Arguably augmented reality : relationships between the virtual and the real

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Part I

What Is Augmented Reality?

1 A First Look

With the advent of augmented reality (AR), virtual content has entered our everyday environment in a profoundly new way. Virtual objects no longer simply appear on the screen of computers, tablets, mobile phones, smart watches, digital information boards, advertisement screens or other displays. Rather, they seem to exist right here, in our physical space, just like real objects do: Wearing a head-mounted display (HMD), virtual, three-dimensional game characters appear to walk on real streets (e.g., Thomas et al., 2000). Looking at the environment through a mobile phone's screen, site-specific information, such as where to find nearby restaurants, metro stops and ATMs appears to be floating through the space in front of us (e.g., *Layar* 2009). Using AR technology, such as the HoloLens headset (Microsoft, n.d.), we can invite virtual characters into our house or turn our living room into the venue of a partially real and partially virtual adventure. With AR, the presence of virtual content in real space has gained a new dimension.

1.1 The Diversity of AR

Augmented reality research and development is usually traced back to 1968, when Sutherland (1968) introduced a head-mounted display (HMD) that allowed users to see both computer-generated images and the real surroundings at the same time.

When Caudell and Mizell (1992) coined the term *augmented reality* in the early 1990s[1], they built on this principle and proposed a heads-up display meant to "augment the worker's visual field of view" (p. 660) by overlaying virtual content onto the worker's view of the real world. Their proposed headset was intended to make the life of assembly and manufacturing workers easier—for instance, by presenting virtual arrows in real space, indicating where to drill (see figure 1.1).

[1] While some sources attribute the term to Caudell and refer to the year 1990 (Chien et al., 2010; K. Lee, 2012) others attribute it to Caudell and his colleague Mizell and refer to the year 1992 (Olsson and Salo, 2011; van Krevelen and Poelman, 2010).

In the meantime, many more researchers and developers have followed the examples of Sutherland (1968) and Caudell and Mizell (1992) and proposed AR systems that integrate computer-generated images into our view of the world by means of a visual display. For instance, the KARMA (Knowledge-based Augmented Reality for Maintenance Assistance) project uses a head-mounted display to superimpose virtual instructions on how to refill the paper tray right

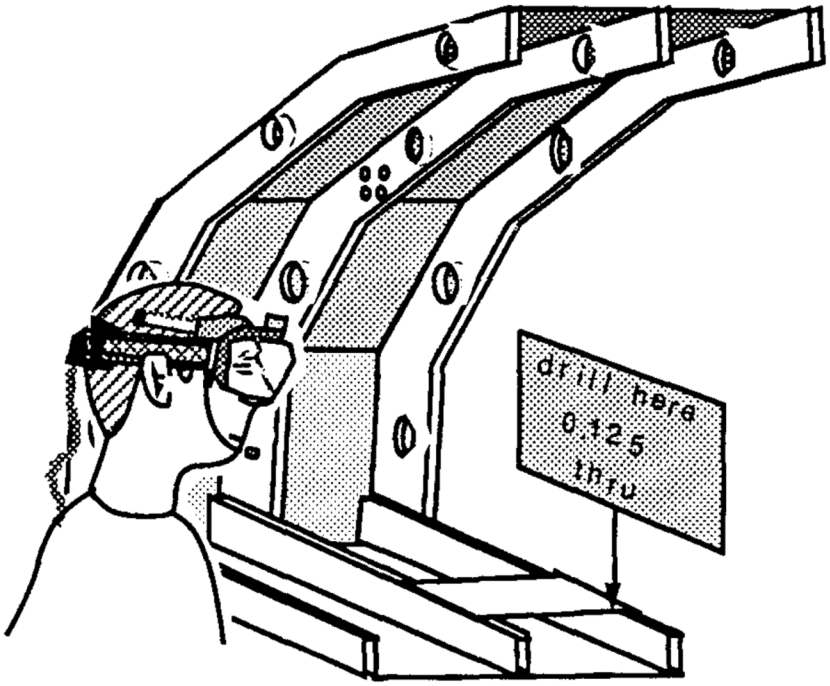

Figure 1.1: Virtual information appears to exist in and extends the real environment. Reprinted from T. Caudell and D. Mizell (Jan. 1992). "Augmented reality: an application of heads-up display technology to manual manufacturing processes". In: *Proceedings of the Twenty-Fifth Hawaii International Conference on System Sciences*. Vol. 2. IEEE, pp. 659–669. Reprinted under fair use.

onto the office printer (Feiner, Macintyre, et al., 1993). The AR version of the popular computer game Quake displays game characters in the real environment (Piekarski and Thomas, 2002; Thomas et al., 2000) by means of an HMD. Looking through an iPhone or iPad, the app Sphero turns a robot ball into a visual virtual beaver (*Sphero* 2011). In the MagicBook project, virtual 3D scenes come alive on the pages of a physical book when the book is viewed through special hand-held glasses (Billinghurst, Kato, and Poupyrev, 2001).

However, not everyone has taken the concept of "augment[ing] the worker's visual field of view with useful and dynamically changing information" (Caudell and Mizell, 1992, p. 660) so literally. Various so-called augmented reality applications approach AR more broadly. To mention just a few examples: The Disney Research team has used weak electric signals that are injected on the user's body to create a tactile-based form of AR that allows participants to feel virtual textures when running their fingers over real physical objects (Bau and Poupyrev, 2012). Visiting a museum, augmented reality audio guides can inform us about the art pieces we encounter by playing back matching pre-recorded sound-files when a visitor is close to certain artworks (Bederson, 1995). Looking at the environment through our phone's screen, we can see overlays of historic photographs (as opposed to 3D computer-generated objects), showing us how the area used to look like a long time ago (*Museum of London: Streetmuseum* 2014). Furthermore, in so-called *spatial augmented reality*, virtual con-

tent is integrated into the real world directly (rather than superimposed onto a participant's view) and, for instance, seemingly transforms the physical architecture of buildings by means of projections (e.g., Valbuena, 2008).

In addition, various AR projects use multi-sensory rather than solely visual displays. For instance, the MetaCookie headset (Narumi, Kajinami, et al., 2010a; Narumi, Nishizaka, et al., 2011b) not only changes the visual appearance of a neutral cookie into the appearance of a specific cookie (e.g. a chocolate flavored, almond or cheese cookie) but also presents the user with the matching olfactory information. (Reportedly, this can alter the taste of the cookie). Also, researchers have explored using force feedback devices such as the Phantom in order to give a tangible dimension to virtual visual objects (e.g., Bianchi et al., 2006).

By now, a wide variety of so-called AR applications exists. In many ways, these projects could not be more diverse. They make use of a broad variety of different technologies, such as headsets, projectors, headphones and tactile displays. In line with this, they present different kinds of sensory stimuli, like visuals, sounds and scents and provide various types of virtual content, among which textual information, photographs and sound recordings. They alter our experience of the real world in various ways; for instance, by seemingly removing physical objects from our view or by integrating additional elements into it. They are designed for many different contexts, such as work, entertainment and education. Accordingly, they serve a variety of purposes. For instance, some AR apps are here to inform us about our surroundings while others exist to keep us entertained.

On first sight, it is rather unclear what the various projects that go under the term *augmented reality* have in common. On the one hand, there seems to be a distinct group of projects that use technologies that overlay virtual content onto a participant's view, making it appear as if this content existed in real space rather than on a screen. On the other hand, there is a diverse group of projects that deviate from this principle, suggesting that there is more to AR. In their totality, the different forms of AR provide a rather blurry picture of AR that raises the questions: *"What is augmented reality?"* and *"What forms can AR take?"*. In this thesis, we address these questions and explore the fundamental characteristics, underlying principles and potential manifestations of AR.

1.2 *Introduction to the Thesis*

This thesis is about augmented reality (AR). AR is commonly considered a technology that integrates virtual images into a user's view of the real world. Yet, this thesis is not about such technologies themselves. Why is that?

We believe that a technology-based notion of AR is incomplete. In this thesis, we challenge the technology-oriented view, provide new perspectives on AR and argue for a different understanding. To be precise, we depart from widespread definitions of AR in three complementary ways.

First, we do not view AR as a technology. Instead, we claim that AR technology enables augmented reality. In this work, we focus on the resulting augmented reality environments, scenarios and experiences rather than on the technologies that enable them.

Secondly, we treat AR as a modalities-encompassing (not only visual) phenomenon and argue that AR engages all our senses. Instead of focusing on what a user or participant *sees*, we focus on non-visual and multimodal aspects of AR.

Third, we view AR as a result of the relationships between the virtual and the real. Whereas AR is generally assumed to involve the spatial integration of virtual content in (a participant's view of) the real world, we believe that other types of relationships between the virtual and the real are possible, potentially leading to other and new forms of AR.

In this thesis, we combine these different points of departure. We approach AR from a fundamental, conceptual, technology-independent, experience-focused, human-centered, modalities-encompassing view and explore the various relationships between the virtual and the real.

By approaching AR from this point of view, we create an unusually broad and diverse image of what AR is, or arguably could be. We learn about the fundamental characteristics of AR and the many possible manifestations it can take, including many forms that do not involve a technology that integrates virtual content in (our view of) the world.

1.2.1 Aim

The aim of this thesis is twofold, *theoretical* and *practical*. On the theoretical side, we strive for a better understanding of what augmented reality is and encompasses. On the practical side, we aim at facilitating, creating and exploring new forms of AR. In particular, we are interested in novel forms of AR that do not imitate reality but provide truly new experiences and interactions that have no equivalent in a purely physical world.

Both the practical and the theoretical aspects of this thesis serve a *fundamental* purpose: They address the underlying question of what AR is and what (else) it can be. More specifically, both address the various relationships between the virtual and the real that shape AR experiences.

This thesis fills a gap in existing AR research, which often either aims at (1) creating or improving AR systems *technologically* or (2) re-

alizing and exploring specific AR *applications*. For instance, there is plenty of research into technologies and techniques that enable or support the integration of virtual objects in our view of the real physical world, such as tracking or calibration techniques (cf. Zhou, Duh, and Billinghurst, 2008). In contrast, our research aims at advancing AR from a fundamental, experience-focused and conceptual, rather than applied or technological perspective. In line with this, technological aspects, such as tracking, fall out of the scope of this thesis. We are not so much interested in how things *are* or what a system does, but primarily interested in the perceptual result—in how things *appear* and what a participant can do, feel, see, hear, smell, taste or touch. Likewise, we are interested in the possible *manifestations* of AR, rather than *applications* of AR.

In existing technological and applied AR research, it is custom to talk about a *user* of AR. As we approach AR in a much broader and freer context, we speak of a *participant* who experiences and acts in AR, rather than a *user* who operates an AR system.

This thesis argues for a new and broader understanding of AR. However, our goal is to provide an *additional* and *complementary* perspective, rather than an *alternative* perspective.

While it might seem as if we aim to *define* the *term* AR, the primary focus of this thesis is not concerned with *terminology* and how the term is or should be used, but on actual AR experiences and scenarios. The question is not so much whether something should be called AR or not, but rather, what forms AR can take.

1.2.2 *Motivation*

Why are we so interested in learning about what AR is and can be? Our main motivation to answer these questions is personal curiosity. In our opinion, fundamental research does not need to be motivated or justified by any reason other than a researcher's desire to know or learn something about the world. However, this does not mean that we do not see any potential benefits of answering these questions. Most importantly, we believe that a better theoretical understanding of AR will inform AR research and practice and lead to novel manifestations of AR. In this regard, our work is motivated by the belief that current AR research and development is adopting an unnecessarily narrow view, and thus might be missing out on exciting opportunities. We hope to free practitioners and researchers alike from restricting ideas, such as the association of AR with *visual* overlays, and thereby inspire and facilitate new and different forms of both AR and AR research. Furthermore, we believe that in order to work and communicate in such a complex field as AR, we have to be able to clearly identify and single out specific forms of AR. We are convinced that a thorough theoretical understanding and an accurate definition will be beneficial

for related scientific disciplines that work with AR, such as medical and educational research.

In addition to the scientific and practical relevance of answering these questions, we are motivated by the social relevance of studying AR. Augmented reality plays an ever-increasing role in our everyday world, and we believe it is important to understand a phenomenon that has the potential to affect (or, as we will argue, *already* affects) our everyday lives.

1.2.3 Methodology

In order to learn more about the fundamental characteristics and possible manifestations of AR, we follow a multidisciplinary, topic-oriented, human-centered, partially practical, partially theoretical, philosophical, argumentative and most of all exploratory approach.

Multidisciplinary and Topic-oriented

This thesis is multidisciplinary in the sense that it draws from and contributes to many domains. The thesis follows the approach of "topic-oriented scholarschip" as defined by van Duijn (2016, p. 19):

> [...] it takes a topic as its starting point and then seeks for the right combination of methods and expertise across multiple disciplines for approaching it, instead of starting from the set of questions and assumptions customary in a particular discipline. Thereby, it aims at making progress not just by contesting existing findings, but also by adding new perspectives on these findings.

Accordingly, our research takes the topic "augmented reality" as a point of departure, and consequently incorporates knowledge and methods from different disciplines, such as engineering, philosophy, perception research, human-computer interaction and media studies in order to gain a better and multifaceted understanding of what AR is and potentially can be. Furthermore, we provide new perspectives on the topic. In particular, we approach augmented reality from a technology-independent, experience-focused, human-centered and modalities-encompassing perspective.

We have chosen for such a broad and multidisciplinary approach because augmented reality is a highly diverse and multidisciplinary research field. For instance, the primary AR conference ISMAR (International Symposium on Mixed and Augmented Reality) regularly featured both a "*Science and Technology*" track as well as a *"Media, Art, Social Science, Humanities and Design"* track).[2] In line with this, existing AR research combines, draws from and contributes to various technological research areas, such as engineering, computer vision, display development, human-computer interaction, wearable, ubiquitous and mobile computing, software engineering and information visualization. At the same time, it is a topic of interest in areas such as media

[2] These two tracks were offered as the two main tracks from 2009 until 2015. The "Media, Art, Social Science, Humanities and Design" first appeared under the name *Arts, Media, and Humanities*. In 2016, it was no longer offered as a second track, but instead took the form of a workshop.

art, design, psychology, communication studies, visual studies, media studies and philosophy.

When it comes to *applications* of AR, an even wider variety of disciplines is involved. Among others, AR has applications in areas such as medicine, manufacturing and education (for an overview, see, e.g., Azuma, 1997). Accordingly, many actual AR projects that we can study to learn about AR have been realized in the context of other research fields or in collaboration with other disciplines. In this thesis, we do not limit ourselves to research, projects or methods from one specific discipline or research direction, because we want to get an overview of the various possible manifestations of AR. This means that examples from a diverse range of domains are considered and included based on whether they reveal insights about what AR is and can be. However, as the focus of this thesis is on the possible AR *manifestations* rather than *applications*, we do not aim to give a comprehensive overview of AR applications. To some extent, we focus on art and entertainment examples (e.g., games). We do this for two reasons. First of all, because this thesis is realized in an art context. More specifically, this research is partially conducted at the Augmented Reality Lab (AR Lab) at the Royal Academy of Art, The Hague, where the author has a guest research position. This lab focuses, among others, on exploratory research in the artistic domain.[3] Secondly, we explore art and entertainment applications because we expect these to focus more explicitly on AR *experiences*. This, however, does not mean that other domains or disciplines were deliberately excluded. At times, the same examples are used repeatedly, to illustrate different points about AR.

[3] Unfortunately, the AR Lab has been closed in 2014.

Theoretical and Practical Research

As mentioned, our study has a theoretical and a practical aim. In line with this, we approach AR both from a practical as well as from a theoretical perspective.

Our theoretical approach includes a review of existing research literature as well as the use of arguments and ideas in order to arrive at a new and better understanding of what AR is and potentially can be. Regarding existing literature, we focus on influential views and descriptions of AR projects that have shaped current understandings of AR. Furthermore, we also pay attention to less common or commonly overlooked literature and AR projects.

In addition to this theoretical study, we also follow a practical approach. This involves actively engaging with existing AR projects, such as the mobile app "Pokémon GO" (*Pokémon GO* 2016) and, more importantly, building our own AR projects. This approach is used to arrive at new ideas and concepts for novel forms of AR. Furthermore, our practical approach is motivated by the belief that "by doing and creating, new scientific insights into the underlying question are encountered." (Media Technology MSc Programme - Leiden University,

n.d.).[4] We believe that creating our own AR scenarios (potentially) results in additional realizations about what AR is and what forms it can take. With respect to the practical exploration, we draw from our own *first-person experience*. Due to the constraints in time, experiments with participants are out of the scope of this thesis.

With respect to the practical aspects, we build upon our experience in the field of Human-Computer Interaction research. Practical projects in this research are—as far as possible—realized with cheap everyday technology rather than typical or special AR equipment (e.g., we use our normal office computer, a webcam and a monitor to test ideas rather than a head-mounted display). Furthermore, projects are realized in a prototypical manner.

[4] This idea is at the basis of the Media Technology program at Leiden University, where this research was carried out.

A Philosophical Approach

We believe that AR is more than just a technology that integrates virtual imagery into our view. Yet, our point of departure is not so much a hypothesis we can test objectively, rather than it is an attitude towards AR and an open question: What does AR entail if we broaden existing definitions and approach AR from a human-centered, technology-independent, modalities-encompassing and relationship-focused perspective? In other words, we are looking for a better understanding of what AR is and potentially can be, and are not concerned with testing an overreaching hypothesis.[5] Because we are interested in the qualities, fundamental characteristics and potential manifestations of AR, we have chosen an exploratory research approach.

[5] However, this does not mean that we have no assumptions or hypotheses at all. For instance, we address the assumptions that virtual objects do not have to behave like real objects in order to appear as a believable part of real space (see chapter 5).

Although our research is interested in the *qualities* of AR, our research approach does not incorporate common qualitative research methods such as focus groups, interviews and participant observation. Instead, it approaches the topic of AR in a rather playful manner. In terms of existing methods, our approach could best be described as *philosophical*. This is because our investigation into AR is driven by reasoning, and uses the instruments of what Sheffield (2004) calls "The Philosopher's Toolbox": we *analyze*, *clarify* and *criticize*. More specifically, we analyze the field of augmented reality with the goal of identifying defining characteristics, criticize existing notions of AR and clarify what else AR is and potentially could be. Moreover, our research shows similarities to dialectic research, which also often aims at developing new understandings rather than at testing hypotheses (Dialectical research, n.d.). Also, like dialectic investigation, we work "with arguments and ideas, rather than data" and examine competing notions and perspectives (Dialectical research, n.d.).

While our methods could be considered philosophical, we would like to emphasize that we do not view this work as philosophy. Likewise, the author does not see herself as a philosopher. Although the term 'augmented reality' might invite this, a philosophical discussion of the nature of reality is out of the scope of this thesis.

Aside from similarities with philosophical research, our research shares qualities with human-computer interaction (HCI) research, which also often incorporates a *human-centered* approach and focuses on the human experience. However, in contrast to much HCI research, we do not tie a human-centered approach to usability. Also, whereas *experience* is often addressed in the context of *User Experience (UX)* when it comes to new technologies, we deliberately do not focus on UX. Instead, we focus on the unique characteristics of AR experiences.[6] Our human-centered approach entails that we ask how things appear to the participant, that we question what a participant perceives and what a participant can do. We do focus on these aspects because we believe that AR is created *for humans*, with the goal of creating certain perceptual results and enabling certain experiences, rather than for technological purposes. It hence seems natural and necessary to look at AR experiences in order to understand the essence of AR.

[6] We would like to direct readers with an interest in UX to the seminal paper "User experience - a research agenda" by Hassenzahl and Tractinsky (2006).

A Cartographic Process

The nature of this research can be best summarized as exploratory. In a metaphorical way, it can be compared to a cartographic process. It explores the "AR landscape" in the hope of discovering "new places", but also with the goal to learn more about "known spaces" by looking at them from new perspectives. Furthermore, it re-evaluates where the lines between AR and other disciplines ought to be drawn and proposes a broader, more encompassing understanding of AR.

Limitations

This thesis does not focus on AR systems and technologies, but on the various forms AR can take, the different relationships between the virtual and the real that shape AR, and the many experiences that AR systems enable.

One limitation of this research is that our observations are based on our own, subjective experiences of AR. Of course, our experience might not fully represent how participants in general perceive AR and we cannot rule out the possibility that our experience is influenced by our expectations and beliefs about AR.

While experiments with participants would be desirable, these fall out of the scope of the thesis. This is because in order to systematically conduct experiments with participants, it is crucial to first understand what characterizes AR, and what types of experiments would foster a better understanding. In this regard, our exploratory study can be seen as a first fundamental step towards facilitating more directed experiments with participants in the future.

Another limitation of this research is that we draw from existing AR literature and other media, such as articles and videos rather than from

a first-hand experience of the documented projects. On the one hand, studying such mediated accounts of AR will surely allow us to learn about AR. On the other hand, it is not always possible to make inferences about AR *environments* and *experiences* from studying textual or visual descriptions that focus on other aspects, such as the workings of the *system*. In fact, our own research argues that descriptions of AR systems do not suffice for describing the resulting AR environments and experiences (what happens on a technological level is rather different from its perceptual result and similar systems can create many different environments and experiences). We hence have to be careful not to draw unsound conclusions about AR environments and experiences from such system-focused accounts of AR.

1.2.4 Results

There are two main contributions of this PhD research: On the theoretical side, it provides a better understanding of what augmented reality is and potentially can be. On the practical side, it suggests novel forms of AR.

1.2.5 Structure and Outline

The thesis is organized into three parts that contain seven chapters of varying length. Part 1 address the question *"What is augmented reality?"* and comes to the conclusion that relationships between the virtual and the real are decisive for AR. Part 2 investigates what forms AR can take and explores the relationships between the virtual and the real. Part 3 concludes the thesis, summarizes our results and presents suggestions for future AR research.

Part 1: What Is Augmented Reality?

Part 1 serves an introduction to the topic of augmented reality and addresses the question *"What is augmented reality?"*. We have a look at so-called AR applications, at definitions and descriptions and present our own perspective on AR.

In this chapter ("A first look"), we have taken an initial glance at examples of AR and illustrated the diversity of the AR landscape. On the one hand, we have encountered various AR works that use some sort of visual display to present virtual content and make it look as if this content existed in the otherwise real surroundings. On the other hand, we have seen examples that deviate from this typical setup, use different technologies (e.g., projectors or audio players), present us with different content (e.g., sound or tactile sensations) and create different experiences (e.g., alter how a real object feels or how a real cookie tastes). Together, the different examples of AR leave us with a rather blurry picture of the AR landscape and raise the question of

what augmented reality is.

In chapter 2 ("Existing views") we investigate how existing research answers this question. We review existing definitions and descriptions of AR and identify three common and intertwined ideas about augmented reality: First of all, AR is generally considered a technology. Second, AR is widely understood in terms of visual virtual overlays that are presented on top of a participant's view of the real world. Third, AR is considered to spatially align virtual content with the real world in three dimensions. These ideas are not at odds but complement each other well. Together, they draw a clear image of AR as a technology that integrates virtual content into our view of the real world.

At the same time, our review of existing AR literature also reveals many divergent and *broader* understandings of AR. For instance, we encounter research that also considers non-visual virtual content (such as sound) in the context of AR and researchers that explicitly argue against seeing AR as a technology. In addition, we notice that there are a variety of different claims about the qualities of the virtual content, the role of the real world in AR, the role of the user or participant and the question of what is augmented in AR.

In their totality, the partially agreeing and partially contradicting views on AR leave little doubt that AR *can* involve technologies that overlay virtual objects onto a participant's view and aligns them with the real world in 3D. At the same time, we get a strong sense that there is more to AR than such technologies. As such, the review leaves us wondering, what, if not just a technology, AR is or can be.

In chapter 3 ("New Perspectives), we respond to our initial findings, challenge commonly accepted views, and argue for new (or at least different) perspectives on AR. First, we depart from the understanding of AR as a technology. Instead, we claim that AR technology enables augmented reality. We focus on the resulting augmented reality environments and experiences rather than on the technologies that enable them. Second, we treat AR as a multimodal and interactive environment and argue that AR engages all our senses. Instead of focusing on what a user or participant sees, we focus on non-visual, multimodal and interactive aspects of both the real world and virtual content. Third, we see AR as a result of the relationships between the virtual and the real. Whereas AR is generally assumed to involve the spatial alignment of virtual content with the real world in 3D, we believe that other types of relationships between the virtual and the real are possible, potentially leading to other and new forms of AR. These three ideas are synthesized and culminate in our definition of AR as an interactive and multimodal environment where a participant experiences a relationship between virtual content and the real surroundings.

Part 2: What Forms Can AR Take?

Part 1 has identified relationships between the virtual and the real as crucial for AR. Part 2 discusses such relationships and explores what forms AR can take. In chapter 4 ("Relationships between the virtual and the real"), we illustrate the different ways in which the virtual and the real can relate to one another. On a fundamental level, we distinguish between *(1) coexistence* (participants do not experience any link between the virtual and the real), *(2) spatial relationships* (virtual content seemingly exists in real space) and *(3) content-based relationships* (the virtual relates to the real content-wise).

Subsequently, we question how virtual content can affect its real surroundings. Based on the role that the virtual content plays in the real space, we distinguish between five forms of AR:

1. *Extended reality:* scenarios where the virtual supplements the real environment.
2. *Diminished reality:* cases where virtual content seemingly removes real elements from the real environment.
3. *Altered reality:* environments where the virtual information changes the apparent qualities of the real world.
4. *Hybrid reality:* scenarios where the virtual completes a physical environment that would be considered incomplete without the virtual additions.
5. *Extended perception:* cases where unperceivable but real aspects of the real world are translated into virtual information that we can perceive with our senses.

We then focus on scenarios where virtual objects seemingly exist in and extend the real world. We notice that the presence of virtual objects in real space opens up possibilities for influences and interaction between the virtual and the real. On this level, we distinguish among two main forms of relationships between the virtual and the real: *(1) physical relationships*, where the virtual and the real seemingly affect each other physically and *(2) behavioral relationships*, where the virtual and the real sense each other and react to one another on a social or behavioral level.

Subsequently, we briefly discuss other possible relationships, such as temporal relationships between the virtual and the real and musical relationships between virtual and real instruments. We conclude the fourth chapter with a summary, general discussion and reflection.

Chapter 5 ("From Imitative to Imaginative Realities: Influences and Interactions Between the Virtual and the Real") is dedicated to the interaction between the virtual and the real. Based on the fact that virtual objects do not have to adhere to physical laws and cannot directly apply forces to real objects, we ask the following questions: What types

of interaction between the virtual and the real are both possible and believable? We explore (1) whether virtual objects can interact with physical objects in a realistic manner as well as (2) whether they can interact in imaginative but believable ways. In order to answer these questions, we follow both a theoretical and a practical approach. We review existing research and AR works, conduct our own initial series of practical experiments as well as reflect upon these experiments. We present a general discussion and conclude that virtual and real objects can believably simulate real-world influences as well as influence each other in imaginative ways that have no equivalent in the physical world.

Chapter 6 ("Sonically tangible objects") builds on the idea that virtual objects can differ from real objects and hence, also could be perceived differently from how we perceive real objects. In order to explore and illustrates such possibilities, we develop and present a prototype of what we call sonically tangible objects. More concretely, we present a virtual, invisible and non-tactile cube that is placed in a real, physical space. This cube can be experienced through exploratory hand gestures and sonic feedback. Touching the cube with one's fingers triggers binaural sounds that appear to originate from the exact spot where the object is touched. Our initial experimentation suggests that this sound- and movement-based approach can result in tactile-like experiences and convey the presence of virtual objects in real space. We discuss the concept behind, implementation of and our experience with the sonically tangible cube and place our research in a broader context.

Part 3: Conclusion

Part 3 concludes the thesis. It contains the final chapter of the thesis ("Conclusion"). In this chapter (7), we revisit our main questions (*"What is augmented reality?"* and *"What forms can AR take?"*) and reflect on the answers we have arrived at. Furthermore, we address pending questions that have surfaced during this trajectory (e.g., *"What is augmented in AR?"*) and that we can answer now that we have a thorough understanding of existing research, hands-on experience and our own comprehensive theory of AR. In addition, we summarize insights that can guide the design of AR experiences. (E.g., we suggest to incorporate both multimodal virtual content as well as multimodal qualities of the real world when working with AR and emphasize that designers can not only give shape to virtual content but also actively design the relationship between the virtual and the real.) Moreover, we discuss methodological and technological limitations of our study, and present possible directions for future AR research and development. For instance, we suggest researching the concept of believability (*"When is the behavior and appearance of virtual objects in real space believable?"*) and to systematically explore which factors contribute to virtual objects

being experienced as present in real space. Finally, we propose to focus less on mimicking our existing reality, and instead, to create new, imaginative and curious forms of AR that have no counterpart in a purely physical world.

1.2.6 Intermezzi

This thesis contains three intermezzi. These intermezzi are short independent articles about AR. Unlike the rest of this thesis, they are written in an entertaining, informal and personal way that is atypical for scientific publications and they provide a yet different perspective on AR. The included intermezzi have appeared in a slightly different form in the AR[t] magazine, a semi-annual magazine series about augmented reality, art and technology that has been edited by the author during her time has a PhD student.

Intermezzo 1 is a short essay that discusses the idea of audio-augmented reality in the context of going for a run with a mobile training application. Intermezzo 2 discusses the similarities between AR and urban dance and explores the idea of creating the impression of virtual objects existing in real space through movement. Intermezzo 3 is an open letter to media theorist Lev Manovich. It presents and discusses questions that have come up during reading Manovich's 2006 article "The Poetics of Augmented Space" and his 2001 book *The Language of New Media*.

The intermezzi are included in between thesis chapters. They can easily be recognized as they are printed on yellow paper and use a different page layout.

1.2.7 Publications and Collaboration

This thesis takes the form of a monograph rather than the increasingly popular form of an article thesis (also referred to "thesis by publication") that bundles independent research papers. Yet, the thesis is based on and includes material from the following published articles:

- H. Schraffenberger and E. van der Heide (2013a). "From Coexistence to Interaction: Influences Between the Virtual and the Real in Augmented Reality". In: *Proceedings of the 19th International Symposium on Electronic Art (ISEA2013)*. Ed. by K. Cleland et al. Sydney, pp. 1–3.

- H. Schraffenberger and E. van der Heide (2013b). "Towards Novel Relationships between the Virtual and the Real in Augmented Reality". English. In: *Arts and Technology*. Ed. by G. De Michelis et al. LNICST 116. Springer, pp. 73–80.

- H. Schraffenberger and E. van der Heide (2014). "The Real in Augmented Reality". In: *Proceedings of the Second Conference on Com-*

putation, Communication, Aesthetics and X (xCoAx 2014). Ed. by M. Carvalhais and M. Verdicchio, pp. 64–74.

- H. Schraffenberger and E. van der Heide (2014b). "Everything Augmented: On the Real in Augmented Reality". *Journal of Science and Technology of the Arts*, 6(1), pp. 17–29.

- H. Schraffenberger and E. van der Heide (2015). "Sonically Tangible Objects". In: *Proceedings of the Third Conference on Computation, Communication, Aesthetics and X (xCoAx 2015)*. Ed. by A. Clifford et al., pp. 233–248.

- H. Schraffenberger and E. van der Heide (2016). "Multimodal Augmented Reality: The Norm Rather Than the Exception". In: *Proceedings of the 2016 Workshop on Multimodal Virtual and Augmented Reality (MVAR '16)*. ACM, pp. 1–6.

- H. Schraffenberger and E. van der Heide (2018). "Reconsidering Registration: New Perspectives on Augmented Reality". In: *Interactivity, Game Creation, Design, Learning, and Innovation. ArtsIT 2017, DLI 2017*. Ed. by A. L. Brooks et al. LNICST 229. Springer, pp. 172–183.

The following published articles from the AR[t] magazine have been included as intermezzi in a slightly different form in this thesis:

- H. Schraffenberger (Nov. 2012). "Chasing virtual spooks, losing real weight". *AR[t], Augmented Reality, Art and Technology*, 2. Ed. by Y. Kolstee et al., pp. 48–51. URL: http://arlab.kabk.nl/ar-magazines. (Intermezzo 1)

- H. Schraffenberger (May 2014). "Hitting imaginary walls, pulling virtual strings". *AR[t], Augmented Reality, Art and Technology*, 5. Ed. by H. Schraffenberger et al., pp. 66–71. URL: http://arlab.kabk.nl/ar-magazines. (Intermezzo 2)

- H. Schraffenberger (May 2013). "Subject: Interview". *AR[t], Augmented Reality, Art and Technology*, 3. Ed. by H. Schraffenberger et al., pp. 18–23. URL: http://arlab.kabk.nl/ar-magazines. (Intermezzo 3)

As one can see, the scientific articles listed above all have been realized in collaboration with my colleague Edwin van der Heide. During this PhD trajectory, Edwin van der Heide has acted as an unofficial daily supervisor, and this work is strongly shaped by our regular discussions. The scientific articles have largely been restructured, rewritten, adapted and extended to accommodate the book format and to incorporate numerous new and additional insights. An exception is chapter 6, which is largely based on our paper "Sonically Tangible Objects" (Schraffenberger and van der Heide, 2015). Also, the second

half of chapter 5 is strongly based on "From Coexistence to Interaction: Influences Between the Virtual and the Real in Augmented Reality" (Schraffenberger and van der Heide, 2013a).

Although we present this thesis as a book, it is important to us that readers can focus on single chapters that raise their particular interest. In order to make sure the individual chapters are readable independently, some arguments and examples are repeated throughout the thesis. The downside of this approach is that the thesis contains some redundant parts. However, we believe the fact that every chapter can also stand on its own outweighs this disadvantage.

During my time as a PhD student, I was lucky to spend several years as a guest researcher at the AR Lab, which was based at the Royal Academy of Art in The Hague. This collaboration has resulted in the above-mentioned AR[t] magazine—a semi-annual magazine about augmented reality, art and technology that was aimed at the general public. We would like to direct the interested reader to this publication series, which also contains several more articles by the author. The AR[t] magazine publications can be found at http://arlab.kabk.nl/ar-magazines.