameters in the same way. Another issue considering the used HMD could arise while rendering oblique content due to low rendering quality or limited resolution, which requires further investigation.

## 5.7 Chapter Conclusion

With the work presented in this paper, we contribute a systematic investigation of the *ceiling* and *floor* as additional content placement areas for AR. Based on a comprehensive treatment of both areas, we described how the content placement process is defined, what perceptual issues could arise, and investigated both areas in a qualitative exploratory and a quantitative user study. The results of our qualitative study show the applicability of the two placement areas as a secondary display space for virtual AR content. In contrast, the second study allowed us to define optimal placement parameters for 2D virtual content in either area. Following our findings, we presented a set of recommendations that can benefit future AR application designers and open research questions.

As I described at the beginning of this chapter, I investigated the environmental characteristic of the placement area. I could demonstrate that user characteristics of physical ergonomics and visual perception must be considered while placing content on available surfaces in the immediate environment. It is possible to envision that both the *ceiling* and the *floor* will become indispensable to future AR systems and user interfaces. Furthermore, this project's findings can also guide the augmentation of other surfaces or objects. Notwithstanding, this project was not focused on information visualization, but its finding can also help author immersive visual analysis systems using information visualizations. While the placement of a complete visualization was deemed challenging, it is imaginable to present micro-visualization as seen in small multiples [DM22; Mac+03] or by offloading UI elements [RED20]. In general, how to author IA environments is yet under-explored. This includes using the immediate environment, like the ceiling and floor, but also existing systems and devices. With that, my next step will lead me to explore such system characteristics, specifically how a combination of AR HMDs and mobile devices can be created and used.

# 6

# Hybrid User Interfaces for Immersive Visualizations

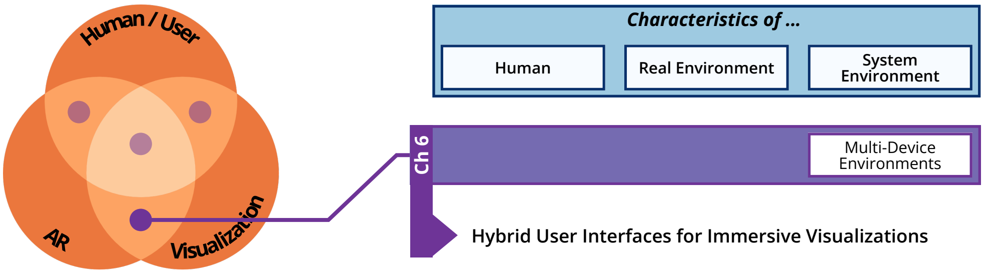

**Fig. 6.1.:** This research project (Ch. 6) is situated in the Augmented Reality (AR) and Visualization cross-section. Within this project, I focus on cross-device setups as system environments to create and author immersive visualization environments.

Information visualizations are widely used in desktop setups and mobile devices [Hor+21a; Lee+18] to generate insights. Another device class to present visualizations are AR HMDs, as also shown in the previous research projects. However, as AR is more frequently used, it becomes essential to identify how to enable Immersive Analytics (IA) [Mar+18], i.e., visual analytics in immersive environments. This also extends to the question of integrating this new emerging device class into the currently used device ecology. Such a combination can be defined as a Hybrid User Interface (HUI), which complements possible shortcomings of one device type with advantageous properties of another. AR devices are often combined with 2D displays like desktop or mobile devices to achieve such a HUI. While visual analytics is individually explored for those devices, the described combination of both is still challenging and worth investigating. Henceforth, within this chapter, I want to realize and design such a combination of common 2D displays with HMD AR devices. For that, we[1] present two systems that allow the data analysis via handcrafted visualizations and the authoring of automatically generated visualizations. To achieve this, we contribute the following:

- A detailed motivation for this research direction (Sec. 6.1), including related work focused on the term of HUIs (Sec. 6.2).

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[1] "We" in this chapter relates to the author Marc Satkowski, as well as Ricardo Langner, Weizhou Luo, Woflgang Büschel, Julián Méndez, and Raimund Dachselt as co-contributors to this research.

- The framework MARVIS, which presents a set of handcrafted visualizations combining up to two tablets and an AR HMD (Sec. 6.3).
- A model describing the authoring process of visualization in post-WIMP interfaces and its related literature (Sec. 6.4.2).
- The system of AR Authoring, which enables the creation of immersive visualization in runtime using a smartphone as an input device (Sec. 6.4).
- A discussion (Sec. 6.5) of our insights on HUIs and their implications for future systems and designs.

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Parts of the research presented in this chapter have previously appeared in:

**Marc Satkowski**, Julián Méndez. "Fantastic Hybrid User Interfaces and How to Define Them". To be published in: *2023 IEEE International Symposium on Mixed and Augmented Reality Adjunct (ISMAR-Adjunct), Workshop Track*. Sydney, Australia, October 16-20, 2023. [SM23]

*Own Contribution:* I was the main contributor to the lightweight literature review and its analysis.
*Applied Changes:* This chapter splits the literature review and the discussion while slightly condensing the content.

Ricardo Langner, **Marc Satkowski**, Wolfgang Büschel, and Raimund Dachselt. "MARVIS: Combining Mobile Devices and Augmented Reality for Visual Data Analysis". In: *ACM Conference on Human Factors in Computing Systems (CHI)*. Yokohama, Japan, May 8–13, 2021. [Lan+21]

*Own Contribution:* My main contribution lies in the development of the prototype application. Furthermore, I partly contributed to creating the design space and conducting and analyzing the expert interviews and reviews.
*Applied Changes:* I strongly shortened the concept and use case chapters compared to the original publication while extending the prototype realization.

**Marc Satkowski**, Weizhou Luo, and Raimund Dachselt. "A Visualization Authoring Model for Post-WIMP Interfaces". In: *Poster Track of IEEE VIS: Visualization & Visual Analytics 2021*. Virtual, October 24–29, 2021. [SLD21a]

*Own Contribution:* I was the main contributor to the creation of the presented model.
*Applied Changes:* This chapter presents a slightly extended version of the poster paper.

**Marc Satkowski***, Weizhou Luo*, and Raimund Dachselt. "Towards In-situ Authoring of AR Visualizations with Mobile Devices". In: *2021 IEEE International Symposium on Mixed and Augmented Reality Adjunct (ISMAR-Adjunct), Poster Track*. Bari, Italy (virtual), October 04-08, 2021. [SLD21b] **The first two authors contributed equally.*

*Own Contribution:* This system was created in close collaboration with my co-authors, leading to shared authorship.
*Applied Changes:* This chapter presents a slightly extended version of the poster paper.

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## 6.1 Motivation

In our everyday lives, we are surrounded by a growing number of different devices, like desktop PCs, mobile phones, smartwatches, and TVs. Each device type can excel at a given property, which leads to its use in specific scenarios or use cases. As presented with the Apple Vision Pro [@App23], AR HMDs will also likely become part of this ecosystem in the near future. However, for that, they have to compete and collaborate with other already existing devices. A combination of devices could compensate for the weaknesses of single components and use already-gained expertise and knowledge of mobile devices within the AR space. This transfer of interaction metaphors or skills can help alleviate gaps while working with the new technology that has not yet permeated the consumer market. Looking at mobile devices, they have fixed size and display space while possessing high-resolution displays and being tangible. On the other hand, AR HMDs enable the presentation of stereoscopic 3D information on a limitless canvas with a lower resolution and no haptic feedback while interacting. This combination of AR devices with common 2D displays can be categorized as Hybrid User Interfaces (HUIs). The term was first coined by Feiner and Shamash [FS91] in 1991. Since then, many research projects have focused on exploring possible systems within this interface category, showing the importance and interest of this term but also highlighting the challenging nature. Those challenges include the communication and synchronization between the different devices used, the decision of where to place content on the shared screen estate, and how to interact with either system.

While HUIs are promising, the creation and design of visualizations, the interaction with those, and the general system architecture behind them are not trivial. In the following, I will present a handcrafted set of visualizations and an in-situ visualization configuration in immersive HUIs. For the former, we present new visualization and interaction concepts, while for the latter, we model a visualization authoring model for post-WIMP interfaces. Lastly, the feasibility of both is demonstrated by a prototype system enabling communication between the different device types.

## 6.2 Background: Hybrid User Interfaces

Commercially usable mobile devices have been part of our daily lives for several years. While mobile devices like smartphones are already capable computing systems on their own, they can also be combined with other device classes, such as large displays [Kis+17; LKD18], desktop PCs and laptops [Hor+19], but also between each other [LHD17; HLD20]. In such setups, mobile devices often enable input and output.

Another possible device type is AR HMDs, which allow embedding and integrating information in, around, or between other devices' display spaces. Such a *"[combination of] heterogeneous display and interaction device technologies"* created so-called Hybrid User Interfaces (HUIs), which was first coined by Feiner and Shamash [FS91] in 1991. The goal of such a combination is to *"take advantage of the strong points of each [device]"* present in a combined interface. The term HUI was further extended or constrained over the last decades. Butz et al. [But+99] highlights that the combination presented through HUIs also extends to *"[various] technologies and techniques, including virtual elements such as 3D widgets, and physical objects such as tracked displays and input devices"*. They also highlight that the so-created global AR space can be shared, which is likewise discussed by Feiner [Fei00], as HUIs combine all devices *"in a mobile, shared environment"*. The definition of Bornik et al. [Bor+06] adds another goal of HUIs, which is to *"pair 3D perception and direct 3D interaction with 2D system control and precise 2D interaction"*. Sandor et al. [San+05] state that *"information in [HUIs] can be spread over a variety of different, but complementary, displays"*. Additionally, in line with Butz et al., they describe that users of HUIs can *"interact through a wide range of interaction devices"*, demonstrating a possible differentiation between input and output devices. This is also the case for Geiger et al. [Gei+08], who state that HUIs *"combine 2D, 3D, and real object interaction and may use multiple input and output devices and different modalities"*. Concerning real objects, Strawhacker and Bers [SB15] present a HUI in which they combine a graphical and tangible user interface. They highlight that *"users [should be able to] switch freely between tangible and graphical input"*, whereof the former relates to wooden blocks.

Besides the term HUIs, other related definitions exist, which show the increasing interest in combining existing devices within an immersive environment. Continuing from the last definition, Transitional Interfaces [BKP01] are also concerned with the transition or switch between different components or devices. Grasset et al. [GLB06] describe them as *"a new way to interact and collaborate between different interactive spaces such as Reality, Virtual Reality and Augmented Reality environments"*. Additionally, Carvalho et al. [CTR12] claims that *"the range of action of a transitional interface may be actually larger than the mixed reality continuum"*. Lastly, Aichem et al. [Aic+22] relate HUIs and Transitional Interfaces by presenting a HUI that *"allows for transitions between these two environments [(i.e., desktop and virtual environment)] at any time during an analytic session"*. Reipschläger et al. [RED20] coined the term Augmented Displays which present *"a new class of display systems* *directly combining high-resolution interactive surfaces with head-mounted Augmented Reality"*. However, such a combination was already classified as a HUI by Dedual et al. [DOF11], who combined a multi-touch tabletop with a head-tracked video-see-through display. HUIs could also be extended to consider the asynchronous use of devices in such an interface. First, Bornik et al. [Bor+06] describe the importance to *"differentiate between two approaches: serial and parallel integration"*. Later, Hubenschmid et al. [Hub+21b] labeled this idea Asynchronous HUI, where *"heterogeneous (i.e., non-immersive and immersive) devices are used sequentially"*. It is also possible to relate again to Transitional Interfaces, as Aichem et al.'s [Aic+22] combination of desktop and HMD are used purely in sequence. Lastly, a relatively recent attempt to unify the different terms was made by Zagermann et al. [Zag+22]. For that, they present Complementary Interfaces as an *"umbrella term that includes combinations of homogeneous and heterogeneous device classes, but also input and output modalities"*. Additionally, such interfaces should *"always feature some degree of heterogeneity in the involved components"*.

Overall, the specifics of HUIs are hard to grasp, as the term has evolved in several directions over the last decades. However, the core principle is still the same: combining 2D displays (e.g., tablets) with 3D displays (i.e., HMDs). While the definition is also concerned about combining the interaction spaces, we can find research not restricted to such display types alone. It can be made use of larger vertical displays [RFD21; Jam+20; Mah+18], desktops [MM17; Wan+20; WBS20; RED20], tabletops [But+18], or even mobile devices like smartphones [ZG20; Gru+15] and tablets [Hub+18; Hub+21a]. Through such device combinations, various use cases were tackled, such as CAD or 3D modelling [MM17; RD19; RED20], Sketching [Aro+18], general office work [Pav+21] and even information visualization systems (e.g., [Voc+21; SBI19; Cav+19b; Cav+19a]).

Concerning our research focus on combining mobile devices like tablets with AR for data analysis, we will highlight previous research projects focusing on such a combination and use case. In general, mobile devices can be integrated in various ways. First, they can be used purely as an input controller for the content presented in AR, where the mobile device either only takes the input of the user [Büs+19; SDS21; Sur+19; Hub+18] or presents a UI on the screen as well [NM19; Gru+15; Voc+21]. Second, the mobile device can be the main content presentation and interaction device. The AR content primarily offers additional and often secondary information to help get and keep a better overview, see more details, or understand the system better (e.g., tooltips) [Gru+15; NM19]. Lastly, systems exist between the previously mentioned combinations, where both devices are equally beneficial and used within the application. Here, both device classes (i.e., a desktop computer) provide different functionalities or views on data, enable different types of interactions, or even show personal views [RD19; RFD21]. This also holds for mobile device setups [Hub+21a; SBI19; ZG20; Luo+21].

To realize a combination of different spatially distributed and moveable devices, it is necessary to provide communication between each device in the system. This can be achieved through, among other things, direct communication between the devices (i.e., peer-to-peer or host-client) [Kru+22; ZG20; NM19] or via a client-server architecture [RFD21; Hub+22; Voc+21]. Depending on the specific system or use case, it also becomes necessary to spatially locate each device within a given environment to align the virtual information in AR with the devices. This can be achieved by, e.g., outside-in tracking systems [ZG20; Büs+19; Kru+22; Aro+18], general inside-out tracking through visual markers like QR codes [NM19; Wu+13; RS99; McD+22] or HMD controller [Hub+21a; Zha+21], placing of virtual anchors [RD19], or object recognition [Moh+19].

## 6.3 Handcrafted Immersive Visualizations in HUIs

**Fig. 6.2.:** The prototype system and HUI based on MARVIS. The system can present additional AR information around, above, and between the tablets.

As described in the motivation, designing and placing content in the shared display real estate is one of several challenges connected to HUIs. This is especially tough since the devices' displays within a HUI, in our case tablets and an AR HMD, are not uniform and have different properties and capabilities. Mobile devices like tablets have a fixed-size but high-resolution display, are tangible and thus provide haptic feedback, and allow for precise interaction via touch or pen input. On the contrary, AR HMDs have a flexible and near unlimited screen space without a fixed form factor, allow stereoscopic 3D perception, and are personal. Any content, like visualizations, must work on or across the displays if both device types are combined. 2D displays of tablets can be oriented in arbitrary ways, as they can be held in hand, moved around on a table, physically arranged, or even obfuscated with other objects in the environment. On the other hand, AR can show immersive content anywhere in the environment. However, the content on both device types should be synchronized and arranged in relation to each other to achieve a cross-device or HUI setup. With that in mind, AR can extend the existing mobile devices by providing additional 2D and 3D information around, above, and even between them (see Fig. 6.2).

Following this idea, we present MARVIS, a conceptual framework that combines **M**obile Devices and **A**ugmented **R**eality for Data **Vis**ualization. This combination is not trivial since it relies on many factors related to the used devices, like display technology, size, interaction capabilities, movement ranges, and many more. Additionally, such factors affect the conceptual design and the realization of a (prototype) system. Within this chapter, I will focus on the design and conceptualization of HUI visualization (Sec. 6.3.1), present example use cases of MARVIS (Sec. 6.3.2), before describing a prototype system facilitating both device types (Sec. 6.3.3). For an in-depth description of the complete MARVIS framework, please refer to the original publication [Lan+21].

### 6.3.1 MARVIS Concepts

We defined several design decisions (based on an expert interview, presented in the original paper) before creating a specific concept for MARVIS. These design rationales enabled us to reduce the scope of our target combination of tablets and an AR HMD. To be more specific, the design rationales in question are:

1. No stationary devices, i.e., tablets and AR HMD can be moved by users
2. Seated usage of the system
3. Mobile devices as the main device type, while AR only provides context
4. Focus on touch interaction on the tablets
5. Devices are spatially aware, i.e., content can be aligned to each device

We can propose several new visualization and interaction concepts based on the design rationales. All concepts are facilitated by the available space near a tablet, which results in general extensions **around**, **above**, and **between** the tablets (see Fig. 6.3). While the first two spaces aim mostly at single mobile device setups, the latter can also be used for multiple mobile devices. The concepts (C) we created are the following:

**C1: Overview+Detail** Using the high resolution of the mobile device to show details while presenting overview information in AR, resulting in separated views.

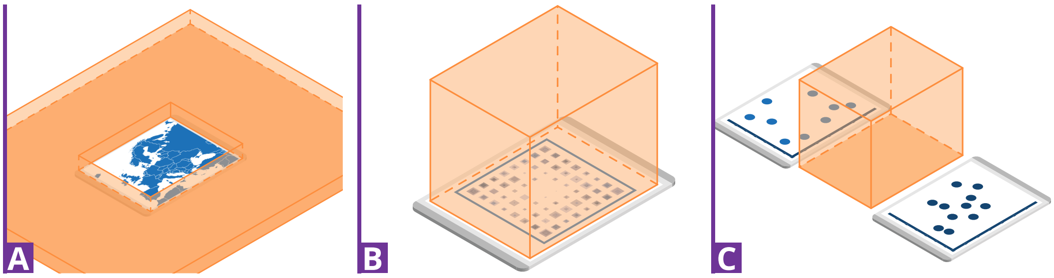

**Fig. 6.3.:** The three areas our conceptual framework makes use of to extend the limited display space of a mobile device, i.e., tablet. Virtual AR content can either be shown **(A)** around or **(B)** above the tablet. With more than one tablet, content can also be shown **(C)** between the devices. For a detailed overview of the design space, please refer to the original publication of MARVIS [Lan+21].

**C2: Focus+Context & Seamless Visualization Extension** Showing detail, i.e., focus, on the mobile device, while AR gives context by extending the content on the mobile device.

**C3: Alternative Visualization Views** Showing additional available visualization or configurations of the same in AR around the tablet.

**C4: Separated Visualization User Interface Components** UI elements can be offloaded to AR to maximize mobile devices' available high-resolution display space.

**C5: Superimposed 3D Visulizations** Additional data dimensions can be presented and encoded in AR by extending the visualization into the third dimension above the mobile device.

**C6: Relation Between Visualizations** Content presented on several mobile devices can be related to each other. In AR, we can provide visual feedback for such relations and dependencies between the devices.

**C7: Combination of Visualizations** Visualization on various tablets can present different views on the same data set. The space between the mobile devices can also be used to show combinatory views, which can react to changes on either device.

**C8: Multi-User Support** AR can help gain insight and understanding of what other users in the current work environment analyze on their corresponding mobile devices.

### 6.3.2 MARVIS Use Cases

Considering the concepts presented in the previous section, we created a set of six use cases (see Tab. 6.1) to demonstrate the wide range of possible visualizations and the feasibility of such a device combination. The use cases are created within our

| Use Case | Concept |
|---|---|
| Scatterplot Matrix Navigation | C1, C3 |
| Map Navigation | C1, C2 |
| Non-Planar Slices on a Map | C4, C5 |
| Scatterplot with 3D Glyphs and Trajectories 3D | C4, C5 |
| Node-Link Diagram and Attribute Visualization | C6 |
| Combined Bar Charts with Heatmap and 3D Stacked Bars | C4, C7 |

**Tab. 6.1.:** Overview of the relation between the use cases designed in MARVIS and the concepts that they aimed to demonstrate.

prototype system, which I will describe in the subsequent section (see Sec. 6.3.3). All use cases presented in this section are focused on demonstrating ways to extend the existing display space of mobile devices (i.e., tablets) through AR. In the following, I will shortly describe each use case's functionalities and detail the relation to the design concepts.

### Scatterplot Matrix Navigation

Scatterplot matrices (SPLOM) [EDF08] allow for a simple representation of multi-dimensional data sets and their attributes' relationships. On the tablet, we show one scatterplot within the matrix, while the space **around** a tablet enables the presentation of other cells in the SPLOM (according to *C1* and *C3*). In our system (see Fig. 6.4A), we present four versions of those cells, either showing (1) all other available cells at the same size as on the tablet, (2) all other available cells as miniatures, (3) only cells in the same column or row as miniatures, or (4) only the direct neighboring cells of the same size as on the tablet. By swiping the visualization's background on the tablet, the currently shown scatterplot on the tablet can be changed. Users can also select objects in the visualization by tapping or lasso selection, highlighting those data points in every SPLOM cell currently visible (on tablet and in AR).

### Map Navigation

Data is often presented on (geographical) maps, highlighting the spatial relations between the data points. For this use case, we visualize a subset of a real-world victim-based crime data set [@Bal]. The tablet shows a city map and nodes representing the different neighborhoods. In AR we extend the map **around** the tablet (according to *C1* and *C2*) by either (1) an abstract representation (i.e., only highways and neighbourhoods) or (2) a detailed one (see Fig. 6.4B). Additionally, details-on-demand can be visualized on the tablet or in AR. Those are accessed by a double tap on a node (on the tablet). A pinch-to-zoom and drag gesture can alter the map's viewport.

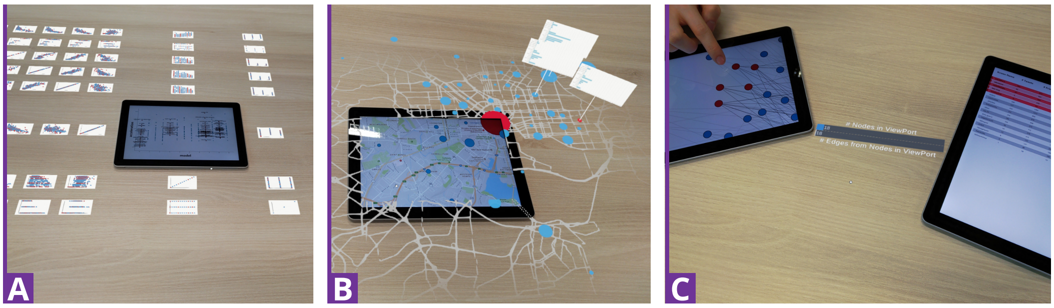

**Fig. 6.4.:** Three of the use cases presented in MARVIS. In **(A)**, we show additional cells of a SPLOM around the tablet. In **(B)**, the map presented on the display gets extended in AR, also displaying the previously opened Details-on-Demand. In **(C)**, a link between the logically connected tablets is showing, highlighting the number of selected and in-view-port nodes.

### Node-Link Diagram and Attribute Visualization

Network or graph data consists of relations between different data points. For our use case, we use network data from Twitter[2]. On the two tablets, we show two different views: (1) a node-link diagram or (2) a scrollable table of attributes for each node within the data set. The nodes of the view-port of the former are used to define the table view content. This relation between both tablets is visually highlighted by showing a virtual connection **between** the tablets in AR (according to *C6*). It encodes the number of nodes in the current viewport and the number of selected nodes (see Fig. 6.4C). To change the viewport of the node-link diagram, a pinch-to-zoom or two-finger pan interaction can be performed. Nodes can be selected by tap or lasso.

### Non-Planar Slices on a Map

Data can contain not only a spatial but also a temporal component that is of interest. For this use case, we use a subset of the gapminder [@Gap] dataset[3] to adapt the technique Great Wall of Space-Time [TS12]. On the tablet, we show a map of Europe. In AR **above** the tablet, we extrude a 3D wall (see Fig. 6.5C) from the country borders on the map (according to *C5*). Additionally, we offloaded UI elements into AR (according to *C4*). To extrude a wall in AR, the user has to select several countries connected on the map by tapping. A pinch-to-zoom and drag gesture can also be performed on the map.

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[2] Source Twitter data: `https://johnguerra.co/viz/influentials/eurovis2018/`

[3] Source unemployment data: `https://www.ilo.org/ilostat` through `www.gapminder.org`

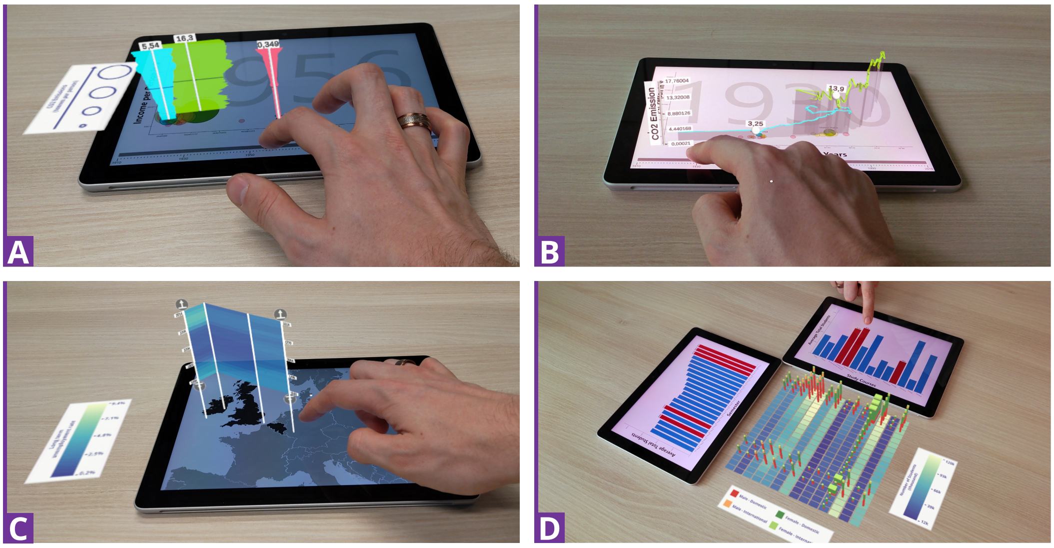

**Fig. 6.5.:** Three of the use cases presented in MARVIS. **(A)** and **(B)** show two possible extensions of a 2D scatterplot that use the third dimension above the tablet. In **(C)**, another wall-like visualization can be constructed above the tablet by selecting countries. With **(D)**, we demonstrate how two views of the same dataset on tablets can be combined as soon as both tablets are in a specific spatial relation. Here, a heatmap of the same data is shown, while selecting a bar shows additional 3D stacked bars.

### Scatterplot with 3D Glyphs and Trajectories

Multiple dimensions can also be encoded differently besides presenting them in a SPLOM. In this use case, we adapt parts of the Gapminder [@Gap] interface[4]. On the tablet, we show a simple scatterplot with a year displayed in the background. In AR, we represent other dimensions **above** the tablet, which is spatially linked to the nodes on the tablet (according to *C5*). Additional UI elements can be shown in AR (according to *C4*). To be specific, we demonstrate two different AR extensions of a scatterplot, either (1) a glyph mapping the change of a parameter over time in the direction of the third dimension (see Fig. 6.5A), or (2) by adding a third axis perpendicular to the tablet and visualizing a 3D line chart (see Fig. 6.5B). Additionally, both types present the current value presented in the scatterplot via either a line in the glyph or a sphere on the line respectively. By default, the AR elements above the tablet are hidden and will only be shown while interacting with the tablet (i.e., time slider). To change the current year presented, users can interact with a slider on the bottom of the tablet. A lasso or tap selection can again highlight different data points.

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[4] Gapminder Tool: `https://www.gapminder.org/tools/`

### Combined Bar Charts with Heatmap and 3D Stacked Bars

More than one visual representation is often used simultaneously to generate insights in multi-dimensional datasets. In this use case, we use multivariate data about university students[5]. On two tablets, we present bar charts of the number of students per course and semester. As soon as both tablets are placed in correct spatial relation to each other, an additional heatmap in AR is shown **between** the tablets (according to *C4* and *C7*). Additionally, stacked bar charts can be shown on top of this heatmap (see Fig. 6.5D). A tap or lasso can be performed to select bars on the tablet. This also highlights the corresponding row or column in the heatmap and creates a row of 3D stacked bars. When a bar on the other tablet is selected, only the bars associated with the specifically selected cells get highlighted. The rest of the bars in the column or row get de-emphasized.

## 6.3.3 Prototype System Implementation

MARVIS' prototype application consists of three components, which we will describe in the following. Those are the mobile device client, AR HMD client, and server application. Lastly, the components' combination will be described as well.

### Mobile Device Client

We implemented the tablet client as a web application written in JavaScript. For the user interface, we made use of Materialize for the frontend (e.g., buttons and sliders), Hammer.js for touch gesture recognition, and D3.js [BOH11] to create visualizations[6]. In MARVIS, we used two Samsung Galaxy Tab S3 tablets (approx. 9.7", $2.048 \times 1.536$px, 430g) or two Microsoft Surface Go tablets (approx. 10", $1.822 \times 1200$px, 522g). However, our prototype also supports other devices with access to a modern web browser.

### AR HMD Client

The AR client was implemented via the Unity 3D engine, C#, and MRTK [@Mic22]. All AR visualizations present within the prototype and use cases were either built from scratch or used the u2vis [RFD21] framework. The client was streamed to or directly deployed on a Microsoft HoloLens 2. This AR HMD has a diagonal field of view of $52°$ and provides a resolution of ca. 2.500 light points per radian [@Mica]. This means that the AR Client is purely used as an output medium.

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[5] Source student data: `https://www-genesis.destatis.de/genesis//online?operation=table&code=21311-0003`

[6] The used frameworks and libraries can be found under the following links: `https://materializecss.com`, `https://hammerjs.github.io`, and `https://d3js.org`

### Server & Auxillary Devices

The server application was implemented using Node.js and Express[7]. The server was run on another PC in the same network as the previously mentioned clients. We used an altered JSON-RPC protocol to communicate between the devices, which we enabled through WebSockets. In total, our server manages the global application state, all connections to client devices, loading of data sets (stored in CSV files), data requests, and spatial positions of devices. The server was also connected to the optical motion tracking system OptiTrack [@Nat]. The outside-in tracking allowed us to get absolute spatial information of the mobile devices within the tracking volume, making the devices spatially aware. The tablets and the HoloLens were equipped with IR-reflective markers captured by five infrared cameras mounted to the ceiling.

### Component Combination & Apparatus Usage

To run MARVIS, the server application has to be started first. The server automatically connects to the OptiTrack system and sends messages received from the OptiTrack system to each target device. After that, the AR client can be opened. Upon start-up, the AR client connects automatically to the server. A QR code is used to align the coordinate system provided by the motion tracking system and MARVIS. This QR code is equipped with infrared reflecting markers and is tracked by the AR HMD[8] and the OptiTrack system. While moving the QR code through the room, a set of three spatial point pairs is created, which will be used to align both coordinates with each other. After that, the mobile client can be started. Upon selecting a specific use case (see Sec. 6.3.2), each device requests a specific subset of the provided data sets from the server to render. After successfully loading the data, an event will be propagated through the server to the HMD, which results in both devices rendering their specific views. As both coordinate systems are aligned, the content of both is also aligned. Input on the mobile device will be sent through the server to the HMD to synchronize the views on both device types.

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[7] The used frameworks and libraries can be found under the following links: `https://nodejs.org/` and `https://expressjs.com/`

[8] Microsoft provided functionality to scan and spatially locate QR codes via `https://www.nuget.org/Packages/Microsoft.MixedReality.QR`

## 6.4 In-Situ Authoring of Immersive Visualizations in HUIs

In the previous section, we presented how visualizations can be designed to stretch across different available displays within a HUI. For that, we specifically handcrafted our presented use cases. However, it is impossible to handcraft visualizations for any given device combination of HUIs. Furthermore, the environments HUIs are used in can differ highly, resulting in other requirements or design rationales. For example, allowing users to freely move around with a mobile device in their hand compared to aiming for seated usage, as we have done with MARVIS (see Sec. 6.3.1), introduces new complexity.

Following this premise, we identified a need for users to create their visualizations at runtime. However, we first explored the general authoring process in an immersive environment before we can achieve an authoring system for cross-device stretching visualizations as seen in MARVIS in the future. Such a process includes creating visualizations and their relation to other visualizations or the environment regarding placement and layouting. Within this chapter, we will present our AR Authoring project, which explores an immersive authoring system using a smartphone as an additional input device. For that, we will describe the visualization authoring process by literature (Sec. 6.4.1) and by a model (Sec. 6.4.2), before presenting the general concept (Sec. 6.4.3) and the corresponding prototype system (Sec. 6.4.4).

### 6.4.1 Background: Visualization Authoring

Visualizations are used to support the generation of insights within complex data sets. However, before a visualization can even be presented and thus consumed, explored, or analyzed, it has to be created and configured in the first place, which is also highly important for AR applications [Ash+20].

The creation of visualizations is an integral part of the data analysis process and is often labeled as visualization authoring (e.g., [Sat+20]) or construction (e.g., [Gra+13; PL12]). There already exist models that describe the configuration of visualizations, like the information visualization pipeline of Card et al. [CM99; CR98] or the visualization construction cycle of Grammel et al. [GTS10]. The user can influence the creation at different stages in the former, while the latter defines when to move from one stage to another within the construction process. However, visualizations are not created entirely individually or separately; data analysis often includes several visualizations simultaneously (e.g., Multiple Coordinated Views [Rob07]). Therefore, the relation or placement of multiple visualizations and their meanings with regard to the construction of other visualizations are necessary for the general visualization authoring process.

Information visualizations can be shown on traditional mediums like paper or a desktop monitor and in more recent computing environments beyond the desktop [Rob+14]. AR counts towards the latter and can often be seen in the context of immersive analytics [Mar+18; Ens+21]. While several visualization frameworks and libraries [RFD21; BLD21; Sic+19] enable the presentation of immersive visualizations, they differ in how great the support for such configurations is. In the example of u2Vis [RFD21], IATK [Cor+19], or VRIA [BJR21], users have to define the visualizations on a desktop computer before the AR application is deployed. At the same time, in the case of MIRIA [BLD21] or DXR [Sic+19], the users can either select from a list of predefined visualizations or create a view via a simple menu inside the AR application, respectively. The current lack of such in-situ visualization authoring tools is further shown and highlighted by other researchers [Ash+20; NS18].

### 6.4.2 Visualization Authoring Model

As shown with IA [Mar+18], it is possible to visualize information in AR quite easily, yet the construction of visualizations using the same technology is rarely supported. In most cases, developers and researchers must create a visualization on their desktop before deploying it to a Post-WIMP environment like AR glasses. This cumbersome situation increases discrepancies between the configuration and presentation process. In the case of an AR system, creating a fully immersive visualization environment becomes impossible when the user always has to leave the said environment to make small changes in the visualization configuration or their placement in the real-world environment. Moreover, as demonstrated by the information visualization pipeline [CM99] or the visualization construction cycle [GTS10], the user is an integral part of the whole construction and authoring process. Therefore, it is necessary to support the user in the Post-WIMP era in creating visualizations by, e.g., overcoming the temporal, spatial, and conceptual distance [Gra+13] of an authoring application, but also by promoting the general flow [TS20] and the iterative nature [GTS10] of the creation process.

To better describe how such a construction process should look like, discussing the possible user and usage perspectives of an authoring process is essential. Based on this, we present our visualization authoring model (see Fig. 6.6). It is inspired by prior work but also considers a fluid interaction [TS20] between different stages and the existence of several visualizations at the same time. In general, this model should promote the flow by minimizing the temporal, spatial, and conceptual distance [Gra+13] as well as the gulf of execution and evaluation [Nor86; TS20].

### User and Usage Perspective

One crucial aspect of authorizing visualizations is understanding who will create the visualization and for what purpose. In particular, data analysis is inherently a collaborative activity among various stakeholders with diverse backgrounds, which can result in a collaborative analysis process or only in presenting results and insights in the form of visualizations. This leads to not only data analysts but also novice, savvy, or expert users [PL12] of information visualization having the desire to configure, author, read, and understand visualizations. Further, it can also be differentiated between the designers or developers and domain users [Van06; Mun14] of visualizations, which vary in the degree of data understanding they have. The goal they want to achieve also changes in association with different types of users. Therefore, it is possible to differentiate between data presentation and data exploration [Gra+13] or between the wish to produce or to consume visualizations [Mun14]. In general, an authoring model and application should aim to enable those diverse usages and different user groups by either supporting their existing mental model or helping them develop a new one [Gra+13].

### Visualization Authoring Model

All abbreviations used throughout the following description can be found within and are related to our model (see Fig. 6.6). At the core of it resides an altered version of the visualization construction cycle (VCC) of Grammel et al. [GTS10]. There, users of an authoring tool can start by either selecting the data attributes (DAS) to visualize or choosing the visualization type they want to see (VTS). In the following visual mapping (VMS), the user can define different aspects of a visualization, like the visual encoding [Mun14], the visual marks to use, the data binding, the scale, axes, or legends, and the layout inside the visualization [Sat+20].

As a result of the previous operations, a visualization output (V) is produced. The view of this output can then be further transformed (VT) [CM99; CR98] by different actions the user can take, like panning and zooming, which in return reshapes the visualization output (V). However, the construction and authoring of visualizations are not only unidirectional but should also allow a user to manipulate different previously made configurations in the authoring pipeline. Therefore, it should be

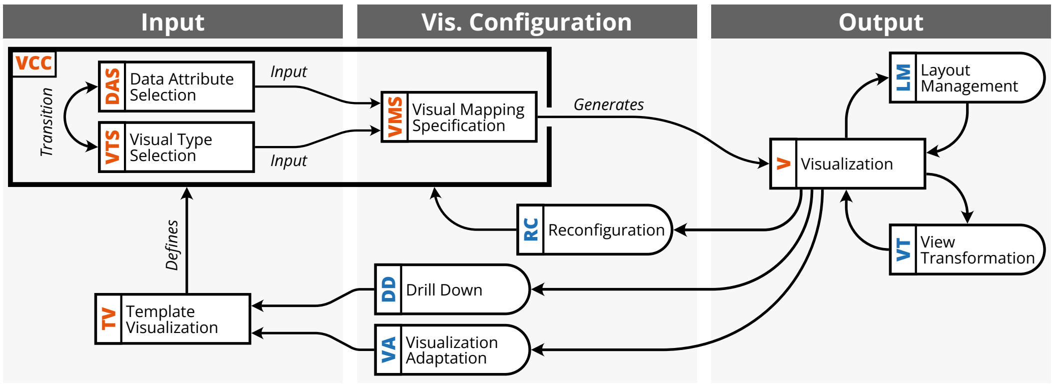

**Fig. 6.6.:** Our proposed authoring model. It can be split up into three different phases: *Input*, *Visualization Configuration*, and *Output*.

possible to reconfigure (RC) different parts of the visualization construction cycle (VCC). However, this reconfiguration alters and therefore destroys the visualization's current visual appearance. To construct an alternative representation of this view (VA), creating a new visualization based on the existing one is possible. Additionally, an existing visualization can also be used as a basis for further aggregations, refinements, or drill downs (DD), based on the source or selected data [Gui+11]. In general, both approaches use another visualization as a template (TV), which can then predefine different values in the visualization construction cycle (VCC). Lastly, the data analysis process often involves multiple visualizations. Creating one or several visualizations is possible simultaneously. This makes it necessary to allow for different layout management behaviors (LM) to structure the presentation of arbitrary groups of visualizations and help with the later sensemaking process. Those layout adaptations could include, e.g., the position of visualizations or uniform axis between each view.

Our authoring model can be split up into three phases focused on the *input*, the *visualization configuration*, and the *output*. In *Input*, users can start from scratch by selecting the data (DAS) or visualization type (VTS) or can use an already created visualization in the environment, which predefines several parameters (TV). This follows the notion of Grammel et al. [Gra+13], which, in contrast to Card et al.'s [CM99] information visualization pipeline, lists two types of visual mapping approaches: data-driven and visualization-driven. In *Visualization Configuration*, the user can specify the visual mapping (VMS) of the data and visualization type. Further, they can change already chosen values (RC) of an existing visualization, use the same for the creation of a new visualization that alters visual or data attributes (VA), or use the visualization as a drill-down (DD) starting point. In *Output*, the created visualization (V) can be transformed (VT) or, in cases with

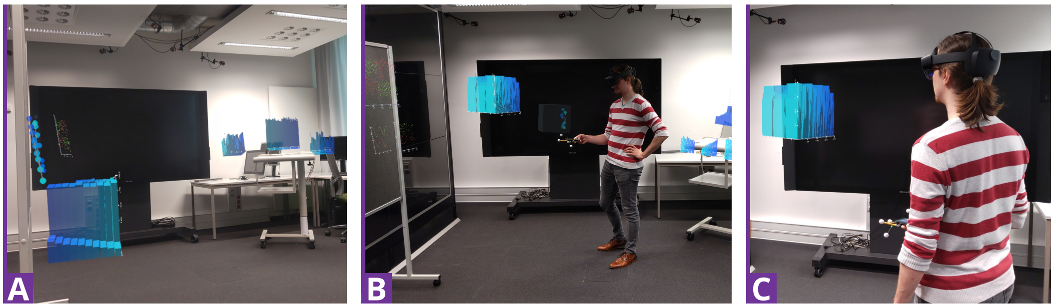

**Fig. 6.7.:** Three figures illustrate the use of the AR Authoring prototype. **(A)** shows the created scene. **(B)** and **(C)** show a user interacting with the system and configuring and placing a visualization.

more than one view, managed the layout (LM) by the user of those visualizations. The three phases and the model itself show the high level of interconnection of the visualization, the configuration process, and the output, making it necessary to bring those phases as closely together as possible.

## 6.4.3 AR Authoring Concepts

Based on our authoring model, we can envision how a future data analyst would author and use visualizations in AR. For that, they can use a spatially-tracked mobile device, which functions as a 3D cursor (e.g., pointing and manipulating AR content) and context menu (see Fig. 6.7). In the following, we sketch a rough scenario in which we embed and propose an initial set of concepts. Parts of this concept were also implemented in another prototype system, which I will present in the subsequent section (see Sec. 6.4.4).

For the scenario, we will follow Paul as he explores a pandemic-related data set in a spacious meeting room.

### Visualization Configuration

To begin the exploration, Paul creates a visualization via a configuration menu on his smartphone. With this, he selects the targeted data set, a line chart representation, the attributes of week, country, and number of administered vaccines, and lastly the attribute mapping to the x and y axis and the line color. While he enters those parameters (see Fig. 6.9), a small AR preview of the view he currently creates will be visible. It is attached to the top edge of the mobile device (see Fig. 6.7B). This enables him to verify if the selected parameters match his imagined visualization.

**Fig. 6.8.:** Three illustrations presenting different envisioned features of the AR Authoring system. **(A)** shows how a user can collect visualizations via a fishnet metaphor, which can be later on **(B)** placed on a surface in the immediate environment via tapping the corner of the device on the surface. **(C)** shows how a filter can be applied to a new visualization by using a selection in another visualization.

### Placement and Transformation

To place and rotate the newly-created visualization, Paul moves his mobile device and the still attached view like a 3D cursor through the space (see Fig. 6.7C). He can even move, rotate, or scale this or other visualizations later by bringing the mobile device close to the view. Thus, a context menu on the mobile device allows him to, e.g., change the scale with a pinch or one-finger zoom gesture on the screen to fit the size of a chalkboard in the room.

### Layout Management

After Paul created several visualizations, he wants to group them, based on the month the data is from. For that, he changes the function of his mobile device from a configuration to a selection tool. Then he “catches” the desired visualizations by moving the device in his hand like a fishnet and all views crossed by this movement are now highlighted. Additionally, a small, corresponding preview stack of selected visualization is shown on the top edge of the smartphone (see Fig. 6.8A). He moves them to a physical whiteboard where the selected visualization should be placed on. He then touches the whiteboard with a corner of his mobile device, which “releases” and transfers all the selected visualizations in the order of their selection to the physical plane. Based on how many visualizations were transferred, the layout could change from a single line to a simple grid, which also re-sizes the views (see Fig. 6.8B).

### Drill Down

The now structured immersive environment gives Paul a better overview of the already created data representations. Therefore, he can further investigate the data related to European countries in the data set. He already selected data points in another visualization via a mid-air gesture. As he now creates a new visualization with his mobile device, he wants to link and apply the mentioned selection to the new visualization as a filter. Thus, he picks up the selection via a mid-air grab gesture. After this, he moves his hand to the mobile device's screen and "drops" the filter into the visualization he currently creates, which applies this set of data points as a filter (see Fig. 6.8C). This connection between the selection and the newly created view can be further visualized with a line between both.

### 6.4.4 AR Authoring Prototype

The AR Authoring prototype was inspired by the system we created in MARVIS (see Sec. 6.3.3). It also consists of the same three components of a mobile device client, an AR HMD client, and a server application. However, each component provides different functionality and is built on another software basis. Especially the server was upgraded to allow for more thorough communication between the connected devices.

#### Mobile Device Client

The smartphone client was implemented with the Unity 3D engine and C#. The UI was created using 2D canvases in Unity, consisting of tabs, dropdown menus, selection buttons, and more simple UI elements. The mobile client provides different functionalities for configuring visualizations (see Fig. 6.9), like defining the dataset to use, filtering the data, defining the visual mapping, or spatially controlling the already present visualizations. Especially the first three follow the steps and stages proposed by our authoring model (see Sec. 6.4.2 and Fig. 6.6). The application is deployed on an Android device, a Huawai Honor 9 (approx. 5.15", $1.080 \times 1.920$px, 155g).

#### AR HMD Client

In the AR client, users can create visualizations by using the authoring interface presented on the smartphone. The visualizations are based on the u2vis framework [RFD21], which is extended by several wrappers to enable a dynamic creation on runtime. As described in the concept, a small preview of the visualization is displayed at the top of the display while creating the data representation. The placement of the visualization in the immersive environment is done by moving the smartphone to the target location and releasing it there.

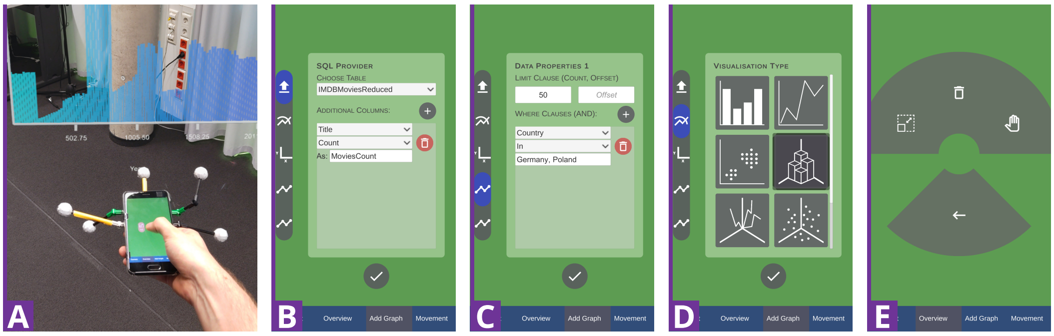

**Fig. 6.9.:** **(B)** to **(E)** demonstrate the UI available on **(A)** the smartphone users hold in their hand. **(B)** shows the selection of a dataset available in the database. **(C)** shows how this dataset can be further filtered by SQL-typical clauses. In **(D)**, the visualization the data should be shown in can be selected. **(E)** shows the radial menu that allows easy manipulations of the visualizations that the device is currently inside of. Those include rescaling, deleting, or picking up a visualization.

### Server & Auxillary Devices

The server follows the same general idea as the one in MARVIS. I developed the server in C# and with WPF and deployed it on an additional PC connected to the same network as all other devices. I chose WPF to provide a frontend for the server, making it simpler to adjust settings and observe the incoming and outgoing messages. At the same time, I implemented server-side logging, which was already used for studies, as seen in Above & Below (see Ch. 5). The server was designed as a generic link for any possible client-to-client communication, so it no longer handles the general application state. The server also functions as a simple bridge between our optical motion tracking system OptiTrack [@Nat] and any client that requests positional information of the currently present devices. The server also provided an interface to an SQLite database to provide data to every device that requests it. The database can be created and updated by using CSV files. The communication itself for every device takes place via WebSockets. This also allowed connecting AR applications written in C# and any arbitrary web application, as already demonstrated in the study apparatus of Above & Below (see Ch. 5).

We again relied on the JSON-RPC protocol for the messages sent over the WebSockets. However, we altered the protocol to fit our needs as we had additional requirements. The new protocol allows us to easily define each message's target device, while a general broadcast to every connected device is also possible. An example of this communications can be seen in Fig. 6.10.

### Component Combination & Apparatus Usage

To start the AR Authoring system, first, the server and the OptiTrack system have to be initiated. After that, each client application can be started. The AR client

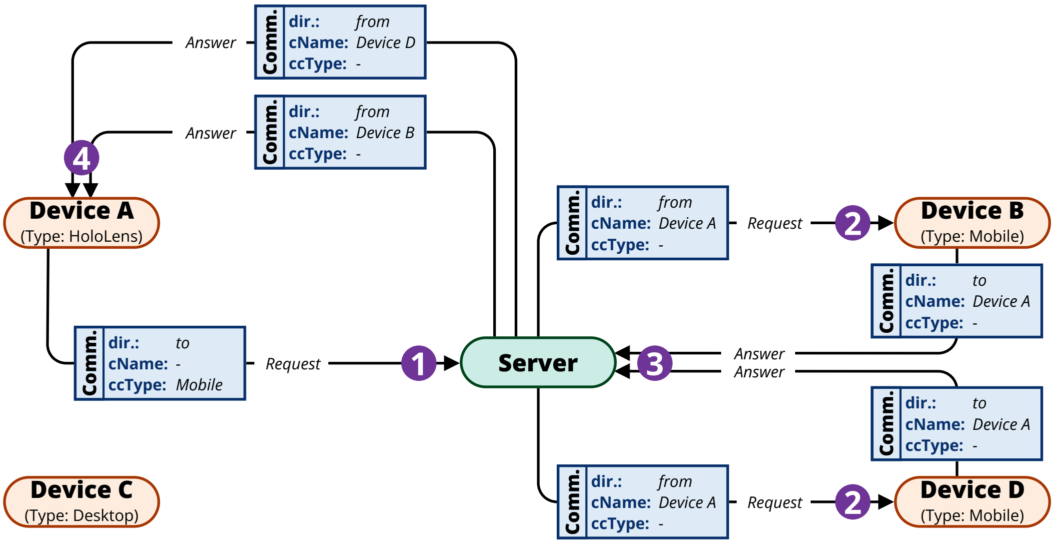

**Fig. 6.10.:** A model describing the client-server (orange-green) communication in the AR Authoring system. Each message has to define communication values (Comm., blue). **(1)** Device A sends a *Request* to all devices of the type "HoloLens" (i.e., Device B and D). **(2)** The server distributes this message to such devices and changes the values of the communication. **(3)** Both devices of the type "HoloLens" process the request and send an *Answer* back to "Device A" over the server. **(4)** The server sends those messages to "Device A".

automatically connects to the server, while users can select the server IP to connect to for the mobile client. We use QR codes (similar to MARVIS, see Sec. 6.3.3) to align the OptiTrack and the HoloLens coordinate systems. Interacting with the system can solely be done using a mobile device. The AR client only displays the visualization in an immersive environment. While a user configures a visualization on the smartphone's screen, each property change will propagate to the AR device through the server. The selected data parameters will be transformed into an SQL query sent to the server for the data requests. The server will process the query and send back the requested data. The visualization preview will be shown once the user sets enough information.

## 6.5 Overall Discussion

We designed, implemented, and demonstrated two systems that illustrate the potential and challenges of HUIs. In the following, I will discuss the implications of such systems on the future design of HUIs for visual data analysis. For that, I will examine the initial findings and impressions of such systems (Sec. 6.5.1), their integration into the real-world environment (Sec. 6.5.2), and their workflow while highlighting different limitations (Sec. 6.5.3).

### 6.5.1 Hybrid User Interfaces

Designing specific user interfaces is challenging and highly dependent on the used devices' factors and the real-world environment. Looking at the visual design, problems regarding the readability of AR content, the positioning of virtual elements, and the size of the displayed content were highlighted[9]. Regarding devices, AR HMDs with their limited FoV or brightness, or mobile devices with their small display size or resolution are essential factors to consider. Responsive design [Hor+21b] already explores which device parameters should be monitored to alter the visual representation, but such responsiveness gets even more complicated as more devices from different classes are involved. Looking at the interaction design, it can become unclear how a user can control the systems, its devices, or even the immersive environment. Generally, using already known input paradigms (e.g., for touch displays) is beneficial as users can easily infer them within a HUI. However, only using device-specific paradigms without combining them leads to frequent focus switches within the HUI. Therefore, it becomes essential for the visual and interaction design to find a balance between how much the capabilities of a single device and a completely fused system are used for the HUI creation.

### 6.5.2 Integration in the Real-World Environment

To integrate AR devices into the existing device ecology, it is necessary to understand the devices in the ecology and where such systems (i.e., the real-world environment) are used. As demonstrated with both usage scenarios, we presented systems that require a spatially tracked device. Such a requirement allowed us to place AR content close to the mobile display and use the mobile device as a 3D cursor. However, such a presupposition is easily achieved in a lab context, not in the real world. Also, tracking accuracy is essential, as minor deviations in the placement position can make it hard to align the AR content to the one on the mobile display. This tracking can also be extended to the immediate environment. As seen in the usage scenario of AR Authoring, placing content directly at or near real-world objects can be beneficial. While pure positional tracking, especially for moveable objects, is tricky, recognizing additional semantic values can also be highly beneficial. Scene understanding of

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[9] In MARVIS [Lan+21], we conducted an expert review of our use cases.

the physical environment such a device combination allows for a more immersive embedding and integration of the virtual content into the real world, which can be used for, e.g., content presentation, analysis, or immersive storytelling.

### 6.5.3 Workflow Support and Integration

We explored HUIs for the use case of visual data analysis – either for the analysis process itself or for configuring immersive visualization environments. While for MARVIS, we demonstrated how a joint representation of visualization could look, in AR Authoring, we focused more closely on enabling existing workflow within such novel device combinations. This leads to insights on how well AR can generally depict and bring existing workflowss into the immersive environment. One example is the work of Méndez et al. [MSR23], who explore and discuss how explainable AI can benefit from HUIs. However, integrating AR HMDs into other cross-device and multi-display environments and setups has great potential [Zag+22]. This includes other device types like desktop PCs or tabletops and collaborative scenarios where users have their personal devices. Lastly, realizing such systems is challenging, as a highly diverse set of heterogeneous devices must be combined. This creates hard-to-fulfill requirements, as seen with spatial tracking of devices. To alleviate this, it is possible to use the potential broad list of capabilities of the different devices in use.

## 6.6 Chapter Conclusion

Within this chapter, we presented two HUIs combining mobile devices with AR HMDs for displaying immersive visualizations. With MARVIS, we designed a series of interactive visualization concepts that address typical visualization challenges and illustrate potential benefits. For AR Authoring, we presented an extended visualization authoring model. It demonstrates the high level of interconnection of visualizations, the configuration process, and its input, which makes it necessary to bring the three phases of the model as closely together as possible for future authoring applications. Additionally, we illustrated an initial set of concepts available by this combination, which could allow for a rich interaction vocabulary in the future.

In this chapter, I explored another type of environmental parameter – the currently present and used system and its devices. Together with my co-authors, we could describe what the integration of AR into the existing system should look like. In the usage scenario AR Authoring, we also highlight the need to include the real-world environment in the authoring process of immersive environments. More importantly, for this thesis, I also described how a cross- or multi-device environment can be realized. Depending on how closely the different devices should interact with each other, the more challenging such a combination will be. Lastly, following the mindset of responsive design, as more devices take part in potential future workflows, the number of possible feature combinations of device characteristics explodes.

# Discussion & Summary

# 7

In the final chapter of my thesis, I recap the different contributions generated throughout and across my research projects. I first summarize each chapter (Sec. 7.1). Next, I present the core contributions of my work along the research questions defined at the beginning of this thesis (Sec. 7.2). Lastly, I will reflect on all insights and formulate further open research questions and future research directions (Sec. 7.3) before I conclude my dissertation with final remarks (Sec. 7.4).

## 7.1 Summary of the Chapters

In **Chapter 2**, I first presented an overview of the literature related to my dissertation's research direction. This includes Augmented Reality, Immersive Analytics, and human-centered and adaptive design literature.

In **Chapter 3**, I presented my study focused on the user's competence to read and understand visualizations. The results revealed a first trend that both the type of visual representation and the competence affect the performance working with the visualization (i.e., bar charts).

In **Chapter 4**, I investigated the influence of a real-world visual background on the visual perception for immersive 2D visualizations. The studies showed that the background is only of influence if users have to interact with the real and virtual world simultaneously. However, users still perceived the background as more distracting than it actually affected their overall performance.

In **Chapter 5**, I explored alternative placement areas for content in AR, namely the ceiling and floor. I studied how those areas affect users' visual perception and physical ergonomics. The results of our two studies demonstrate that both placement areas are usable, allowing us to define the best possible placement in both.

Lastly, in **Chapter 6**, I realized two Hybrid User Interface (HUI) systems for visual data analysis. Both systems combine mobile devices (i.e., tablets or smartphones) with an AR HMD. For that, I created two prototype applications displaying either handcrafted or runtime configurable visualizations.

## 7.2 Core Contributions

At the beginning of this thesis, I presented several research questions (see Sec. 1.1), which guided my general research process. Each of the previously presented research projects is connected to those questions while at the same time generating valuable insights on their own. Additionally, the research projects and questions are linked by a set of (independent) parameters that I investigated with the projects (see Fig. 2.12 on page 23).

In the following, I first want to come back and reflect on those research questions and their connected parameters (Sec. 7.2.1) before also describing some additional overarching findings (Sec. 7.2.2).

### 7.2.1 Core Contributions

**RQ1: What factors should be considered for designing AR applications in a human-centered way?**

In *RQ1*, I focused on exploring human factors that can be of interest to the design of future AR and visualization systems. However, as AR faces *“many challenges in human factors”* [Kim+18], I selected a set of three interesting parameters to investigate: competence, visual perception, and physical ergonomics.

First, I investigated visualization literacy, a **competence** of users to read, interpret, and understand visualizations (Chapter 3). This skill (i.e., visualization literacy) is not explicitly affected by AR or immersive environments. Nevertheless, it is equally needed and essential in those new environments [Hur22], as AR devices can display more complex information through situating in the environment or using the third dimension. In this investigation, we employed a de-emphasis approach for alternative visualization designs to explore how missing competence can be alleviated. The findings suggest that considering the user’s competency may be a promising way to create adaptations tailored to individual needs.

Second, I was interested in the **visual perception** of immersive content presented through an AR device. I hypothesized that the latter could influence perception as AR integrates virtual information in a real-world environment. For that, I investigated the visual clutter of the real-world background (Chapter 4) and the surface orientation of real-world objects to which virtual content can be aligned (Chapter 5). Interestingly, I could find no influence of the visual background for the former, which changed after integrating a task that was embedded into the real world. For the latter, we could confirm preferred placement behaviors (e.g., achieving the most readable and visible content). However, those did not always align with specific user preferences, resulting in the wish to "overwrite" those.

Thirdly, I also explored the **physical ergonomics** of users for the placement of immersive content (Chapter 5). I specifically focused on the optimal human movement ranges for heads and eyes, as well as the general height of users. Through the investigation, I could confirm that users want to reduce the strain on their necks or eyes while optimizing the placed content's ergonomics.

Through the exploration of the three parameters mentioned above, I'm now able to answer this research question as follows: Future AR applications should highly consider their users. Such considerations can reach from more general applicable factors (i.e., competence) to visualization-specific factors (i.e., visualization type), but can also focus on AR-specific ones (i.e., presence of the real-world environment). Overall, I suggest that future AR applications consider the relationship between the virtual content, the immersive environment, and the users with regard to the user's competence, visual perception, and physical ergonomics.

### RQ2: What influences does the environment have within AR applications?

In *RQ2*, I focused on the immersive environment AR applications create. Specifically, I was interested in the properties of the real world that could influence the presented virtual content. For that, I selected two parameters to investigate: visual background clutter and real-world placement areas.

First, I investigated the **visual background** of real-word environments on the perception of virtual content in AR (Chapter 4). For that, I designed several real-world background configurations based on a measure for visual clutter (i.e., feature congestion [Ros+05]) to study. I considered different properties of backgrounds, like the color, the orientation of lines, or the movement within a background. Overall, users could ignore and compensate for the distraction the different backgrounds caused. However, if the background was integrated into the task the user had to perform, it affected how fast they could solve it.

Secondly, I explored two **placement areas**, i.e., the ceiling and floor, virtual content can be aligned to in immersive environments (Chapter 5). I surveyed the literature for ceiling and floor content representation before describing the different properties of both areas. Following, I was able to describe the placement on either placement area and define a model to calculate the optimal perceivable placement. This resulted in recommendations for optimal placement on either ceiling or floor and to the general acceptance by the users. While I only focused on two extreme placement areas, my findings can also be transferred to other placement areas like tables.

Through the exploration of the two parameters mentioned above, I'm now able to answer this research question as follows: Future AR applications need to consider the real-world environment in which they are used in more closely. As AR mainly alters the visual channel, the placement of the virtual content in relation to the environment's visual appearance and orientation are already essential to factor in. This becomes even more important the closer the virtual content is coupled to objects in the environment (e.g., a task integrating the background). However, other parameters not directly affecting the visual channel should also be focused on, like the presence of other persons or noises.

### RQ3: How can AR applications be combined with existing systems and devices?

In *RQ3*, I explored how immersive environments are constructed with regard to the used devices. To be more precise, I explored **multi-device environments**, which combine tablets, smartphones, and AR HMDs into one system.

I designed two Hybrid User Interfaces (HUIs) for immersive visualizations (Chapter 6) based on two use cases: immersive analytics and in-situ visualization authoring. The tablets are the main device in the former, while AR gives additional information and supports the analysis workflow. The latter used a smartphone as an input controller to create and manipulate immersive visualizations. Additionally, I have also used multiple devices in my other research projects, either as an additional information display (Chapter 4) or as an input device (Chapter 5). Overall, all AR research projects demonstrate the primary goal of HUIs: to complement one device class by integrating and using another.

Through the exploration of HUIs, I'm now able to answer this research question as follows: AR will not replace the existing device ecology but will be added as another device class. This will force AR applications to incorporate other devices on a regular basis to reach a broad acceptance and use of AR devices[1]. However, this widespread usage within multi-device environments depends on how expensive such integration is (e.g., the development of such a system), how well a combination of devices is achieved (e.g., UI and content spanning across devices), or how useful its addition is (e.g., allows stereoscopic vision). Especially the latter has to consider if AR augments another device or if another device is integrated into AR to add additional functionalities.

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[1] Interestingly, this is also demonstrated by the introduction of the Apple Vision Pro [@App23].

### 7.2.2 Overarching Considerations

In addition to the contributions related to my research questions, other overarching topics emerged. In the following, I will discuss the notion of human-centered design for AR applications and how to evaluate such systems.

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Parts of the research presented in this section have previously appeared in:

**Marc Satkowski**, Wolfgang Büschel, and Raimund Dachselt. "Experiences with User Studies in Augmented Reality". In: *Workshop on Evaluating User Experiences in Mixed Reality, on ACM Conference on Human Factors in Computing Systems (CHI)*. Yokohama, Japan, May 8–13, 2021. [SBD21]

*Own Contribution:* I was the main author of this paper. I organized the discussion with my co-authors and generated the general structure of this work.
*Applied Changes:* This work was compressed and only partly embedded into Sec. 7.2.2.

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#### Human-centered Design

Throughout my dissertation, I focused on users of future AR applications and how to achieve the best possible experience for them. For that, I looked at several characteristics and properties that influence users in immersive environments.

One such parameter that can be found across my research projects is the expertise or familiarity of users with a system or its content (e.g., visualization). To be more precise, we used visualization literacy as the core of an investigation (Chapter 3), verified a given familiarity with visualization in a study (Chapter 4, see appendix Fig. B.1), and invited HCI and visualization experts to help us design and evaluate a prototype (Chapter 6). While having a certain degree of expertise is helpful for such research projects, it is also hard to define and measure it precisely. This holds true for both extremes: experts and novices. For example, in Chapter 4, we asked participants to fill in the appropriate terms in a visualization schema to verify a general understanding (see Fig. B.1). While such a test is straightforward, it helped us ensure that the participants could understand the questions asked throughout the study. In Chapter 3, we used one specific visualization literacy test [Boy+14]. While this was already a good starting point, there also exist other such tests [LKK17; BBG18; FDL20] or their recent advancements [PO23]. However, the question arises how specialized a given competence assessment should be. In cases of visualizations, either a global score for the general skill to read visualization [LKK17; BBG18] or for single visualization types [Boy+14; FDL20] can be constructed and used. In contrast, the term novice is ambiguously defined as recently described by

Burns et al. [Bur+23]. Such a definition can be based on what knowledge novices lack, the relation to domain-specific knowledge, or being the opposite of an expert.

As described with the contribution to *RQ1*, I also investigated other user characteristics, like visual perception (Chapter 4), physical ergonomics (Chapter 5), or the general usage behavior (Chapter 6). Responding and adapting to such parameters and their changes over time are essential when designing a system, even if this was not the focus of my dissertation. While adapting to changes in a single parameter is not too hard, possible parameter combinations are challenging. Additionally, it is also essential to define what the goal of a future adaptation is. Both user performance and experience can be affected by changes in the visual design, provided interaction techniques, or support for novices or experts. Throughout my research projects, I have come to the opinion that the user experience is equally vital compared to pure quantitative performance measurements. In Chapter 3, the visual background only had a marginal influence on the performance; this means only on the task completion time if both the real-world background and virtual foreground were part of a task. However, the user experience was affected nevertheless. With that, I can imagine that an extended feeling of being less efficient in a system will likely affect how well humans perform.

### Evaluating AR Applications & Designs

In all of my research projects, I conducted user evaluations to understand how a given parameter affects task performance, usability, or the general user experience. However, designing and running studies, especially in AR, can be rather challenging, like conducting in in-the-wild [Dey+18; FP19; SD21; Mer+20] or long-term user studies [Ens+21], and generating insights [Mer+20] even under the best possible condition [Ens+21]. This shows a need for *"new evaluation methods that could capture more accurately the user experience in AR"* [Kim+18]. Connected to those challenges and needs, we[2] can derive questions like: "How can we ensure that the participants can easily give answers?" or "How can experimenters ensure that participants correctly solve tasks and that the study prototype works as intended?".

Looking at the input capabilities of commonly used HMD devices, we see problems associated with using free-hand gestures in studies. Participants are generally inexperienced with AR devices and, therefore, require training that often only leads to a shallow understanding of the target system. This also affects input errors, as the tracking generally is also error-prone, fluctuation among the participants due to the general understanding of the techniques, input techniques like text input, which

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[2] "We" in this section relates to the author Marc Satkowski, as well as Wolfgang Büschel and Raimund Dachselt as co-contributors to this research.

is not efficient in AR, and greater exhaustion due to increased body movements. To alleviate some of those problems, we followed different approaches, like reducing the number of gestures to learn, using specialized and simple input devices, like the Microsoft Clicker (Chapter 4), making use of mobile devices as participants are familiar with those, or let the participants orally answer the questions or tasks.

Another essential part of user experience investigations is the ability to talk with participants about the presented systems or designs, to verify and log what the participants do, and to communicate with the participants about specific parts of a system. However, an AR HMD allows only one person to interact with the virtual content, which prevents the experimenter from observing the study participants. In general, it is possible to give the experimenter a better understanding of what the participants experience in the immersive environment. Those utilize, for example, an additional experimenter client on a desktop computer that logs specific events, the streaming capabilities of the HMD to see what the participant see, or an additional experimenter AR client. In general, those additions allow for better communication between the experimenter and the participant but also have relatively high costs regarding development expenses and performance.

## 7.3 Open Research Questions & Future Work

This thesis describes my research over the last few years, resulting in several internationally published research articles. However, such a work cannot exhaust every possible parameter, user group, or technology. In turn, several new research questions and avenues emerged after the here made observations. With that said, I want to focus on three aspects, namely immersive environments (Sec. 7.3.1), visual data analysis (Sec. 7.3.2), and the adaptation of AR systems (Sec. 7.3.3).

### 7.3.1 Future Immersive Environments

The focus of this thesis lies in the exploration of future immersive environments. However, I only explored a fraction of potential properties related to the same. I will describe a few research directions worth investigating further in the following.

Parts of the research presented in this chapter have previously appeared in:

Mats Ole Ellenberg*, **Marc Satkowski***, Weizhou Luo*, and Raimund Dachselt. “Spatiality and Semantics - Towards Understanding Content Placement in Mixed Reality”. In Proceedings of: *Extended Abstracts of the 2023 CHI Conference on Human Factors in Computing Systems (CHI EA)*. Hamburg, Germany, April 23–28, 2023. [Ell+23] **The first three authors contributed equally.*

*Own Contribution:* In collaboration with my co-authors, we designed the study and design space. I further generated all the figures.
*Applied Changes:* I only use the terminology defined in this publication, present an altered design space schematic, and highlight future research directions in Sec. 7.3.1.

### Relationship of Physical Objects and Virtual Content

Humans are always in environments that are not empty. On the contrary, environments accommodate several objects, animals, or other humans. With that in mind, it is impossible to look at AR and its immersive content in isolation – it is even the aim of research directions like situated and immersive visualizations [WJD17]. Therefore, it becomes important to consider the relationship between real-world objects and the virtual content present in an immersive environment. In Chapters 4 and 5, the virtual content was only close to objects or surfaces in the environment. In contrast, Chapter 6 presents AR visualization based on the tablet’s content, demonstrating a strong semantic coupling. Following this, we[3] already proposed a two-dimensional design space that integrates spatial and semantic coupling (see Fig. 7.1) to define the perceived unity [Ell+23]. In short, spatial coupling describes the geometric alignment (i.e., spatial attributes), semantic coupling the presence of informational meaning (e.g., data source, related concepts), and perceived unity the state of forming a complete and harmonious whole between virtual content and physical objects. But still, how the granularity of real-world objects (i.e., whole table vs. paper on this table), their texture, or the spatial parameters used to create an alignment (e.g., shape or rotational alignment) influences how connected the virtual content to the real world feels has yet to be investigated.

### Understanding How Immersive Environments are used

The physical environment shapes human motion and behavior, which is also the case for immersive environments as those combine virtual and real-world aspects. However, studies conducted in Chapters 4 and 5 forced the participants to sit or stand still in one position. Only with the prototype presented in Chapter 6 could the users actively engage with the tablets or the environment. Especially with the

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[3] “We” in this section relates to the author Marc Satkowski, as well as Mats Ole Ellenberg, Weizhou Luo, and Raimund Dachselt as co-contributors to this research.

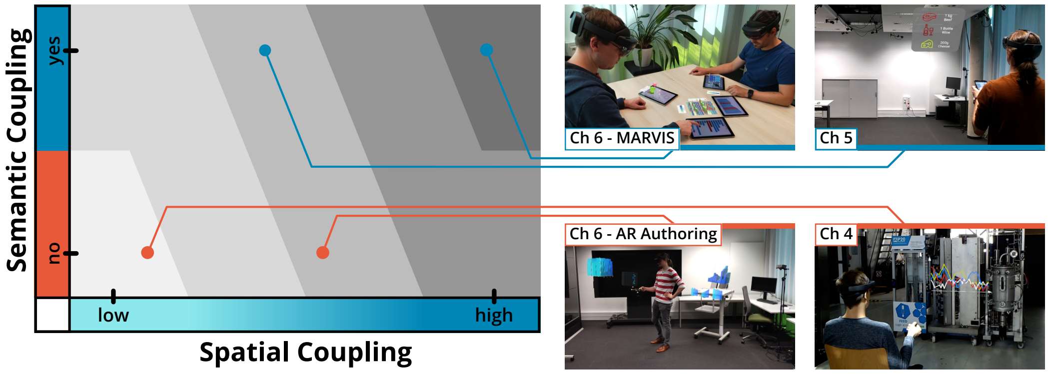

**Fig. 7.1.:** Schematic of a two-dimensional design space combining spatial and semantic coupling, based on [Ell+23]. The gray gradient within the design space illustrates the perceived unity, with a darker color corresponding to a higher "unity". It is possible to situate all AR research projects of this thesis within this design space.

AR Authoring system, a user can freely move around and position visualizations near to other objects like whiteboards. With that, it also becomes necessary to understand how users move and interact with objects in the real world or immersive environments. Systems like MIRIA [BLD21], ReLive [Hub+22], AvatAR [Rei+22], or PEARL [Luo+23] already enable such an in-situ exploration. Especially the latter allows for exploring movement data in relation to physical referents, i.e., a spatially static object placed in the environment (see Fig. 7.2). However, even as those systems already enable such analysis, open questions remain, like how to reliably detect and label the environment automatically or how to work with moving objects (either inanimated or humans).

### Hybrid User Interfaces

I combined an AR HMD with other device types for different purposes through most of this thesis chapters (see Sec. 7.2.1). With that, HUIs can utilize the benefits of one of the linked devices but also allow to transfer familiarity of one device in a new system. However, AR HMDs, as used in my projects, are not widely available due to costs, missing standalone applications, or the wish to not replace and only extend the current workflows and systems. Subsequentially, the investigation into heterogeneous device setups working within shared mixed reality space should be considered. This encompasses questions like enabling seamless communication and interaction across device types or exploring the same information space with missing features like depth perception. Furthermore, it is also necessary to correctly categorize and define such systems. However, the current term of HUIs is somewhat fragmented, which results in several research questions that I already presented in workshop publication [SM23], like do HUIs have to consist of only heterogeneous devices or require HUIs the users to use the different devices in parallel?

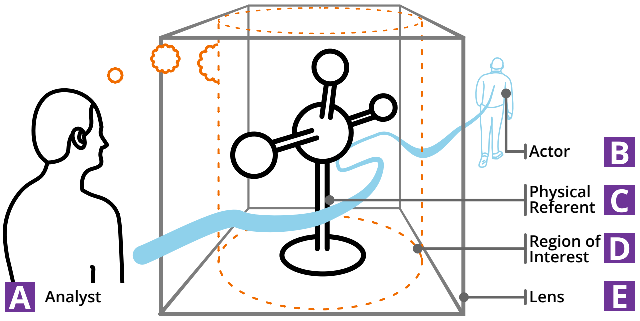

**Fig. 7.2.:** The schematic model of PEARL [Luo+23]. PEARL allows to analyze the usage of (immersive) environments. The movement of humans **(B)** is shaped by the presence of other objects **(C)** within an environment. An analyst **(A)** is interested in such objects **(D)** and can analyze them by creating a lens **(E)** encapsulation a referent object.

## 7.3.2 Visual Data Analysis

Visuals, and in the case of this thesis, visualizations are an important component in many AR systems.

### Classical and New Visualization Concepts in AR

Throughout my work, I made use of classic, basic visualizations [SED19] like line charts, bar charts, or scatter plots. Those allow transferring from traditional computing devices to AR spaces more easily as users and study participants are already familiar with them. Existing immersive visualization frameworks (e.g., [RFD21; Cor+19]) also enable the creation of such visualizations. However, those types were not explicitly designed for AR usage, so they do not fully utilize AR devices' capabilities or the immersive environment. This, in turn, makes it interesting to consider creating new visualization types fitted to immersive environments and AR devices. In Chapter 6, we combined traditional 2D visualization by extending them into the third dimension, making the presented visualization more graspable. Furthermore, how to transit between such new and commonly used types can also be of interest [Lee+23].

### Visual Mapping & Visual Perception

The visual perception of visualizations is essential to understanding the presented content well. In Chapters 4 and 5, I explored visual perception concerning visual clutter and placement areas. Those projects presented the high complexity of immersive environments compared to common desktop or mobile interfaces. Such complexity also leads to even more issues, like color correction of not completely opaque content [Dav+14], color matching to environmental objects, or lighting condition fitting. As working with visualizations relies on how well users perceive them, such visual properties must be taken care of to optimize general readability. With that, the question arises of which parameters to which extent must be considered to achieve the best visual perception for users.

### 7.3.3 Scalability & Adaptation

One goal of this thesis was to generate insights into what parameters are of interest for the future adaptive and responsive design of AR systems.

#### Scalability in AR

The term scalability has many aspects, like for network proecesses [Bon00], visuals [EK02], or even perception [YN06]. Especially the latter two also played a role throughout my thesis since I considered the characteristics of humans, the environment, and the systems (see Sec. 2.3). However, while scalability can encapsulate so many different directions [Ric+22], no specific scalability for AR applications has been defined yet. As described throughout my thesis, immersive environments have many possible factors to consider. In this thesis alone, I already focused on the users' competence, visual perception, physical ergonomics, and the real-world environments' visual background and placement areas. The simultaneous existence of this variety of factors makes it challenging to create future AR systems so that they can easily adopt, respond, or scale to changes – especially considering the combination of all those factors.

#### Measuring Parameters

The adaptation of systems always depends on recognizing a change in value or state. However, this, in turn, needs a proper way to measure a factor of interest. Looking at Chapter 3, I used the Visualization Literacy test of Boy et al. [Boy+14] to measure the competence of the study participants. In Chapter 4, I used the Feature Congestion value from Rosenholtz et al. [Ros+05] to calculate the visual clutter of a real-world background. However, as both methods have flaws (also described in the corresponding chapters), improving those is essential, especially with AR systems in mind. Additionally, further advances in sensor technology and corresponding algorithms are needed to recognize and assess the real-world environment within an immersive environment. This also extends to recognizing the user's condition or even intent (i.e., task to perform).

### Adaptation Strategies

After measuring factors, they can be used to change the visuals or behavior of the system. Chapter 3 explored how well a simple highlighting technique can counter missing competencies. In Chapter 5, we investigated the optimal placement parameters for the ceiling and floor in relation to the presented content type. Exploring other highlighting and supporting techniques directly in AR is promising for the former. In contrast, the usefulness of the proposed values in other situations, like a user in motion, has to be verified for the latter. Generally speaking, further investigating and designing how a system should react to a changing parameter is quite promising.

## 7.4 Final Remarks

In the future, we can embed and situate the ever-growing data into our existing work processes and environments through Mixed Reality. This opens up many possibilities for the presentation of and interaction with information. However, the combination of both virtual and real-world content and objects within one joint user interface has many challenges to address. Therefore, in this thesis, I explored an initial set of parameters essential for a user-centered design of immersive environments. Those include the users' competence, visual perception, physical ergonomics, and the environments' visual background and available placement areas. To summarize, throughout my study-focused research approach, I contributed findings that describe the influence of the different characteristics of humans, the environment, and the system. I hope my work can inspire future research to consider how an ergonomic and human-centered design of Augmented and Mixed Reality systems should look.

Additionally, I want to reiterate why a human-centered view on the future of MR is, in my opinion, essential. As technology (including wearable or smart textiles) comes ever closer to us, and with that becoming personal, it will be increasingly important to consider the individual user of such a system. In contrast, desktop applications or websites are already designed to be responsive, which means adjusting themselves to the specific device type they are used on. However, the individual users' need in front (or in the case of an AR HMD under) the device is poorly integrated. Personally, I'm interested to see where the development in HMD technology will head. With the growing sensor and AI technology, it should become easier to adapt any application on a given device type to the individual user besides the general preferences that must be actively set in the options menu. While this seems promising, it also opens up many other questions, like "How much personal information or metrics do we want to share with a device?” or “How do we even model an adaptable system with an increasing number of parameters to consider?”. With that said, I believe that MR will provide a highly personalized experience in work contexts (like visual data analysis) and private environments soon. However, how fast and successful the following endeavors are remains to be seen.

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# A

# Appendix for Chapter 3 (Study Material)

This appendix provides supplementary material for the conducted user study described in Ch. 3. This material includes the survey (Sec. A.1) and the specific tasks the participants had to perform (Sec. A.2).

## A.1 Lime Survey Questions

The following questionnaire was used in our LimeSurvey [@Lim] online study. Afer the "Pre-Study" block, we conducted the Visualization Literacy (VL) assessment. Originally, both (i.e., for scatter plot and bar charts) linked to an online version of the VL assessment of Boy et al. [Boy+14], but this is no longer available[1].

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[1] You can find the code of the assessment in the GitHub repository: `https://github.com/INRIA/Visualization-Literacy-101`

## Pre-Study: Demographic Questionnaire

| | |
|---|---|
| What device are you using to fill out this survey? | ☐ Laptop / Desktop ☐ Tablet ☐ Smartphone |
| What is your age? | ☐ 15 - 19 ☐ 20 - 23 ☐ 24 - 27 ☐ 28 - 31<br>☐ 32 - 35 ☐ 36 - 40 ☐ 41 - 50 ☐ 51+ |
| To which gender do you most identify? | ☐ Female ☐ Male ☐ Transgender-Female<br>☐ Transgender-Male ☐ Non-conforming<br>☐ Prefer not to answer ☐ Other: ............................. |
| What is the highest degree or level of education you have completed? | ☐ High School ☐ Bachelors Degree ☐ Masters Degree<br>☐ Ph.D. or higher ☐ Trade School ☐ Prefer not to say |
| How would you describe your current main occupation? | ☐ Student ☐ Employee ☐ Other |
| (If Student) How many semesters have you been studying? | ☐ 1 - 2 ☐ 3 - 4 ☐ 5 - 6 ☐ 7 - 10 ☐ 11 or more<br>☐ Prefer not to say |
| What is the field of your study or work? | ☐ Natural sciences and mathematics (e.g. Chemistry, Mathmatics, Psychology) ☐ Civil and Environmental Engineering (e.g. Architecture, Civil Engineering, Economics) ☐ Engineering Sciences (e.g. Computer Science, Electrical E., Mechanical E) ☐ Humanities and social sciences (Art History, Philosophy, Linguistics) ☐ Medicine ☐ Teaching profession ☐ Other: ............................. |
| Do you have any eye conditions? | ☐ Yes ☐ No |
| If so, please specify. | ☐ visual impairment (short sighted, far sighted) ☐ Red-green color blindness ☐ Blue-yellow color blindness ☐ Total color blindness ☐ Other |

| How familiar are you with the following visualizations? | 1<br>Never heard of it | 2 | 3 | 4 | 5<br>Daily Use |
|---|---|---|---|---|---|
| Pie Chart (Donut Chart) | ☐ | ☐ | ☐ | ☐ | ☐ |
| Bar Chart | ☐ | ☐ | ☐ | ☐ | ☐ |
| Area Chart | ☐ | ☐ | ☐ | ☐ | ☐ |
| Scatterplot (Bubble Chart) | ☐ | ☐ | ☐ | ☐ | ☐ |
| Scatterplot (Bubble Chart) | ☐ | ☐ | ☐ | ☐ | ☐ |
| Polar Chart (Radar Chart; Nightingale Rose) | ☐ | ☐ | ☐ | ☐ | ☐ |
| Tree Map | ☐ | ☐ | ☐ | ☐ | ☐ |
| Network Graph | ☐ | ☐ | ☐ | ☐ | ☐ |

## Post-Condition: UEQ+

| | -3 | -2 | -1 | 0 | 1 | 2 | 3 |
|---|---|---|---|---|---|---|---|
| While using the visualization I perceived it as | unpredictable<br>☐ | ☐ | ☐ | ☐ | ☐ | ☐ | predictable<br>☐ |
| | obstructire<br>☐ | ☐ | ☐ | ☐ | ☐ | ☐ | supportive<br>☐ |
| | not secure<br>☐ | ☐ | ☐ | ☐ | ☐ | ☐ | secure<br>☐ |
| | not meeting expectations<br>☐ | ☐ | ☐ | ☐ | ☐ | ☐ | meeting expectations<br>☐ |
| I consider the visualization as | useless<br>☐ | ☐ | ☐ | ☐ | ☐ | ☐ | useful<br>☐ |
| | not helpful<br>☐ | ☐ | ☐ | ☐ | ☐ | ☐ | helpful<br>☐ |
| | not beneficial<br>☐ | ☐ | ☐ | ☐ | ☐ | ☐ | beneficial<br>☐ |
| | not rewarding<br>☐ | ☐ | ☐ | ☐ | ☐ | ☐ | rewarding<br>☐ |
| In my opinion, using the visualization is | difficult<br>☐ | ☐ | ☐ | ☐ | ☐ | ☐ | easy<br>☐ |
| | illoagical<br>☐ | ☐ | ☐ | ☐ | ☐ | ☐ | logical<br>☐ |
| | not plausible<br>☐ | ☐ | ☐ | ☐ | ☐ | ☐ | plausible<br>☐ |
| | inconclusive<br>☐ | ☐ | ☐ | ☐ | ☐ | ☐ | conclusive<br>☐ |

## Post-Study: Visualization Rating and Task

| | |
|---|---|
| Which scatter plot do you prefer? | ☐ Non-Adaptaded (see Fig. 3.3C)<br>☐ Adapted (see Fig. 3.3D) |
| Make a comment on your choice: | ............................. |
| Which bar chart do you prefer? | ☐ Non-Adaptaded (see Fig. 3.3A)<br>☐ Adapted (see Fig. 3.3B) |
| Make a comment on your choice: | ............................. |
| What frustrated you most during these tasks? | ............................. |
| What did you like most about the barchart/scatterplot visualizations or their parts (e.g. Labels, Legend, Tasks)? | ............................. |
| Do you have any additional critique or comments? | ............................. |

## A.2 Study Tasks

In total, 20 multiple-choice questions were presented to our study participants. Each of those questions (see Tab. A.1) was associated with one visualization (see Fig. A.1) and one set of possible answers (see Tab. A.2).

| | Condition | | | |
|---|---|---|---|---|
| # | Chart Type | Adap. | Task | Question |
| 1 | Bar Chart | NA | DV (Average) | What is the average Life Expectancy for the 4 Countries belonging to Arab States below? |
| 2 | Bar Chart | NA | Range | What is the Range of values for Children per Woman in South Asian Countries? |
| 3 | Bar Chart | NA | DV (Sum) | What is the sum of GDP per Capita for all Countries with a GDP per Capita above 3000 in the year 2015? |
| 4 | Bar Chart | NA | DV (Average) | What is the average Child Survival Rate in South Asian Countries? |
| 5 | Bar Chart | NA | DV (Count) | In how many regions is the Life Expectancy of 2006 above 70 years? |
| 6 | Scatter Plot | NA | DV (Average) | What is the average Life Expectancy for the 5 East-Asia & Pacific Countries below? |
| 7 | Scatter Plot | NA | Range | What is the Range of Values for Children per Women in OECD Countries? |
| 8 | Scatter Plot | NA | DV (Sum) | What is the sum of GDP per Capita for all Countries with a GDP per Capita above 35000 in the year 1996? |
| 9 | Scatter Plot | NA | DV (Average) | What is the average Child Survival Rate for East-Asian & Pacific Countries? |
| 10 | Scatter Plot | NA | DV (Count) | In how many Regions is the Life Expectancy of 1990 higher than 65? |
| 11 | Bar Chart | A | DV (Average) | What is the average Life Expectancy for the 4 Sub-Sahara African Countries below? |
| 12 | Bar Chart | A | Range | What is the Range of values for Children per Woman in Latin American Countries? |
| 13 | Bar Chart | A | DV (Sum) | What is the sum of GDP per Capita for all Countries with a GDP per Capita above 2500 in the year 2012? |
| 14 | Bar Chart | A | DV (Average) | What is the average Child Survival Rate for East-European & Centr.-Asian Countries? |
| 15 | Bar Chart | A | DV (Count) | In how many regions is the Life Expectancy of 1977 below 60 years? |
| 16 | Scatter Plot | A | DV (Average) | What is the average Life Expectancy for the 5 Latin American Countries below? |
| 17 | Scatter Plot | A | Range | What is the Range of Values for Children per Woman in East-Asian & Pacific Countries? |
| 18 | Scatter Plot | A | DV (Sum) | What is the sum of GDP per Capita for all Countries with a GDP per Capita below 30000€ in the year 2000? |
| 19 | Scatter Plot | A | DV (Average) | What is the average Child Survival Rate for Arab States? |
| 20 | Scatter Plot | A | DV (Count) | In how many Regions is the Life Expectancy of 2018 higher than 70? |

**Tab. A.1.:** All questions used in the presented study. The condition for the questions consists of the used visualizations (refered by number and linked to Fig. A.1) and the adaptation state (NA = Non-Adapted, A = Adapted). Each question combines two types of low-level analysis tasks: Filter with either Range or Compute Derived Value (DV). The available answers for each of the questions can be seen in Tab. A.2

|  | Condition |  |  |  |  |  |  |
|---|---|---|---|---|---|---|---|
| # | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
| 1 | 62.6 | 68.1 | 69.2 | 72.4 | 66.1 | 64.3 | 75.5 |
| 2 | 2.4 - 2.5 | 2.0 - 5.9 | 1.2 - 5.4 | 2.6 - 5.4 | 1.9 - 3.6 | 2.4 - 5.1 | 2.2 - 3.6 |
| 3 | 13100 | 22400 | 19600 | 46200 | 18300 | 11400 | 28900 |
| 4 | 97.2 | 72.5 | 85.4 | 87.8 | 93.1 | 82.0 | 90.0 |
| 5 | 3 | 4 | 5 | 6 | 2 | 1 | - |
| 6 | 91.2 | 55.8 | 57.5 | 71.1 | 62.0 | 63.8 | 61.1 |
| 7 | 2.7 - 2.9 | 1.4 - 3.0 | 2.6 - 5.4 | 1.7 - 2.8 | 1.6 - 1.7 | 1.6 - 2.1 | 1.5 - 1.8 |
| 8 | 20500 | 130200 | 221300 | 420400 | 80200 | 139200 | 152600 |
| 9 | 90.0 | 88.3 | 93.0 | 91.1 | 87.2 | 88.9 | 94.1 |
| 10 | 1 | 3 | 5 | 4 | 2 | 6 | - |
| 11 | 53.4 | 60.0 | 62.1 | 87.8 | 54.2 | 57.3 | 65.8 |
| 12 | 1.9 - 2.5 | 1.6 - 6.6 | 1.4 - 5.9 | 2.2 - 2.9 | 3.4 - 5.2 | 2.2 - 4.7 | 2.0 - 4.5 |
| 13 | 12300 | 9400 | 90200 | 17740 | 23500 | 13300 | 44000 |
| 14 | 96.7 | 91.2 | 86.7 | 81.3 | 93.0 | 99.1 | 93.2 |
| 15 | 1 | 6 | 2 | 5 | 4 | 3 | - |
| 16 | 75.4 | 93.1 | 72.2 | 91.1 | 95.1 | 69.4 | 71.1 |
| 17 | 4.0 - 5.9 | 1.6 - 6.6 | 2.2 - 3.4 | 2.7 - 5.9 | 1.2 - 3.4 | 2.8 - 5.7 | 2.5 - 4.1 |
| 18 | 80400 | 43200 | 234000 | 20900 | 68300 | 217000 | 56600 |
| 19 | 94.7 | 85.0 | 89.2 | 98.4 | 91.1 | 97.1 | 92.0 |
| 20 | 6 | 1 | 5 | 4 | 7 | 2 | 3 |

**Tab. A.2.:** All answers to the questions (see Tab. A.1) asked to the accordingly numbered visualizations (see Fig. A.1). The green highlighted cells present the correct answers to this question.

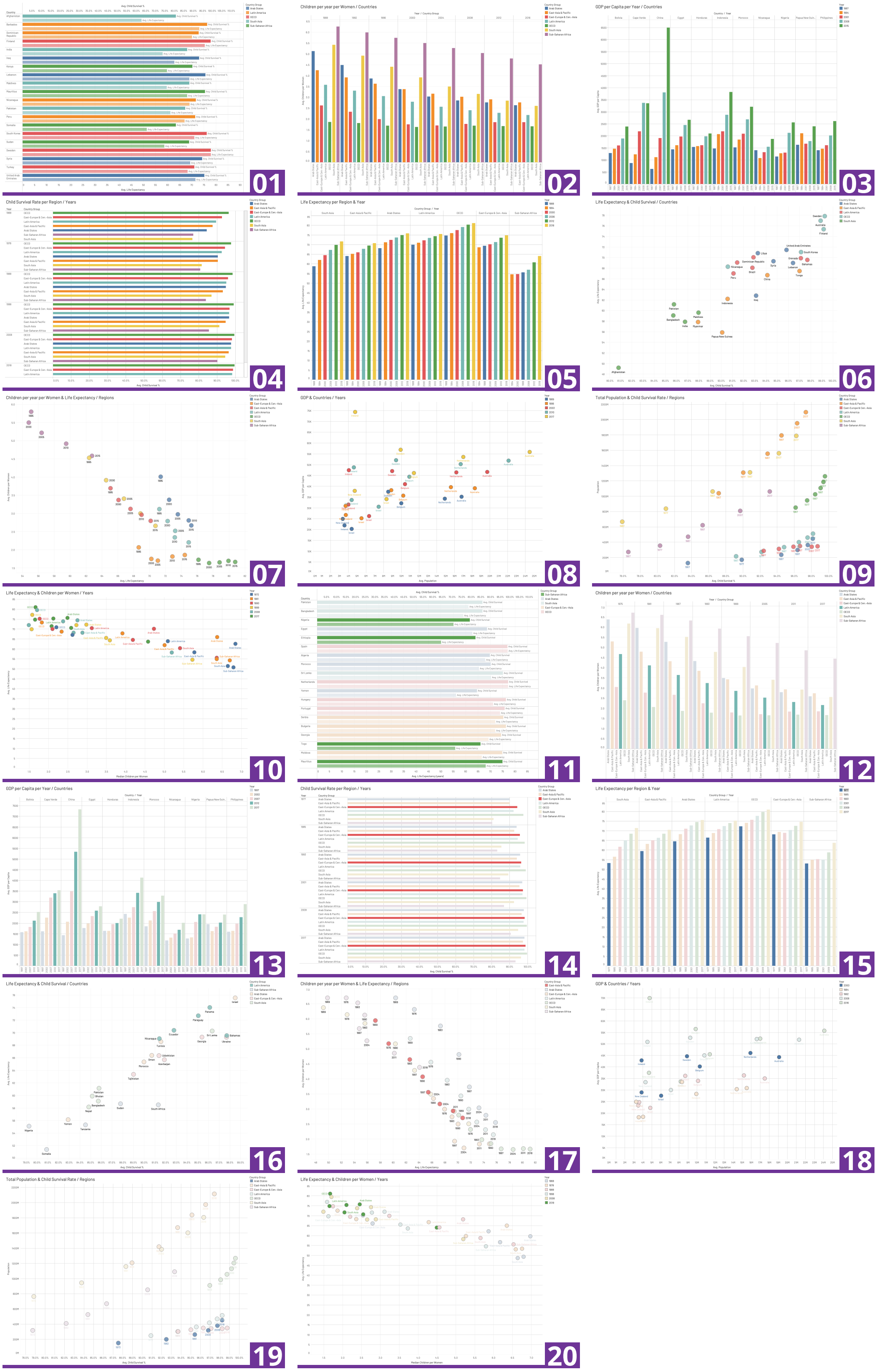


**Fig. A.1.:** All 20 visualizations used in this study. Each visualization was created via Tableau [@Tab] and is linked to a specific task (see Tab. A.1 and A.2). **(1-5, 11-15)** present bar charts, while **(6-10, 16-20)** present scatter plots. **(1-10)** present visualiztation without adaptation, while **(11-20)** show visualization with de-emphasis.

# Appendix for Chapter 4 (Study Material)

# B

This appendix provides supplementary material for the conducted user studies described in Ch. 4. This material includes the questionnaires (Sec. B.1) and the tasks the participants had to solve (Sec. B.2) for both studies.

## B.1 Questionnaires

The questionnaires for study 1 (Sec. B.1.1) and study 2 (Sec. B.1.2) are partly similar.

### B.1.1 Questionnaire for Study 1

The questionnaire used in study 1 of “Influence of Real-World Backgrounds on the Perception of AR Visualizations”.

**Pre-Study: Demographic Questionnaire**

| | |
|---|---|
| Gender | ............................ |
| Height | ............................ cm |
| Age | ............................ years |
| Highest level of education | ............................ |
| Activity/field of study | ............................ |
| Do you need visual aid? | ☐ Yes ☐ No |
| If so, are you currently wearing them? | ☐ Yes, glasses ☐ Yes, contact lenses ☐ No aid |
| Do you have color vision deficiency? | ☐ Yes ☐ No |
| Do you have a limitation of spatial perception? | ☐ Yes, ............................ (specify) ☐ No |
| Do you have a limitation of movement? | ☐ Yes, ............................ (specify) ☐ No |

| | 1<br>Non / Never | 2 | 3<br>Occasional Use | 4 | 5<br>Daily Use |
|---|---|---|---|---|---|
| How often have you had experiences with Augmented Reality in general, e.g., on smartphones (Pokemon Go, etc.), Nintendo 3DS, ...? | ☐ | ☐ | ☐ | ☐ | ☐ |
| How often have you had experience with head-mounted displays (e.g., HoloLens) for Augmented Reality? | ☐ | ☐ | ☐ | ☐ | ☐ |
| How often have you had experiences with Virtual Reality (e.g., Oculus Rift, HTC Vive)? | ☐ | ☐ | ☐ | ☐ | ☐ |
| How often do you work with different visualization types (e.g., line, bar, or pie charts) to analyze data? | ☐ | ☐ | ☐ | ☐ | ☐ |

## Pre-Study: Health Condition before the Study

| Your physical condition at this moment. | 1<br>Not at all | 2 | 3<br>Medium | 4 | 5<br>Greatly |
|---|---|---|---|---|---|
| How tired/fatigued are you? | ☐ | ☐ | ☐ | ☐ | ☐ |
| How concentrated are you? | ☐ | ☐ | ☐ | ☐ | ☐ |
| How motivated are you? | ☐ | ☐ | ☐ | ☐ | ☐ |
| Do you have headaches? | ☐ | ☐ | ☐ | ☐ | ☐ |
| How dry or irritated are your eyes? | ☐ | ☐ | ☐ | ☐ | ☐ |

## Post-Study: Health Condition after the Study

| Your physical condition at this moment. | 1<br>Not at all | 2 | 3<br>Medium | 4 | 5<br>Greatly |
|---|---|---|---|---|---|
| How tired/fatigued are you? | ☐ | ☐ | ☐ | ☐ | ☐ |
| How concentrated are you? | ☐ | ☐ | ☐ | ☐ | ☐ |
| How motivated are you? | ☐ | ☐ | ☐ | ☐ | ☐ |
| Do you have headaches? | ☐ | ☐ | ☐ | ☐ | ☐ |
| How dry or irritated are your eyes? | ☐ | ☐ | ☐ | ☐ | ☐ |
| What impact did the study have on your health condition in comparison to before the study took place? | .............................. | | | | |

## Post-Study: Visualization and Background Perception

| | 1<br>do not agree | 2 | 3<br>partly agree | 4 | 5<br>agree |
|---|---|---|---|---|---|
| The presentation of the visualization in a real environment irritated me. | ☐ | ☐ | ☐ | ☐ | ☐ |
| The real background did not affect me. | ☐ | ☐ | ☐ | ☐ | ☐ |
| I was able to suppress the real background. | ☐ | ☐ | ☐ | ☐ | ☐ |
| To what extent have particular areas in the background caused you problems? | .............................. | | | | |

| | |
|---|---|
| How did you approach solving the tasks? | .............................. |
| Did other details exist that made it difficult for you to solve the task? | .............................. |
| To what extent did you notice the background while working on the tasks? | .............................. |

| How well were you able to identify ......... in general? | 1<br>not at all | 2 | 3<br>moderate | 4 | 5<br>very |
|---|---|---|---|---|---|
| Lines | ☐ | ☐ | ☐ | ☐ | ☐ |
| Axis Labels | ☐ | ☐ | ☐ | ☐ | ☐ |
| Tasks | ☐ | ☐ | ☐ | ☐ | ☐ |
| **How much did the background affect your perception of .........?** | **1<br>not at all** | **2** | **3<br>moderate** | **4** | **5<br>very** |
| Lines | ☐ | ☐ | ☐ | ☐ | ☐ |
| Axis Labels | ☐ | ☐ | ☐ | ☐ | ☐ |
| Tasks | ☐ | ☐ | ☐ | ☐ | ☐ |

| | |
|---|---|
| Were there any other influences that bothered you in the study environment? | .............................. |
| If there were influences, to what extent did these other influences bother you? | .............................. |

| | |
|---|---|
| Which background do you perceive as the one with the highest disturbance factor? | Please rank them (1 highest confounder - 4 lowest confounders) of the 4 images (A, B, C, D) (see Fig. 4.9):<br>1.: 2.: 3.: 4.: |
| Any other comments? | .............................. |

## B.1.2 Questionnaire for Study 2

The questionnaire used in study 2 of “Influence of Real-World Backgrounds on the Perception of AR Visualizations”.

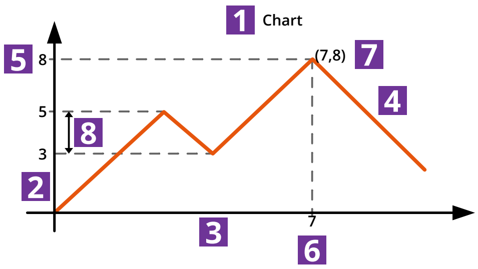


**Fig. B.1.:** A question in S2, where we asked the participants to fill in the blank values (numbered from 1-8). We provided the following list of terms that the participants had to assign to one of the blanks: **(1)** line, **(2)** x-axis, **(3)** y-axis, **(4)** line, **(5)** x-value, **(6)** y-value, **(7)** data point, **(8)** value range.

## Pre-Study: Demographic Questionnaire

| | |
|---|---|
| Gender | .............................. |
| Height | .............................. cm |
| Age | .............................. years |
| Highest level of education | .............................. |
| Activity/field of study | .............................. |
| Do you need visual aid? | ☐ Yes ☐ No |
| If so, are you currently wearing them? | ☐ Yes, glasses ☐ Yes, contact lenses ☐ No aid |
| Do you have color vision deficiency? | ☐ Yes ☐ No |
| Do you have a limitation of spatial perception? | ☐ Yes, .............................. (specify) ☐ No |
| Do you have a limitation of movement? | ☐ Yes, .............................. (specify) ☐ No |
| Fill in the following terms with their corresponding numbers in the boxes of the diagram. | see Fig. B.1. |

| | 1 Non / Never | 2 | 3 Occasional Use | 4 | 5 Daily Use |
|---|---|---|---|---|---|
| How often have you had experiences with Augmented Reality in general, e.g., on smartphones (Pokemon Go, etc.), Nintendo 3DS, ...? | ☐ | ☐ | ☐ | ☐ | ☐ |
| How often have you had experience with head-mounted displays (e.g., HoloLens) for Augmented Reality? | ☐ | ☐ | ☐ | ☐ | ☐ |
| How often have you had experiences with Virtual Reality (e.g., Oculus Rift, HTC Vive)? | ☐ | ☐ | ☐ | ☐ | ☐ |
| How often do you work with different visualization types (e.g., line, bar, or pie charts) to analyze data? | ☐ | ☐ | ☐ | ☐ | ☐ |

## Pre-Study: Health Condition before the Study

| Your physical condition at this moment. | 1<br>Not at all | 2 | 3<br>Medium | 4 | 5<br>Greatly |
|---|---|---|---|---|---|
| How tired/fatigued are you? | ☐ | ☐ | ☐ | ☐ | ☐ |
| How concentrated are you? | ☐ | ☐ | ☐ | ☐ | ☐ |
| How motivated are you? | ☐ | ☐ | ☐ | ☐ | ☐ |
| Do you have headaches? | ☐ | ☐ | ☐ | ☐ | ☐ |
| How dry or irritated are your eyes? | ☐ | ☐ | ☐ | ☐ | ☐ |

## Post-Condition: Health Condition

| Your physical condition at this moment. | 1<br>Not at all | 2 | 3<br>Medium | 4 | 5<br>Greatly |
|---|---|---|---|---|---|
| How tired/fatigued are you? | ☐ | ☐ | ☐ | ☐ | ☐ |
| How concentrated are you? | ☐ | ☐ | ☐ | ☐ | ☐ |
| How motivated are you? | ☐ | ☐ | ☐ | ☐ | ☐ |
| Do you have headaches? | ☐ | ☐ | ☐ | ☐ | ☐ |
| How dry or irritated are your eyes? | ☐ | ☐ | ☐ | ☐ | ☐ |

What impact did the study have on your health condition in comparison to before the study took place? ..............................

## Post-Condition: Visualization and Background Perception

| | 1<br>do not agree | 2 | 3<br>partly agree | 4 | 5<br>agree |
|---|---|---|---|---|---|
| The presentation of the visualization in a real environment irritated me. | ☐ | ☐ | ☐ | ☐ | ☐ |
| The real background did not affect me. | ☐ | ☐ | ☐ | ☐ | ☐ |
| I was able to suppress the real background. | ☐ | ☐ | ☐ | ☐ | ☐ |

To what extent did you notice the background while working on the task? ..............................

To what extent have particular areas or features of the background caused you problems? ..............................

| How much did the background affect your perception of .........? | 1<br>not at all | 2 | 3<br>moderate | 4 | 5<br>very |
|---|---|---|---|---|---|
| Lines | ☐ | ☐ | ☐ | ☐ | ☐ |
| Axis Labels | ☐ | ☐ | ☐ | ☐ | ☐ |

**Post-Study: Tasks and Backgrounds**

| The additional observation of the colored numbers in the background has ……… | 1<br>not at all | 2 | 3<br>moderate | 4 | 5<br>very |
|---|---|---|---|---|---|
| made it difficult for me to solve the task. | ☐ | ☐ | ☐ | ☐ | ☐ |
| made me take longer to answer the questions. | ☐ | ☐ | ☐ | ☐ | ☐ |
| made the answers to the questions more imprecise. | ☐ | ☐ | ☐ | ☐ | ☐ |
| took a large part of my attention/concentration. | ☐ | ☐ | ☐ | ☐ | ☐ |
| made me suppress the background harder. | ☐ | ☐ | ☐ | ☐ | ☐ |

| | |
|---|---|
| How did you approach the tasks? | .............................. |
| What details made it difficult for you to solve the tasks? | .............................. |
| To what extent did these details make the solving difficult? | .............................. |
| Were there any other influences that bothered you in the study environment? | .............................. |
| If there were influences, to what extent did these other influences bother you? | .............................. |
| Which background did you tend to notice when answering the questions? | .............................. |
| Why did you choose the specified background? | ☐ Algae Reactor ☐ Module Combination |
| Any other comments? | .............................. |

## B.2 Tasks

Both studies asked the participants to solve tasks based on line charts. The questions used in study 1 and study 2 can be found in Tab. B.1 and Tab. B.2, respectively.

| Block | Task Nr. | Task Type | Question |
|---|---|---|---|
| 1 | 1 | Find Extremum | At which X-value is the highest Y-value? |
| | 2 | Retrieve Value | What is the Y-value at that X-value? |
| | 3 | Find Extremum | At which X-value lies is the fourth smallest Y-value? |
| | 4 | Derive Value | What is the Y-value difference between those two mentioned values? |
| 2 | 1 | Find Anomalies | At what X lies an outlier point? |
| | 2 | Retrieve Value | What is the Y-value at that X-value? |
| | 3 | Retrieve Value | What is the smallest Y-value of this line? |
| | 4 | Filter | How many lines have a smaller Y-value than the last mentioned Y-Value? |
| 3 | 1 | Filter | How many lines have a Y-value higher than 45? |
| | 2 | Determine Range | What is the Y-value range for those lines? |
| | 3 | Derive Value | What is the average Y-value for all Y-values of those lines? |
| 4 | 1 | Filter | How many lines have at least three Y-values smaller than 35? |
| | 2 | Find Extremum | At what X-value is the highest Y-value of those lines? |
| | 3 | Retrieve Value | What is the Y-value at that X-value? |
| | 4 | Derive Value | What is the average Y-value for all Y-values of all lines? |

**Tab. B.1.:** The tasks used in study 1. Each question is connected to one low-level analysis task [AES05]. In this study, a total of 15 questions distributed over four blocks were presented.

| Block | Task Nr. | Task Type | Question |
|---|---|---|---|
| 1 | 1 | Filter | Which lines have at least 3 Y-values between 5 and 10? |
| | 2 | Find Extremum | At what X-value is the highest Y-value of the selected lines? |
| | 3 | Retrieve Value | What is the Y-value at that X-value? |
| | 4 | Derive Value | What is the average Y-value of the line the last Y-value was selected from? |
| 2 | 1 | Sort | What is the descending order of all lines according to their highest Y-value? |
| | 2 | Retrieve Value | What is the Y-value of the highest line in the sorting at 24? |
| | 3 | Compare | Of the two highest lines of the sorting, which has the smaller average Y-value? |
| | 4 | Determine Range | Of the two smallest lines of the sorting, what is their Y-value range? |
| 3 | 1 | Cluster | At what X-value is the distance of all lines to each other the smallest? |
| | 2 | Derive Value | What is the difference between the highest and the smallest Y-value at that X-value? |
| | 3 | Retrieve Value | From the line with the highest Y-value at that X-value, what is its lowest Y-value? |
| | 4 | Compare | Lies the mentioned Y-value lower than the average Y-value of all lines? |

**Tab. B.2.:** The tasks used in study 2. Each question is connected to one low-level analysis task [AES05]. In this study, a total of 12 questions distributed over three blocks were presented.

# Appendix for Chapter 5 (Study Material)

# C

This appendix provides supplementary material for the conducted user studies described in Ch. 5. This material includes the questionnaires (Sec. C.1) and the content elements presented (Sec. C.2) used in both studies.

## C.1 Questionnaires

Study 1 was structured along different interview blocks (Sec. C.1.1). A pre-study questionnaire (Sec. C.1.2) was also provided. In study 2, another questionnaire (Sec. C.1.3) was used across the conditions.

### C.1.1 Interview Script for Study 1

Study 1 was structured along an interview script focusing on different aspects of the potential use of ceiling and floor. Following, those interview blocks (IB) will be presented:

**IB1: Relationship distance to content type and information density**
Different content types can be displayed on the two surfaces. First of all, we want to get a feeling for the influence of distance on the perception of the content and the role played by the information density. Test out the application. After that, we have some questions for you.

| Question Nr. | Question |
|---|---|
| 1.1 | What differences do you notice between the content elements in terms of the maximum distance at which you can still perceive or work with the content?<br>• Why do you perceive them differently?<br>• What do you think distinguishes the individual content types? |
| 1.2 | Which of the content elements do particularly well on the ceiling? |
| 1.3 | Is it the same on the floor? |
| 1.4 | Do you prefer one of the two placement areas?<br>• If so, why? |

### IB2: Relationship of distance to public and personal content

Six different content elements have already been presented. Some of them are only intended for you (e.g., message notification), while others could also be generally available in an environment (e.g., the supermarket floor plan). Does the distance also have an influence on this perception?

| Question Nr. | Question |
|---|---|
| 2.1 | Do you recognize a distance threshold for personal?<br>• Where is it located? |
| 2.2 | Does the classification of public and personal depend on the placement area?<br>• If so, can you define this difference? |
| 2.3 | Which of the two placement areas do you prefer for public or personal content right now?<br>• Why? |

### IB3: Other properties for public and personal content

Personal and public content can be distinguished not only by the distance, but also by other characteristics.

| Question Nr. | Question |
|---|---|
| 3.1 | How should personal and public content be distinguished from each other?<br>• How about visually, with e.g., border, color, ... ? |
| 3.2 | One variant to distinguish the two content types is the billboarding functionality, which aligning the objects to your position. We have prepared a scene to test this out. We invite you to walk through the room. Some of the content you see now has billboarding enabled. For which elements and in which situations do you find billboarding helpful?<br>• Always and for all elements/for example? Triggered by proximity? Or gaze? only content with text? |
| 3.3 | Does billboarding draw unwanted attention in the sense of being distracting/ perceived as disruptive?<br>• How do you feel about it? How would you imagine it in public space? |

### IB4: Relationship of posture to general perception

Now that you've walked around the room, maybe your perception of the virtual content has changed. AR glasses are not only used while sitting, but often also while standing when e.g., maintaining machines or shopping. Now stand at the same position where you were sitting before and use the distance slider in scene 1 again.

| Question Nr. | Question |
|---|---|
| 4.1 | Has your preference for one of the two areas changed or increased based on the posture you were in?<br>• What brought you to this decision?<br>• Proximity/distance? |
| 4.2 | <br>• Running, lying down, kneeling?<br>• Table at which you sit, sitting in a car, supermarket with shelves? |

### IB5: Interaction with content on ceiling and floor

It is not only important to be able to see the content on the ceiling and floor, but also to interact with it.

| Question Nr. | Question |
|---|---|
| 5.1 | Do you find implicit interaction (by looking) sufficient for our design space?<br>• What would you want to interact with in the first place? |
| 5.2 | Would you rather have a different, more direct way of interacting?<br>• Is there a difference between interacting with the ceiling or floor?<br>• If so, which would it be? Foot-based, Proxy-based, . . . |
| 5.3 | Imagine you want to view a more complex content, like the recipe, for a longer time. Would you find the ceiling/floor suitable as a display surface for this? |
| 5.4 | Do you like the idea of information coming down to the eye level as well?<br>• How would you want to trigger this change?<br>• In which cases? |
| 5.5 | In scene 3, we have implemented two interaction variants and would like you to try them out. What do you think of them?<br>• Which one do you like better? |

### IB6: Final questions

Finally, we have some general questions that we like you to answer. Feel free to put down the HoloLens if you like.

| Question Nr. | Question |
|---|---|
| 6.1 | For which functionalities could you also imagine to use the ceiling and floor?<br>• What do you think of, e.g., Storage of information, . . . |
| 6.2 | The ceiling and floor are currently mainly for secondary content. Could you imagine it for primary activities like data analysis as well?<br>• Are there other primary activities you would like to be supported? |
| 6.3 | How would you assess the influence of ergonomics while using the HoloLens for content on the ceiling and floor?<br>• Is there a difference between both areas?<br>• Is it dependent on the device?<br>• Dependent on viewing duration? |
| 6.4 | What (other) problems do you see with the use of the ceiling and floor?<br>• Dark Pattern?<br>• Out-of-View? |

## C.1.2 Questionnaire for Study 1

The questionnaire used in study 1 of “Understanding AR Content Placement on Ceiling and Floor”.

## Pre-Study: Demographic Questionnaire

| | |
|---|---|
| Gender | .............................. |
| Height | .............................. cm |
| Age | .............................. years |
| Highest level of education | .............................. |
| Activity/field of study | .............................. |
| Do you need visual aid? | ☐ Yes ☐ No |
| If so, are you currently wearing them? | ☐ Yes, glasses ☐ Yes, contact lenses ☐ No aid |
| Do you have color vision deficiency? | ☐ Yes ☐ No |
| Do you have a limitation of spatial perception? | ☐ Yes, .............................. (specify) ☐ No |
| Do you have a limitation of movement? | ☐ Yes, .............................. (specify) ☐ No |

| | 1 Non / Never | 2 | 3 Occasional Use | 4 | 5 Daily Use |
|---|---|---|---|---|---|
| How often have you had experiences with Augmented Reality in general, e.g., on smartphones (Pokemon Go, etc.), Nintendo 3DS, ...? | ☐ | ☐ | ☐ | ☐ | ☐ |
| How often have you had experience with head-mounted displays (e.g., HoloLens) for Augmented Reality? | ☐ | ☐ | ☐ | ☐ | ☐ |
| How often have you had experiences with Virtual Reality (e.g., Oculus Rift, HTC Vive)? | ☐ | ☐ | ☐ | ☐ | ☐ |

## Pre-Study: Health Condition before the Study

| Your physical condition at this moment. | 1 Not at all | 2 | 3 Medium | 4 | 5 Greatly |
|---|---|---|---|---|---|
| How tired/fatigued are you? | ☐ | ☐ | ☐ | ☐ | ☐ |
| How concentrated are you? | ☐ | ☐ | ☐ | ☐ | ☐ |
| How motivated are you? | ☐ | ☐ | ☐ | ☐ | ☐ |
| Do you have headaches? | ☐ | ☐ | ☐ | ☐ | ☐ |
| How dry or irritated are your eyes? | ☐ | ☐ | ☐ | ☐ | ☐ |

## Post-Study: Health Condition after the Study

| Your physical condition at this moment. | 1 Not at all | 2 | 3 Medium | 4 | 5 Greatly |
|---|---|---|---|---|---|
| How tired/fatigued are you? | ☐ | ☐ | ☐ | ☐ | ☐ |
| How concentrated are you? | ☐ | ☐ | ☐ | ☐ | ☐ |
| How motivated are you? | ☐ | ☐ | ☐ | ☐ | ☐ |
| Do you have headaches? | ☐ | ☐ | ☐ | ☐ | ☐ |
| How dry or irritated are your eyes? | ☐ | ☐ | ☐ | ☐ | ☐ |

What impact did the study have on your health condition in comparison to before the study took place? ..............................

## C.1.3 Questionnaire for Study 2

The questionnaire used in study 1 of “Understanding AR Content Placement on Ceiling and Floor”.

### Pre-Study: Demographic Questionnaire

| | |
|---|---|
| Gender | .............................. |
| Height | .............................. cm |
| Age | .............................. years |
| Highest level of education | .............................. |
| Activity/field of study | .............................. |
| Do you need visual aid? | ☐ Yes ☐ No |
| If so, are you currently wearing them? | ☐ Yes, glasses ☐ Yes, contact lenses ☐ No aid |
| Do you have color vision deficiency? | ☐ Yes ☐ No |
| Do you have a limitation of spatial perception? | ☐ Yes, .............................. (specify) ☐ No |
| Do you have a limitation of movement? | ☐ Yes, .............................. (specify) ☐ No |

| | 1 Non / Never | 2 | 3 Occasional Use | 4 | 5 Daily Use |
|---|---|---|---|---|---|
| How often have you had experiences with augmented reality in general, e.g., on smartphones (Pokemon Go, etc.), Nintendo 3DS, ...? | ☐ | ☐ | ☐ | ☐ | ☐ |
| How often have you had experience with head-mounted displays (e.g., HoloLens) for augmented reality? | ☐ | ☐ | ☐ | ☐ | ☐ |
| How often have you had experiences with virtual reality (e.g. Oculus Rift, HTC Vive)? | ☐ | ☐ | ☐ | ☐ | ☐ |

### Pre-Study: Condition Reflection

| Your physical condition at this moment. | 1 Not at all | 2 | 3 Medium | 4 | 5 Greatly |
|---|---|---|---|---|---|
| How tired/fatigued are you? | ☐ | ☐ | ☐ | ☐ | ☐ |
| How concentrated are you? | ☐ | ☐ | ☐ | ☐ | ☐ |
| How motivated are you? | ☐ | ☐ | ☐ | ☐ | ☐ |
| Do you have headaches? | ☐ | ☐ | ☐ | ☐ | ☐ |
| How dry or irritated are your eyes? | ☐ | ☐ | ☐ | ☐ | ☐ |

### Post-Condition: Health Condition after the Study

This block was repeated after each of the three conditions.

| | |
|---|---|
| Did you have a special procedure for setting the parameters? | .............................. |
| What was your goal while setting the parameters? | .............................. |
| Did the objective or procedure differ depending on the area (ceiling or floor)? If yes, how? | .............................. |

### Post-Study: Health Condition after the Study

| Your physical condition at this moment. | 1<br>Not at all | 2 | 3<br>Medium | 4 | 5<br>Greatly |
|---|---|---|---|---|---|
| How tired/fatigued are you? | ☐ | ☐ | ☐ | ☐ | ☐ |
| How concentrated are you? | ☐ | ☐ | ☐ | ☐ | ☐ |
| How motivated are you? | ☐ | ☐ | ☐ | ☐ | ☐ |
| Do you have headaches? | ☐ | ☐ | ☐ | ☐ | ☐ |
| How dry or irritated are your eyes? | ☐ | ☐ | ☐ | ☐ | ☐ |

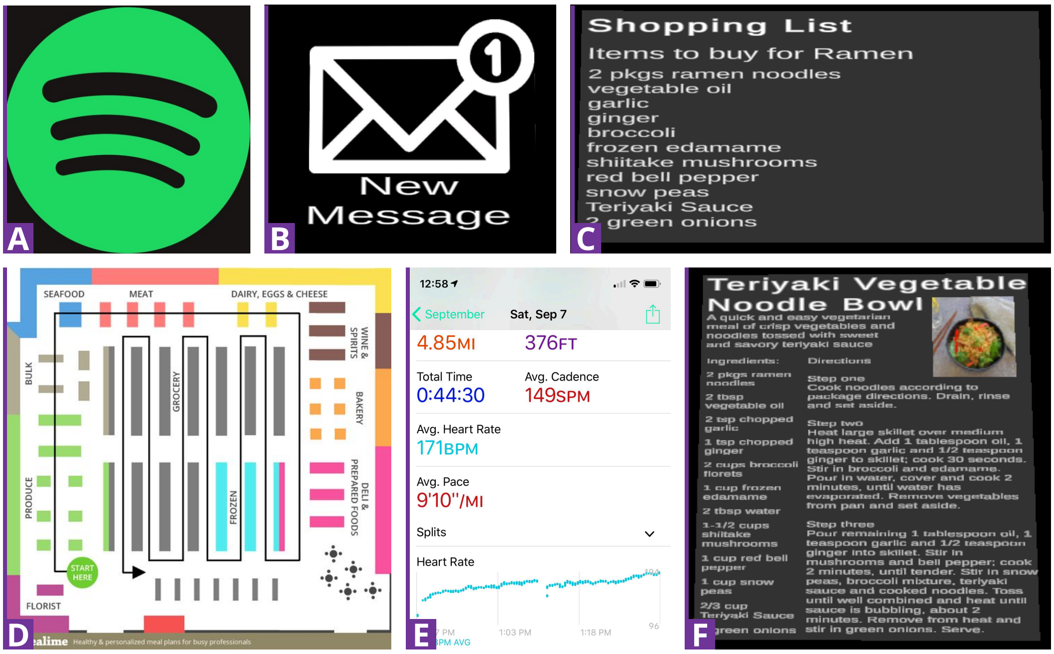
### Post-Study: Parameter and Placement Area Reflection

| | |
|---|---|
| Did your approach or goal change depending on which parameter was not freely adjustable? Or depending on which combination of the three parameters (distance, size, tilt) was adjustable? | .............................. |
| Which parameter was most important for you? Explain why this is the case. | ☐ Distance ☐ Tilt ☐ Size |
| Why did you gave this rating? | .............................. |

| | -3<br>Especially for the ceiling | -2 | -1 | 0<br>Equal for both areas | 1 | 2 | 3<br>Especially for the floor |
|---|---|---|---|---|---|---|---|
| Icons (low information density) | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| Images (medium information density) | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ |
| What is the reason for your preference? | .............................. | | | | | | |

## C.2 Content Elements

In both studies, we showed different content elements to the participants. Those can be found in Fig. C.1 and Fig. C.2, respectively.



Shopping List
Items to buy for Ramen
2 pkgs ramen noodles
vegetable oil
garlic
ginger
broccoli
frozen edamame
shiitake mushrooms
red bell pepper
snow peas
Teriyaki Sauce
2 green onions

12:58
September Sat, Sep 7
4.85MI 376FT
Total Time 0:44:30
Avg. Cadence 149SPM
Avg. Heart Rate 171BPM
Avg. Pace 9'10''/MI
Splits
Heart Rate

Teriyaki Vegetable Noodle Bowl
A quick and easy vegetarian meal of crisp vegetables and noodles tossed with sweet and savory teriyaki sauce

Ingredients:
2 pkgs ramen noodles
2 tbsp vegetable oil
2 tsp chopped garlic
1 tsp chopped ginger
2 cups broccoli florets
1 cup frozen edamame
2 tbsp water
1-1/2 cups shiitake mushrooms
1 cup red bell pepper
1 cup snow peas
2/3 cup Teriyaki Sauce
green onions

Directions

Step one
Cook noodles according to package directions. Drain, rinse and set aside.

Step two
Heat large skillet over medium high heat. Add 1 tablespoon oil, 1 teaspoon garlic and 1/2 teaspoon ginger to skillet; cook 30 seconds. Stir in broccoli and edamame. Pour in water, cover and cook 2 minutes, until water has evaporated. Remove vegetables from pan and set aside.

Step three
Pour remaining 1 tablespoon oil, 1 teaspoon garlic and 1/2 teaspoon ginger into skillet. Stir in mushrooms and bell pepper; cook 2 minutes, until tender. Stir in snow peas, broccoli mixture, teriyaki sauce and cooked noodles. Toss until well combined and heat until sauce is bubbling, about 2 minutes. Remove from heat and stir in green onions. Serve.

**Fig. C.1.:** All content elements used in the first two scenes of S1. The six elements vary in their visual complexity (VC), ranging from **(A)** low to **(F)** high. The content elements show: **(A)** a music app symbole, **(B)** mail notification symbol with text, **(C)** grocery shopping list, **(D)** floor plan for a supermarket, **(E)** fitness data overview with diagram and text, **(F)** a cooking recipe. The content for scene 3 can be seen in the main chapter in Fig. 5.9.

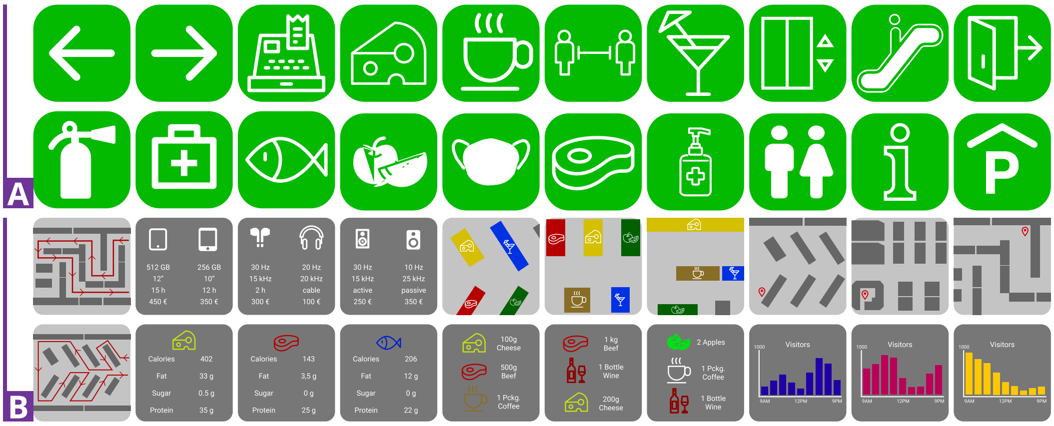


**Fig. C.2.:** All content elements used in S2. The presented content elements differ in their VC. **(A)** shows low while **(B)** shows medium VC content.