TOWARDS THE HUMAN-CENTERED DESIGN OF MIXED REALITY ENVIRONMENTS

THESIS

Submitted in Partial Fulfillment of

the Requirements for

the Degree of

MASTER OF SCIENCE (Integrated Digital Media)

at the

NEW YORK UNIVERSITY
TANDON SCHOOL OF ENGINEERING

by

Shannon Holloway

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Shannon Holloway is passionate about solving complex problems with human-centered design methods. Her experience working in venture capital ignited her interest in innovation and her pivot into a career in user experience design. Shannon has consulted for a range of clients from startups to large corporations. She has lead cross-functional teams to develop UX strategies, define requirements, improve operational processes, and promote knowledge sharing.

Shannon's design abilities are greatly influenced by her background in the arts. She received her BA in the Practice of Art with Honors from the University of California at Berkeley. She was awarded a scholarship to study figure drawing at Otis College of Art and Design. Shannon's paintings have been exhibited at BRIC Arts | Media House, Curate NYC, Worth Ryder Gallery, and Galería Victoria Hidalgo. Her acting and modeling work has been featured on MTV, the Discovery Channel, HBO, and in Petrie Inventory Magazine.

In her career at NYU Tandon School of Engineering, Shannon was awarded a merit-based scholarship for academic excellence. She served as a Studio Lead in Design for America NYU, where her team was awarded a Greenhouse grant from the NYU Prototyping Fund. Shannon was named a 2016-2017 James Dyson Design Leader. She is a member of the Human Factors and Ergonomics Society and the Environmental Design Research Association.

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ABSTRACT

TOWARDS THE HUMAN-CENTERED DESIGN OF MIXED REALITY ENVIRONMENTS

by

Shannon Holloway

Advisor: Dana Karwas

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The line is blurring between our physical and digital worlds. Mixed reality poses new challenges for interactions in both real and virtual worlds. In mixed reality environments, humans interact with real and virtual objects together in context. However the technologies that enable mixed reality are designed for direct user interaction rather than considering the larger context within which a human interacts with a system. A design process focused on human needs in context contributes to more positive user experience outcomes and user acceptance of mixed reality technologies. How might we promote the human-centered design of mixed reality environments?

In this thesis I researched and designed a method for human-centered design in mixed reality environments. I first approached this study using user-centered design methods, literature review, and exploratory interviews in an attempt to compile best practices. My research findings demonstrated that none of the existing methods adequately capture the user needs, people, space, and tools in a user's context to inform the design of mixed reality environments. I ultimately developed a framework for describing the context within which a user interacts with a system. This paper presents two case studies of users in mixed reality environments and application of the Context Map, a lightweight tool for the design process.

Keywords: mixed reality, user context, user experience, human-centered design, design tools

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INTRODUCTION

The line is blurring between our physical and digital worlds. There is a new hybrid existence being created by the proliferation of displays in our real environment and the integration of the real world in virtual environments. Mixed reality is a continuum of environments between completely real environments and virtual ones. Mixed reality poses new challenges for interactions in both our physical and virtual worlds. In mixed reality environments, humans interact with real and virtual objects together in context. However the technologies that enable mixed reality are designed for direct user interaction rather than considering the larger context within which a human interacts with a system. This creates a fragmented user experience and forces users to be split between real and virtual worlds. A design process focused on human needs in context contributes to more positive user experience outcomes and user acceptance of mixed reality technologies. How might we promote the human-centered design of mixed reality environments?

In this thesis I researched and designed a method for human-centered design in mixed reality environments. When I observed the need for contextual user experiences, I first approached this study using user-centered design methods, literature review, and exploratory interviews. My research findings demonstrated that none of the existing methods adequately capture the user needs, people, space, and tools in a user's context to inform the design of mixed reality environments. I ultimately developed a framework for describing the context within which a user interacts with a system. This paper presents two case studies of users in mixed reality environments and application of the Context Map, a lightweight tool for the design process.

BACKGROUND

Mixed Reality Environments

Mixed reality (MR) is a class of environments in which real and virtual objects are presented together with various levels of immersion along a virtuality continuum (Milgram and Kishino 1321). Figure 1 illustrates the range of MR environments which consists of Augmented Reality (AR), where the real world is augmented by virtual objects, and Augmented Virtuality (AV), a predominantly virtual world with real objects. The proliferation of displays in our real environment and the integration of real world objects in virtual environments have blurred the distinction between AR and AV. While the success of AR mobile applications has made AR a familiar term, it describes only one area within the range of MR environments. Therefore the term MR is most relevant in this discussion and includes the variety of environments in the center of the virtuality continuum.

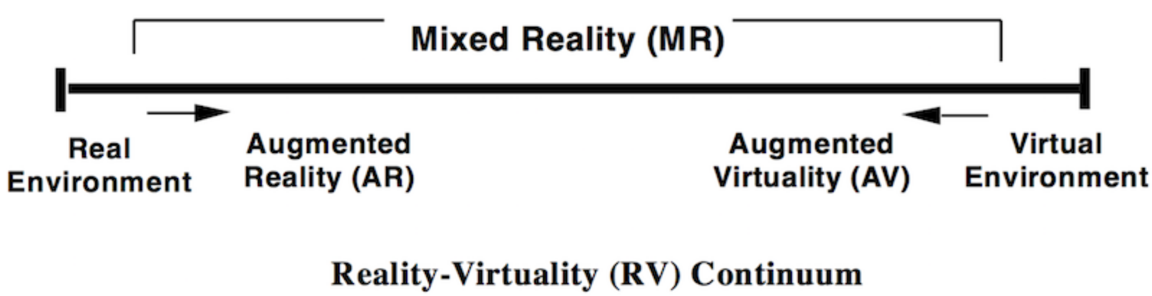


Figure 1. Reality-Virtuality Continuum from Milgram and Kishino, 1994.

The rapid development of technologies enabling MR environments pose new challenges to our interactions in our physical and virtual worlds. MR applications are available on mobile devices and head-mounted displays (HMD) and use a variety of user inputs such as gesture, voice, and gaze. The users' goal is to have seamless interactions between virtual content and the real world surrounding them. MR applications present virtual content in the field of view (FOV) of the user and reveal world-locked content embedded in the real world. While initial demand will be driven by enterprise, it is predicted consumer applications will ultimately take over the market (Azuma 234). Further research is needed to ensure user safety to prevent the occlusion of critical objects in the real world such as traffic signals or stairs (Lebeck et al. 3). It may seem only a matter of time before technological advances and consumer demand will lead to widespread adoption of MR applications. However, their success requires significant research and design efforts to avoid critical usability issues unique to MR environments.

While one vision of MR environments is shaped by particular MR applications on mobile devices and HMDs, another vision assumes computers will dissolve into the world around us. This vision, called ubiquitous computing or pervasive computing, posits "the most profound technologies are those that disappear" (Weiser 94). Ubiquitous computing is becoming a reality enabled by the Internet of Things (IoT). IoT devices are being embedded in environments everywhere to make them "smart" such as smart homes, smart buildings, and even smart cities. These devices have sensors that respond to a variety of user inputs such as voice and locomotion, and are networked with other devices and applications.

Regardless of the technologies enabling MR environments, the new range of input modalities creates a paradigm shift from one-to-one interaction between a human and an interface (Greenfield 16). Inputs such as gesture, voice, gaze, and locomotion provide many opportunities for interactions that are more intuitive than a touchscreen or keyboard. However they also provide more room for breakdowns in communication and user error. Sensing raises new questions as to how a user knows if the system has received and understood a request, is executing a task, or how to undo a mistake (Bellotti et al. 415).

This dramatic shift in interactions not only impacts the relationship between users and systems. These interactions take place in context and will impact the people and environment in that context. Other people in the context can include secondary users, people who occasionally interact with the system or interact through an intermediary (Eason 91). Tertiary users are people who are not directly using the system but are affected by it (Eason 93). There is a gap between the development of digital systems and the physical environments that they will be integrated with. Different teams of people design the digital or physical deliverables, each focused on their own timelines and processes and not the overall user experience in context. An information and temporal gap exists between environmental requirements defined at conception versus the conditions in the implementation environment at runtime. While there is a body of research on the implementation of AR systems in the built environment, there is little research to inform guidelines or evaluate usability in the built environment (Wang et al.

7). The implementation of MR environments is outpacing our understanding of their broader impact on the people and physical space in context.

The Human Factor

The discipline of human factors, also known as ergonomics, focuses on human-artifact interactions from perspectives including science, engineering, design, technology and management (Karwowski 3). The purpose of human factors research and practice is to optimize human well-being and the performance of systems. The history of human factors can be traced to World War II when problems emerged in human interactions with new technologies and studies were conducted to improve performance and safety ("HFES History" 1). Since then, human factors work has been applied to many industrial sectors and contributes to the design of systems, jobs, and environments.

While human factors work includes computers, computers are complex tools with many uses. As early as the 1960s it was recognized that the growing number and diversity of computer users meant that "the need of the future is not so much for computer-oriented people as for people-oriented computers" (Nickerson 178). The complexity of computers lead to the emergence of the specialized field of Human-Computer Interaction (HCI) in the 1980s. The field of HCI includes perspectives from primarily computer science, behavioral sciences, and design.

HCI distinguished itself from human factors by having more theoretical underpinnings and seeking "cognitive coupling" between human and computer (Bannon 44). Cognitive modeling is a predominant method in HCI in which the human mind is likened to an information-processing system (Card et al. 24). Researchers measure human perceptual, cognitive and motor processes in order to design systems compatible with humans. However these approaches are based on models of human behavior and do not capture the diverse needs, levels of expertise, and cognitive and physical abilities of real humans interacting with systems. In contrast, user-centered design (UCD) is a framework for design processes in which end-users are the focus (Norman and Draper 7). Actual users of the system are involved in multiple stages of the design process, from requirements gathering to testing and evaluation. The term human-centered design (HCD) is related and sometimes used interchangeably with UCD. However an important distinction is that HCD considers how humans that are not necessarily end-users are impacted by systems. The people in context should be prioritized and designed for, and dimensions such as gender, race, and class are to be considered (Ritter 43).

The concept of user experience (UX) is defined as “a person's perceptions and responses that result from the use or anticipated use of a product, system or service” (qtd in Stephanidis et al. 1381). However UX is hard to define as it is a person’s subjective experience influenced by a wide range of factors. UX has been accepted by the HCI community in academia and industry as important in system design. The embrace of UX coincides with the third wave of HCI which Bødker described in 2006 recognizes the broader range of application types and contexts of use (Bødker 1). While the second generation focused on workplace settings and rigid guidelines, the third wave includes human-computer interaction in everyday life and in public and private spheres.

The core of UX may be the interactions between a person and a system, but a more comprehensive view of UX goes beyond the transactional:

> "UX is about technology that fulfils more than just instrumental needs in a way that acknowledges its use as a subjective, situated, complex and dynamic encounter. UX is a consequence of a user's internal state (predispositions, expectations, needs, motivation, mood, etc.), the characteristics of the designed system (e.g. complexity, purpose, usability, functionality, etc.) and the context (or the environment) within which the interaction occurs (e.g. organisational/social setting, meaningfulness of the activity, voluntariness of use, etc.)." (Hassenzahl and Tractinsky 95)

It is clear that UX is shaped by a user's context, and arguably all experience is contextual. A user's context includes their internal user needs as well as factors in the social and physical environment surrounding them when they interact with a system. While a group of people can experience together, only individuals have feelings and experiences (Law et al. 726). Therefore the unit of analysis for UX is on the individual level.

UX is a major factor in whether or not people use a system. Figure 2 illustrates how a user's overall attitude toward a system, as a function of the perceived ease of use and usefulness, is critical to user acceptance (Davis 476). UX goes beyond usability to include characteristics that are hard to quantify or predict. For example, a mobile AR application's delivery of content specific to the user context contributes to both perceived usefulness and ease of use (Kourouthanassis et al. 1067). Having a comprehensive understanding of user motivations, goals, and context equips designers with the

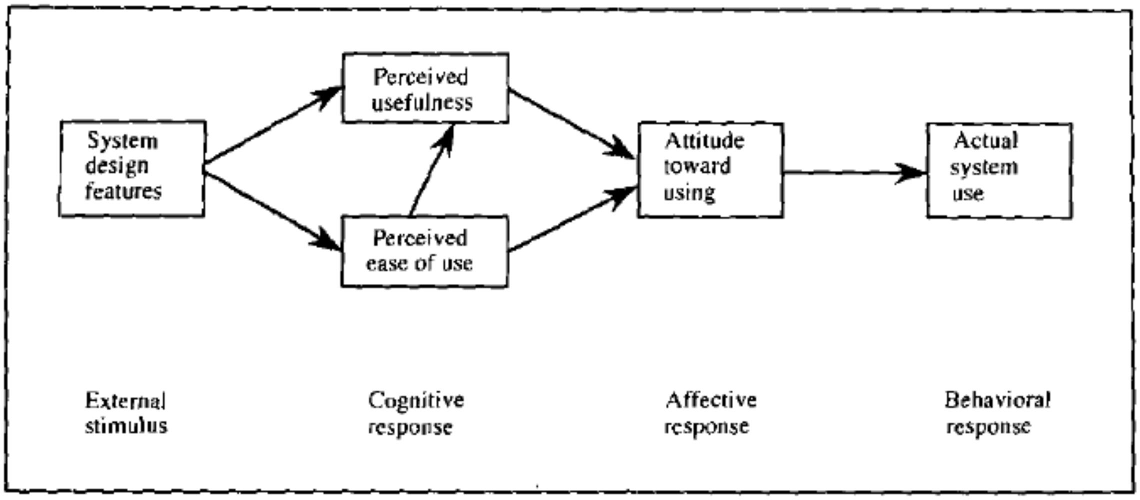


Figure 2. Technology acceptance model, Davis 1993.

information they need to design useful solutions for user problems. Technology should be human-centered and empower humans, and if it does not then the design of the technology must change instead of humans adapting to the technology (Nielsen 1). Further, the design of our technologies should reflect human physical, cognitive, and social capabilities (Buxton 1).

Current State of the Field

Failures in software projects cost the US economy an estimated $25 to $75 billion annually, and many of the reasons for failure are preventable (Charette 1). UX research conducted up front can help avoid some of these failures such as badly defined system requirements, poor communication among customers, users and developers, and stakeholder politics. Delivery without adequate requirements from customers and users is a problem found in 73% of failed software projects (Cerpa and Verner 133). However the current state of the field prioritizes shipping product over proper UCD process.

UCD Approach	Agile Approach
Use about five users that fit predefined user profiles	Put system increments into production ASAP to get real-world feedback
Start evaluating using low-fi designs	Evaluate production-ready code at the end of each iteration
Use methods such as hands-on testing and collect metrics, such as efficiency and satisfaction	Demonstrate the working code to obtain an accept or fix verdict

Table 1. Differences between UCD and agile, McInerney and Maurer 2005.

The software industry's reaction to failed projects has been to abandon traditional plan-based methods in favor of agile software development practices. Agile methods have impacted the way software is developed worldwide even though there is little empirical evidence on their effects (Dybå and Dingsøyr 834). Agile dismisses up-front research and requirements planning in favor of quick delivery because business needs change. However this conflicts with the UCD approach to research and design at the beginning of a project (McInerney and Maurer 19). Table 1 compares UCD and agile methods. An important difference is that UCD begins evaluation early with low-fidelity designs to test with users and iterate on, while agile emphasizes production-ready code to be evaluated at the end of an iteration. UX research is necessary to understand users, whose needs change little over time, while the features and technologies change rapidly (Beyer et al, 2004). Lightweight tools for the UCD process, such as scenarios and personas, are effective ways to make it more agile and to communicate a strategic UX vision with team members and stakeholders (Kollmann et al. 15).

Mixed reality applications pose additional challenges on the design and development process. While bringing any technology to market requires skilled technical resources, the development of mixed reality technology requires advanced programming skills (Abawi et al. 1). There is currently a lack of structured approaches to the design of mixed reality experiences and trial and error is the best choice (Geiger 1). Rapid prototyping, also known as low-fidelity prototyping, is a way of quickly making ideas tangible, testing them, and iterating on them before devoting significant time to development (Rettig 21). High-fidelity prototypes does not always solicit helpful feedback by shifting a user’s focus to visual details rather than functional ones (Rettig 22). Low-fidelity are valuable tools for requirements gathering and identifying major interface problems in earlier phases of a project (Rudd et al. 79). As the UCD process progresses, designs are presented in higher fidelities to test closer simulations to the final product. While there are many approaches to rapid prototyping for web and mobile interfaces, there is a lack of tools and methods for prototyping mixed reality experiences.

The Gap Between Research and Practice

There is a notable gap between UX research and practice. Researchers pursue intellectual merit without the real-world constraints faced in practice. Practitioners lack time or sufficient background to interpret research for practical applications. Invaluable research findings may never lead to changes in the field, and practical needs can be overlooked by research efforts. The field of HCI needs intermediaries to translate research findings into a format useful for practice as well as translate business needs into topics for researchers to investigate (Norman 12). This project aims to translate my research into a useful design tool for practitioners in the field. In my personal experience as a UX designer in industry, I was frustrated by the inadequate tools and business demands that impair good software design. I returned to academia believing research would provide more advanced tools and skills for practice. Unfortunately, I have been struck by the profound gap between academia and industry. While this research was conducted in academia, I have maintained my focus on the needs of practitioners and actively sought feedback from them throughout the lifecycle of this project.

The research-practice gap is beyond organizational and reflects the ontological dichotomy between abstract and concrete, or rather between thinking and doing. While rapid prototyping techniques are indeed the best way to quickly build, test, and iterate upon designs with user feedback, the findings are limited to the specific context they were originally designed for. For example, lessons learned from prototyping a mobile MR application may not be applicable to HMDs or systems integrated into the built environment. These empirical methods make it difficult to share knowledge across different technologies to advance the field and collectively develop best practices. A theoretical framework can supplement these findings by providing a “top down” way to organize them and a common language for describing and designing for contextual user experiences (Kaptelinin et al. 28).

Existing Tools

In my research, I explored various tools used to understand user context in the design process as this is critical for MR environments. These tools ranged from lightweight tools used in practice to theoretical methods from research. I analyzed two design tools, personas and the Empathy Map, and two theoretical frameworks, the MUSiC method and activity theory. I identified their strengths and weaknesses providing information on a user's context and their capacity to support the design process.

Personas

Personas are a design tool providing generalized user descriptions that lack context-specific information. Personas are profiles of hypothetical users that describe their user needs, goals and tasks (Blomquist 1). Figure 3 depicts an example of a persona including a name and photo, demographic information, technology and level of expertise (Cakir 1). In practice, a lack of resources dedicated to persona development results in them having sparse information (Billestrup 363). The descriptions focus on user

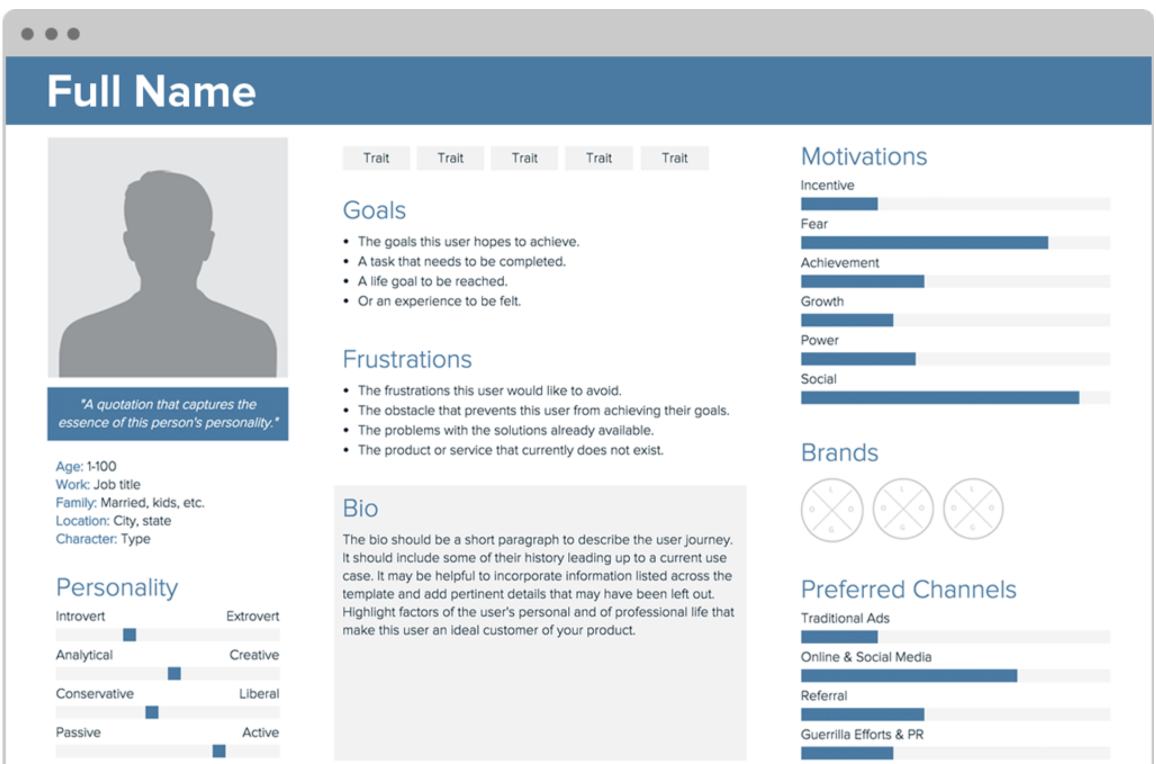


Figure 3. Persona template (Cakir 1).

characteristics and needs related to the system while overlooking the context of use. For example, a persona may be described as using a desktop PC at work and communicating on her personal iPhone when outside of the office. Further details are lacking on the people and surrounding environment, and context-specific preferences such as using voice input when she is in her car. Personas provide insufficient contextual information for MR use.

The Empathy Map

While the goal of The Empathy Map is to better understand customers by empathizing with them (Osterwalder and Pigneur 126), this superficial tool is best fit for market research rather than user research. Originally developed to empathize with customers in the design of business models, the tool has been adapted for various design projects and even used in the development of personas (Ferreira 1). The Empathy Map features a cartoon drawing of a customer's head in the center and fields around it for what the customer sees, thinks and feels, hears, says and does. Below are fields for their pain points and what they needs are. Figure 4 shows the visual organization of the tool. The Empathy Map provides designers with some contextual information on the people around them and what they see in their environment. However it is a general tool and does not include enough detail on the context of use for the design of contextual user experiences.

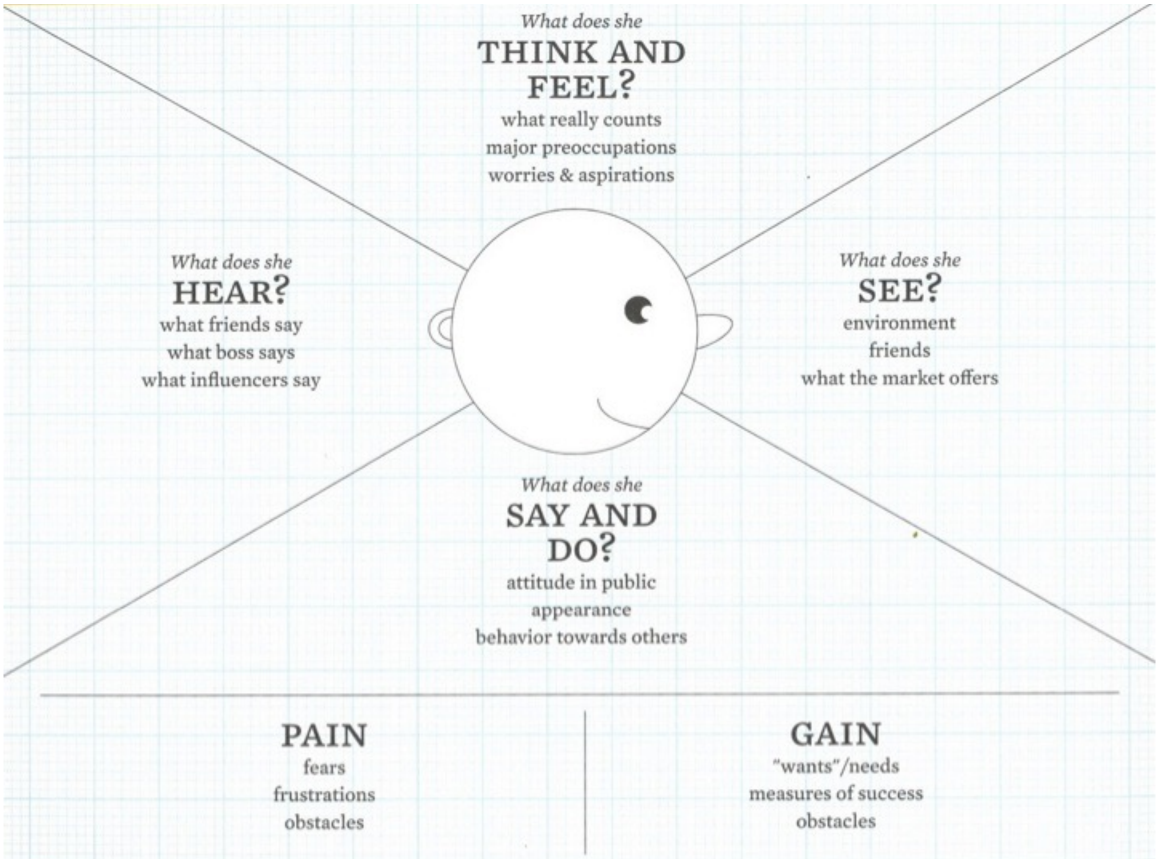
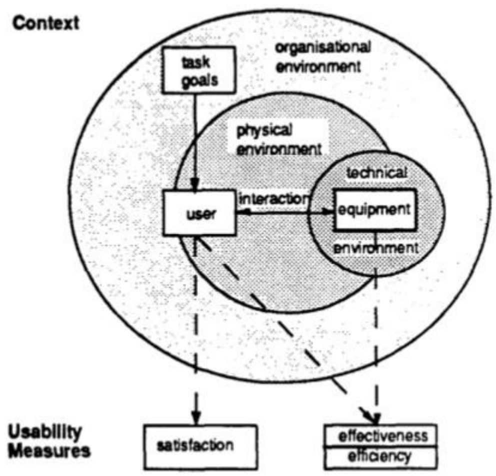


Figure 4. The Empathy Map, Osterwalder and Pigneur 2010.

The MUSiC Method

A more comprehensive but less human-centered approach is the MUSiC (Metrics for Usability Standards in Computing) methodology from usability engineering research. The MUSiC project aimed to develop a methodology for usability measurement and specification, defining usability as the quality of an interaction in the context of use (Bevan and Macleod 123). Figure 5.1 provides a breakdown of the relationship between context and usability measures, and Figure 5.2 lists characteristics of the context of use. Just as the natural sciences routinely collect details on the context of conducting an experiment for it to be reproducible, the MUSiC method was intended to detail the context of measurement for a usability study to see how it relates to the intended context



Users
- personal details
- skills and knowledge
- physical and mental attributes

Equipment
- basic description
- specification

Tasks
- job characteristics
- task characteristics

Organisational Environment
- structure
- attitudes and culture
- worker control

Technical Environment
- hardware, software
- reference manuals

Physical Environment
- workplace conditions
- workplace design, safety

Figure 5.1. Context and usability measures. Figure 5.2. Characteristics of context of use.

Bevan and Macleod, 1992.

of use. The method provides a valuable framework for capturing the context of use when a user interacts with a system. However, the method does not offer insight from the perspective of the user. All user interaction is subjective to the context in which it occurs. Understanding the user's subjective experience in context is essential to designing good user experiences.

Activity Theory

The existing method that is closest to capturing user context in a way that supports the design process is activity theory. Activity theory has its origins in Soviet psychology in the 1920s and was embraced by HCI researchers in the 1990s. Activity theory posits that consciousness is not located in isolated cognition but in everyday practice, and human activity is inextricably linked to its context (Nardi 7). Context is the relationship between an individual, or subject, and other people and artifacts.

Human activity is motivated by transforming an object into an outcome (Kutti 27). A subject directs their activity towards an object to transform it with an outcome in mind. An object can be material or less tangible such as a plan. The subject's activity with the object is mediated by tools, which includes material and symbolic tools such as signs and language. Figure 6.1 illustrates the mediated relationship between the individual and the object.

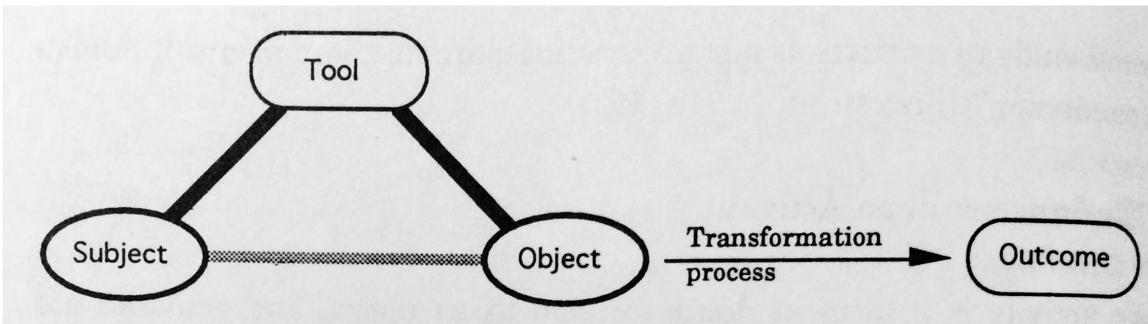


Figure 6.1. Mediation at the individual level, Kutti 1996

An individual subject's activity is embedded in its context. The community mediates the relationship between subject and object as they share the same object. In addition, the relationship between the subject and the community is mediated by rules such as laws or implicit social norms. Meanwhile the division of labor mediates the relationship between community and object as they are involved in transforming the object into the outcome. Figure 6.2 shows the overall structure of an activity.

HCI researchers in the 1990s saw activity theory as a potential solution to understanding a user's context. The framework could be used to describe a user's object-oriented activity mediated by tools for a desired outcome (Kaptelinin 28). The Activity

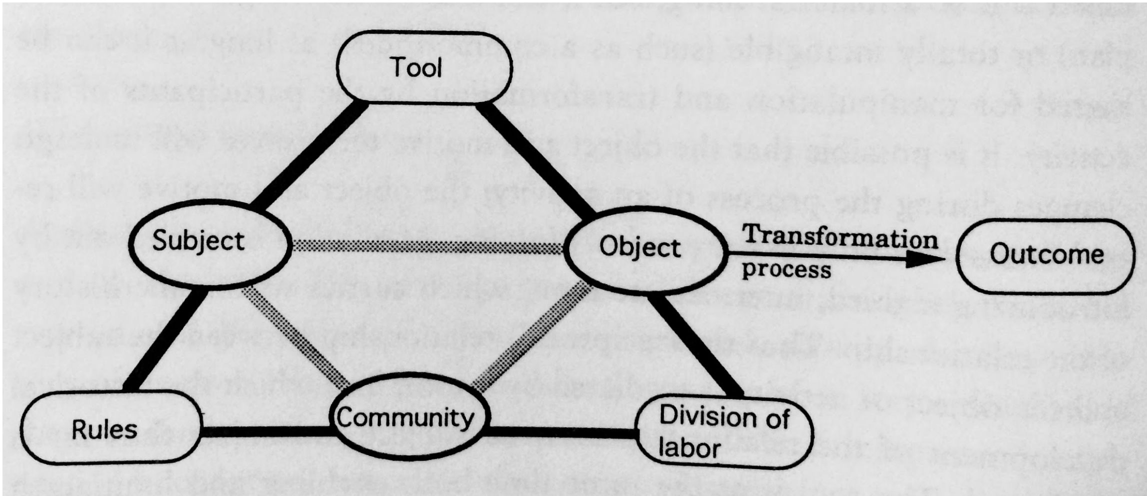


Figure 6.2. Overall structure of an activity, Kutti 1996.

Theory Checklist is an attempt at presenting activity theory in a format more suitable for use in practice (Kaptelinin 36). Figure 7 is a snapshot of the Activity Checklist published in Interactions in 1999. The Checklist is a comprehensive list of considerations specific to HCI with versions for design and evaluation. However the tool has significant limitations

DESIGN VERSION				
	Means/ends	**Environment**	**Learning/cognition/ articulation**	**Development**
USE	People who use the target technology Goals and subgoals of the target actions (target goals) Criteria for success or failure of achieving target goals Decomposition of target goals into subgoals Setting of target goals and subgoals Potential conflicts between target goals Potential conflicts between target goals and goals associated with other technologies	Role of existing technology in producing the outcomes of target actions Tools, available to users Integration of target technology with other tools Access to tools and materials necessary to perform target actions Tools and materials shared between several users Spatial layout and temporal organization of the working environment. Division of labor,	Components of target actions that are to be internalized Time and effort necessary to learn how to use existing technology Self-monitoring and reflection through externalization Possibilities for simulating target actions before their actual implementation. Support of problem articulation and help request in case of breakdowns Strategies and procedures of providing help to	Use of tools at various stages of target action "life cycles"—from goal setting to outcomes Transformation of existing activities into future activities supported with the system History of implementation of new technologies to support target actions Anticipated changes in the environment and the level of activity they directly influence (operations, actions, or activities)

Figure 7. Snapshot of the Activity Theory Checklist, Kaptelinin 1999.

from its abstract quality and structure not mapping to the design process. The Activity Checklist is not a very usable tool for understanding user context in the design process.

My research into the available tools for user context in the design process left me frustrated. More than ever I was convinced that designing for a user's context was a critical need in the field and designers were poorly equipped for the task. The tools used in practice were easy to use but did not provide enough information. The tools from research were abstract and difficult to use. I decided to try compiling best practices towards the HCD of MR environments.

THE SEARCH FOR BEST PRACTICES

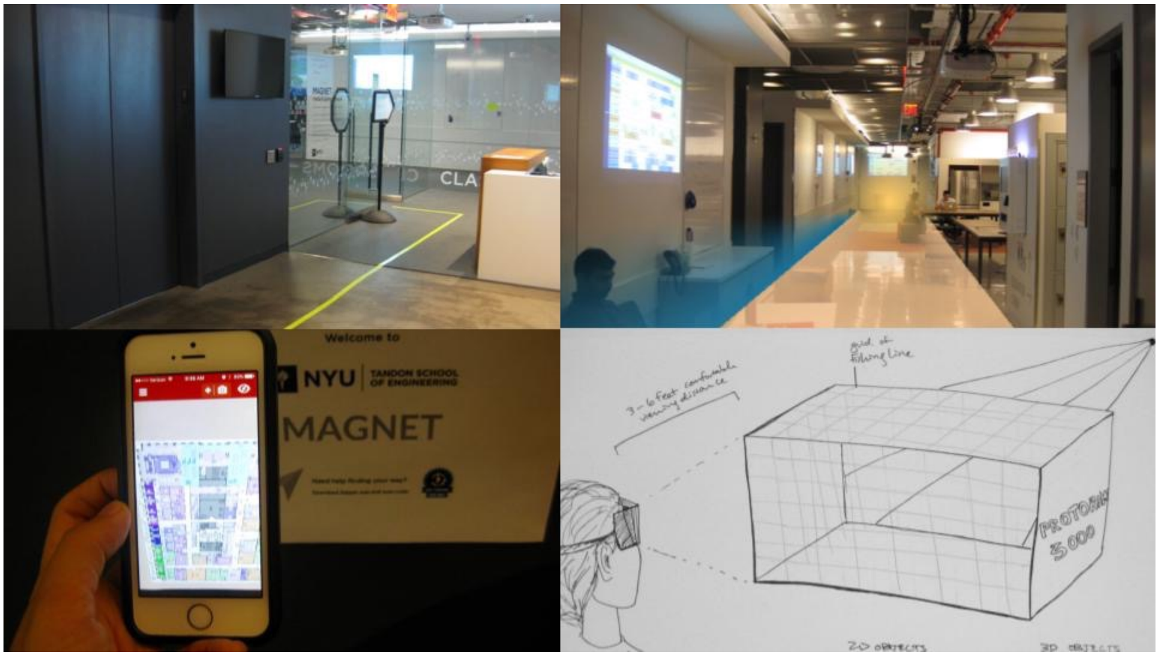
Learning by Doing

In my mission to make MR environments more human-centered I was left with more questions than answers. I found the available design tools and theoretical frameworks for context of use inadequate. Research on MR focused on the technologies and overlooked its impact on the social and environmental context. I decided to try rapid prototyping MR experiences in the context of use to quickly test and iterate on designs in an effort to make them more human-centered. I hoped that creating a case study would inform a conceptual framework and design guidelines.

I designed prototypes for navigation in MR environments as this is a critical usability issue. Navigation is an enduring problem with web design today (Schade et al. 1). Researchers of virtual environments have found that despite a wide variety of wayfinding assistance available, many users experience disorientation and difficulty navigating leading to frustration and even discontinued use (Dodiya and Alexandrov 1). As we rely more on digital communication systems to support our daily activities, the buildings that house these activities have transformed and been reconfigured into architectural mutants (Mitchell 23). Wayfinding is a spatial problem-solving process used when navigating to a destination (Passini 17).

The research site was MAGNET (Media and Games Network) in NYU Tandon School of Engineering. MAGNET has a complex floor plan, an existing wayfinding system, and digital navigation aids. The space hosts many events and a daily influx of new visitors that have difficulty finding their way around. The scenario used in the design process was a visitor arriving in the elevator lobby and finding their way to their destination. I designed MR experiences that worked in tandem with the existing wayfinding system in the built environment.

I tried to create prototypes that were not built around specific technologies, however these assumptions inevitably made their way into the designs. Figure 8.1 shows neon duct tape used to simulate virtual wayfinding elements in the space. I experimented with wayfinding cues found in nature to create the digital mockup in Figure 8.2. I developed the “protorama” in Figure 8.3 building on research with 3D physical interfaces built with objects hanging from fishing line (Cockburn and McKenzie 2). Figure 8.4 is a mobile AR navigational aid.



Clockwise from top left: Figure 8.1. Neon duct tape 8.2. Digital mockup 8.3. "Protorama" 3D physical interface 8.4. Mobile AR navigational aid.

Low-fidelity prototypes using physical materials can provide a rough substitute for testing designs early in the process. However their material qualities limited their capacity to simulate virtual objects integrated with physical ones. Furthermore, rapid prototyping tends to follow the assumptions of the specific technologies delivering the experience. For example, a mobile experience designed to be held at arm's length and use touch input cannot easily be translated into a HMD experience with different FOV and input modalities. Prototypes may be designed only considering the capabilities and limitations of particular technologies. I found it difficult to generalize my findings in order to apply designs to various technologies or develop design guidelines. After building 12 prototypes I felt like I was doing the same thing over and over again and expecting different results. To gain some perspective I spoke with practitioners in the field about what methods worked for them.

Getting Out of the Building

In my search for better tools, I decided to conduct exploratory interviews with UX researchers and designers in industry. I thought these Subject Matter Experts would be willing to speak about their methods and this research could contribute to a list of current best practices. I targeted designers and researchers working on smart home technologies because this work is more context dependent rather than focused on one particular interface. Unfortunately, I discovered many have signed Non-Disclosure Agreements that prevent them from discussing their work. While it is reasonable for an organization to protect their proprietary technologies, I was stunned to find out practitioners were not able to speak on methods and approaches. This is a severe impediment to progress in the field. However it supports my hypothesis that practitioners are focused on their particular product and not considering a more holistic experience integrating technologies and spaces experienced by a user in context.

The two practitioners I interviewed echoed the sentiment that the field is changing rapidly and there is little shared knowledge. To be able to keep up, these professionals adopt or adapt new methodologies and are open to better ways of approaching problems they face in their work. One study participant had an extensive engineering background and was launching his own startup company. He previously worked as a product and system architect for a smart home technology startup managing a team of software developers. He admitted that in a startup “you have engineers design product which is problematic if you don’t understand product design”. He praised the book *The Lean Startup* (Ries) as his main resource for understanding UX. Indeed, the lean startup movement has spurred the lean UX movement. Arguably, the methods put forward in *The Lean Startup* are new terms for long-used UX practices such as “getting out of the building” corresponds to a contextual inquiry (Sharon 1). He is an avid reader of UX blogs and looking for new methods to incorporate.

Another participant was a UX manager and product design lead for a large corporation. His team focuses on the integration of third-party services into their smart home platform. He emphasized the importance of testing products in their appropriate context since “the lab is no substitute for real life”. Part of his job includes testing smart home products in his own home because “the only real way to understand this stuff is to live with it yourself”. He described the experience as “pretty intimate. I don’t know if that’s the right word”. However, intimacy seems accurate because of the domestic context in which these technologies are integrated. With regard to his process, he preferred user archetypes over personas because they helped him “understand their mindset and motivation”. He cited the book *Sprint*, a book for entrepreneurs written by three partners at Google Ventures, as one of his top resources for methods. Sprint proposes a five-day process to answering critical business questions through designing, prototyping, and testing (Knapp et al.). Whether this method identifies with the lean UX movement, it certainly follows the same pattern of presenting the UCD process in new packaging aimed at entrepreneurs. He was aware of many researchers in his company being active in the ACM SIGGCHI community but it did not appear to have an impact on his practice

The findings from these interviews confirmed the need for new tools and knowledge sharing in practice. These practitioners were scrambling to use any methods that could help them in approaching problems. The methods they used were designed for the time-restricted environments they operated in. But because these methods are working to solve for immediate business problems does not mean they are best practices. Were there nuggets of wisdom in the HCI literature that could find their way into the real world? I decided to move forward with applying theoretical frameworks to the design of MR environments.

THEORY IN PRACTICE

The Activity System

My research into activity theory and its validation by the HCI research community convinced me to try applying it to the design of MR environments. My first design tool prototype stayed true to the original activity system conceptualized by Engeström (1987) only because I had not yet discovered Kutti's simplified version (Kutti 27). I designed a large-format Activity System seen in Figure 9. Then I printed it out as a 11x17 poster so it was large enough to work with traditional design tools - post-its and sharpies. I decided the only way to see if it was effective was to test it in a case study with a real user in an MR environment. I hoped that observations, interviews and contextual inquiry would provide true insight that can only be gained by understanding users.

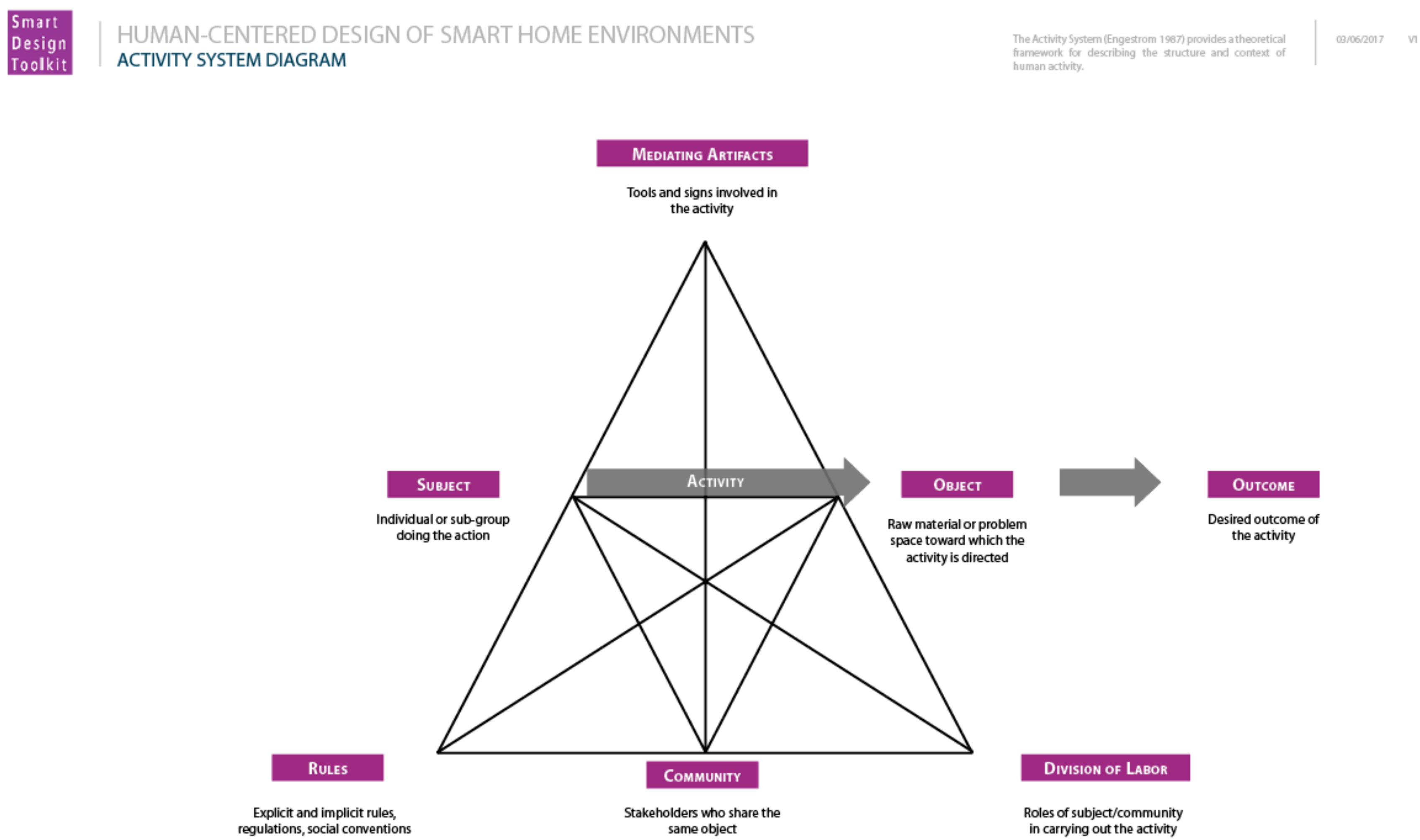


Figure 9. Prototype v1 of the Activity System.

Smart Home Case Study

I interviewed a smart home user in his home environment. The participant was a startup founder with an engineering background who lives in a one-bedroom apartment with his cat. His motivation to use smart home technologies was to automate processes to adjust his environment to his preferences while he was at home and save energy while he was away. When he arrived at home he relied on his smart home technologies to adjust the lights and the temperature. He would say "Alexa, turn on library" to the Amazon Echo in his kitchen in order to turn on the lights. "Library" is an instance of two Philips Hue lights in the living room. I created a scenario around his arrival at home, Figure 10.

Figure 10. Scenario for the smart home case study.

The smart home scenario proved the value of the Activity System in action (Figure 11). The subject is interacting with the Amazon Echo with the desired outcome of turning on the lights in the living room. I identified the various mediating artifacts involved to make this activity happen, including user voice input. The Community included guests in his home, the catsitter when he travels, Amazon, and perhaps any third parties buying his data. Under Division of Labor I described each party’s actions when this interaction occurs. In Rules I put quotes of the participant describing some of the implicit social conventions he expected from his technology.

Figure 11. Smart home case study in v1.

Analyzing this scenario in the Activity System gave me the perspective I was searching for. It provided a clear definition of the activity and the contextual factors involved. The use of post-its made it feel like a natural design tool and helped to visualize the components of the activity. However, it was difficult to use at first because of the terminology and scale involved. Even after I clarified what a term meant, I found there were so many possible items to place in a category because the theory was broad enough to encompass all human activity.

The Rules section provided rich UX insights in the scenario. As the head of the household, the user felt undermined when he had to repeat himself to the device and said “I need it to respect my authority”. Such rules have direct implications on possible design enhancements for the Amazon Echo. Some design solutions could be to increase the radius and volume to which it responds to voice input, accommodate a wider vocal range and various pronunciations, and have it respond in a way that is more deferential to the user’s authority.

However I found there to be some redundancy in the findings under “Division of Labor” and “Community”. I realized the unit of analysis in this framework is much larger than the scenario I was using it for and this was irrelevant. I also found that contextual factors in the physical space were overlooked. I tested out replacing “Division of Labor” with “Environment” in my case study, Figure 12. I found this change enabled me to include findings that were more relevant to the design process. For example, there is another Amazon Echo in the adjacent bedroom that sometimes responds to voice input from the entryway. This finding would be important to note for improving the Amazon Echo UX. I created prototype v2 to reflect this change, Figure 13.

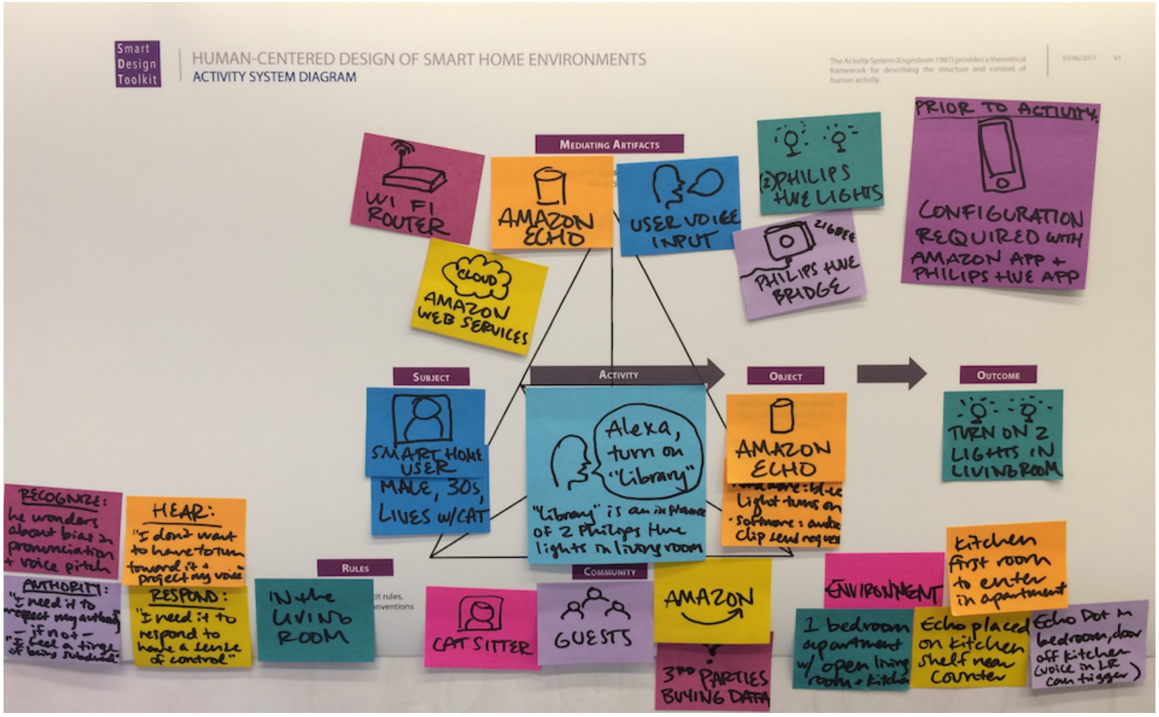


Figure 12. Smart home case study in v2.

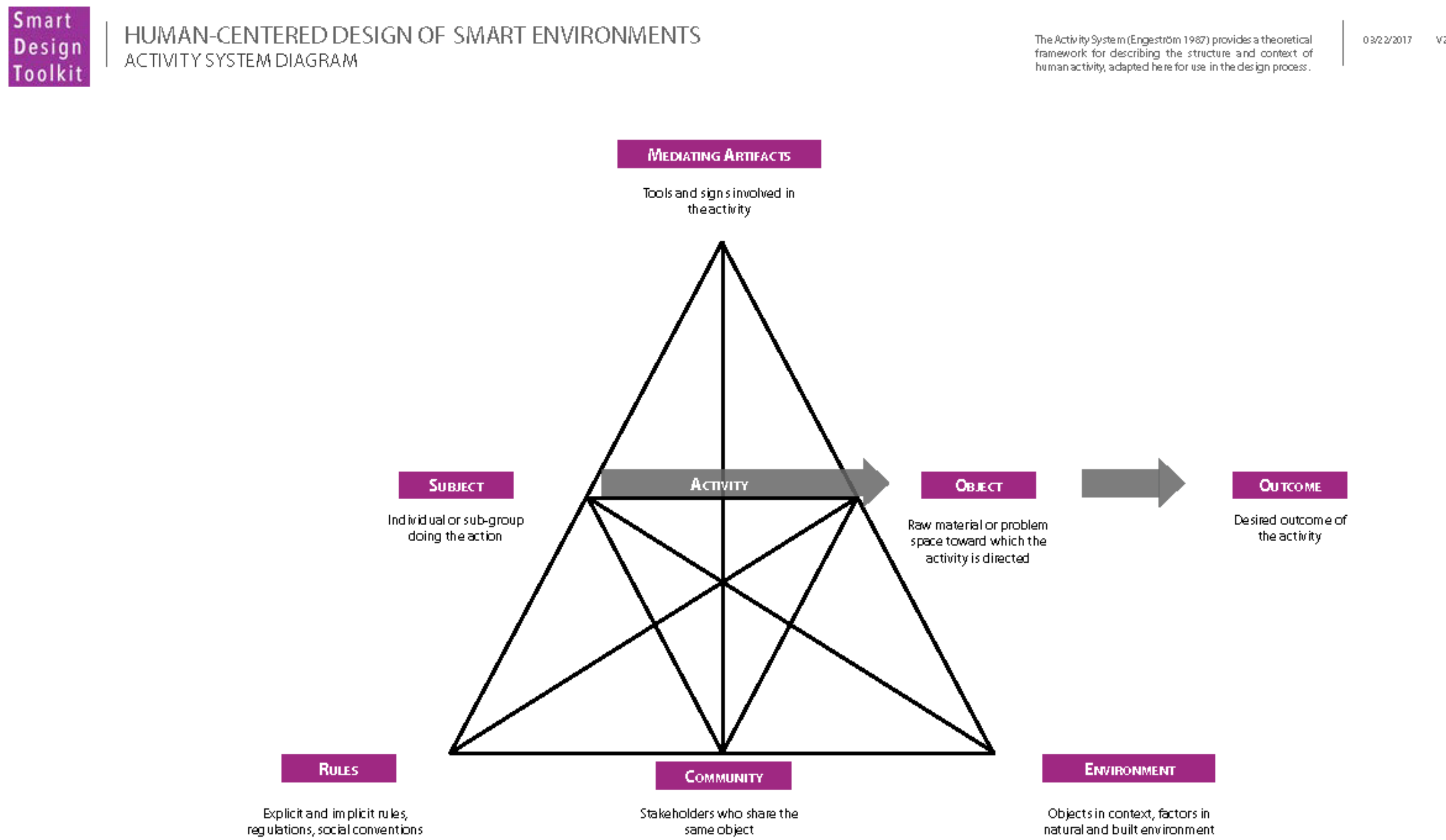


Figure 13. The Activity System v2.

User Testing v2 with UX Researchers

I had the opportunity to test out my v2 prototype with 35 UX researchers at the NYC UX/User Researcher Meetup. First I gave an overview of mixed reality environments and introduced my Activity System as a tool I have found useful in my research. Then the researchers split into groups for an interactive workshop using MR scenarios. I presented three scenarios for the groups to choose from and develop research approaches. Printed copies of my Activity System were on the tables for the groups' use. Almost immediately one person was overwhelmed and confused by the Activity System and desperately asking what they were supposed to do with it. Many groups ignored it while they discussed technical constraints in their scenarios and research methods they were more familiar with. Finally, each team shared their research approaches I asked if it was different working with an MR scenario. There was consensus that MR environments were very different from their current work.

Out of 35 users the majority did not actively engage with the system during their team research planning. However after the workshop, 5 people I will call "super users" took copies of the system with them and it really resonated with them. What the super users had in common was they already had some background in order to understand the system's value - either they were familiar with the theoretical side or they had experience in the mixed reality space. One had a background in cognitive science and this system reminded him of distributed cognition so he recognized this way of analyzing human activity through ethnographic methods and use of tools. Another was working on an Internet of Things project for a client.

User testing provided some key findings to consider in improving my prototype. First, the design of the document was not approachable or easy to understand. This was most evident in the overwhelmed researcher asking what they were supposed to do with it. Second, the system requires more thorough explanation/onboarding before use. I suspected more researchers would have used it in their scenario if they had a better grasp of how to use it. Third, it appeared that the system was more suitable for the synthesis phase rather than at the outset of a project. The researchers were working with scenarios that had sparse information on the user and would need more information in order to find the Activity System useful. I incorporated these findings into further improvements to my new design tool.

THE CONTEXT MAP

Fitting the Tool to the Job

The project evolved further from an adaptation of activity theory to a new tool for use in the design process. I realized the purpose of my adaptation is to suit a specific purpose and took ownership of it. Activity theory provided a good foundation for analyzing context. However I needed to adapt it to understand a user's context in their interaction with a system incorporating digital and physical components. I designed prototype v3 for this purpose called the Concept Map, Figure 14. I redesigned it to have blank fields in each category to easily fill in research findings. I made a deliberate choice

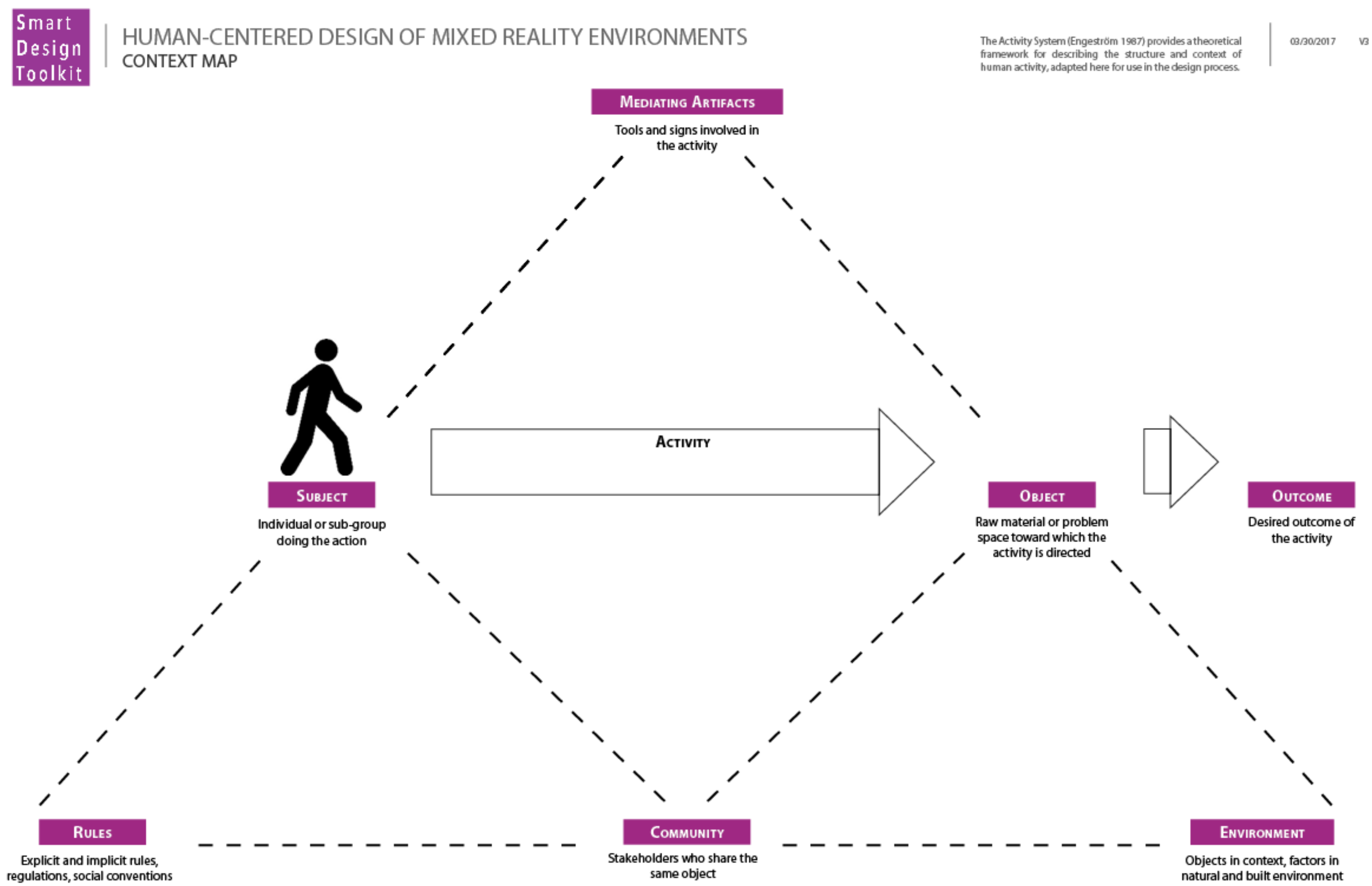


Figure 14. The Context Map, prototype v3.

to represent the subject with a full body stick figure to reinforce the point that consciousness is intertwined with human activity in context. Interaction with these systems is not an isolated cerebral process but can happen with inputs such as gaze, voice, gesture, locomotion, etc.

Prototype v3 took full ownership of The Context Map separate from activity theory. But v4 established it as a working tool for designers, Figure 15. I made the tool more accessible and easy to use by incorporating language specific to the design process. Subject became User, Mediating Artifacts became Tools, Community was updated to People, and Outcome was rephrased as Goal. The most significant change was replacing Object with Touchpoint. This defined the point of interaction between the user and the system rather than a material being transformed in the activity. I changed the colors to black and white so it can be easily printed and added fields ‘Designed for’ and ‘Designed by’ to make it a worksheet ready to be used on projects. It was time to test the Context Map with a case study in another MR environment.

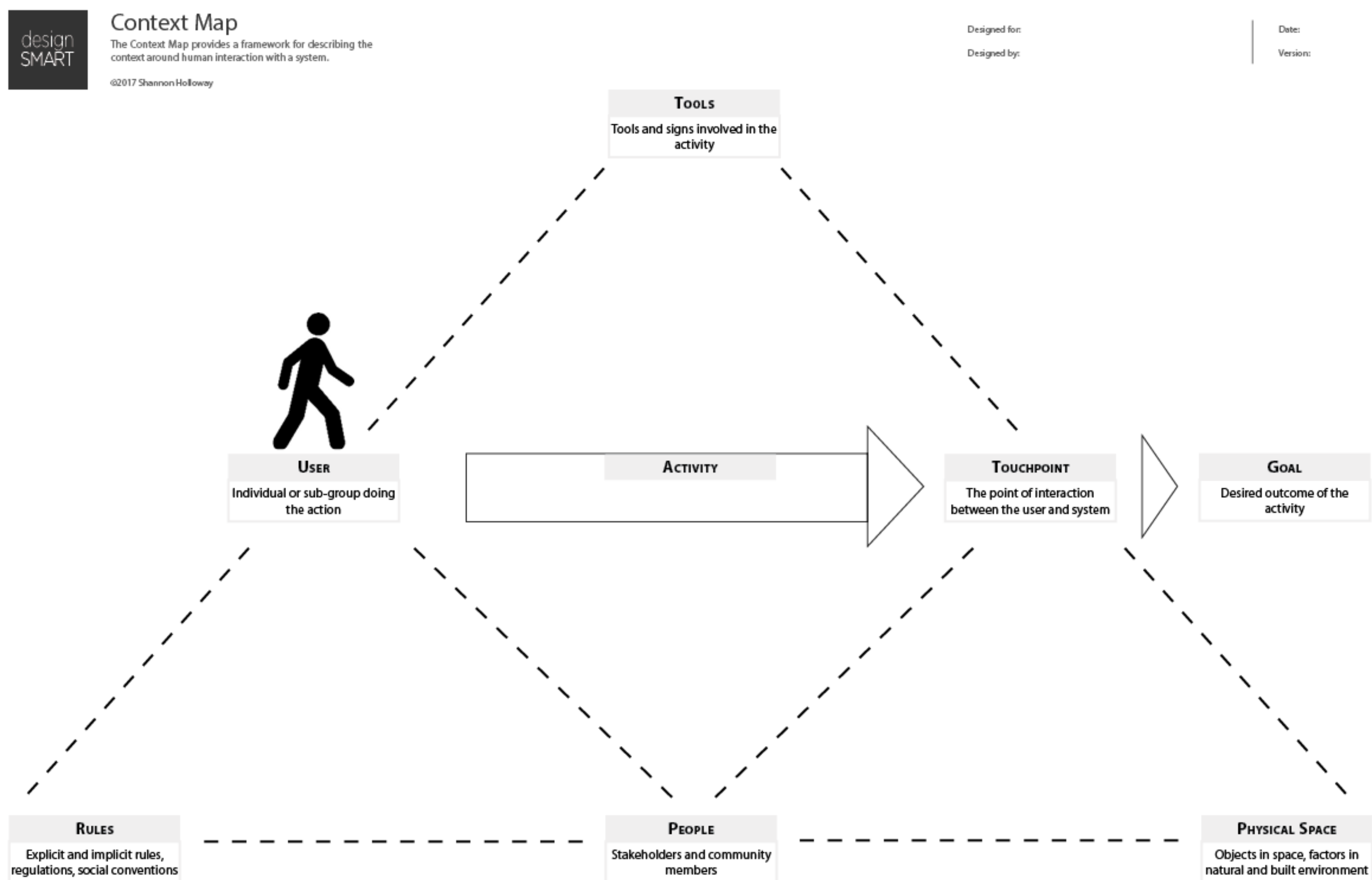


Figure 15. The Context Map, prototype v4.

MR HMD Case Study

For my MR HMD case study I chose to work with the Microsoft HoloLens. Interestingly, this HMD is marketed as MR instead of AR because 3D interactive holograms are projected into the user's FOV and spatially mapped to their surrounding environment. My user was a graduate student at NYU Tandon School of Engineering using the HoloLens in a classroom at MAGNET. In my interview with her she described her research on virtual avatars and the importance of being able to see and interact with them in 3D space. I created a scenario around her workflow in which she would record a POV video of her interaction with a 3D hologram in space to provide feedback to collaborators or design managers, Figure 16. From the Holograms app she selected a

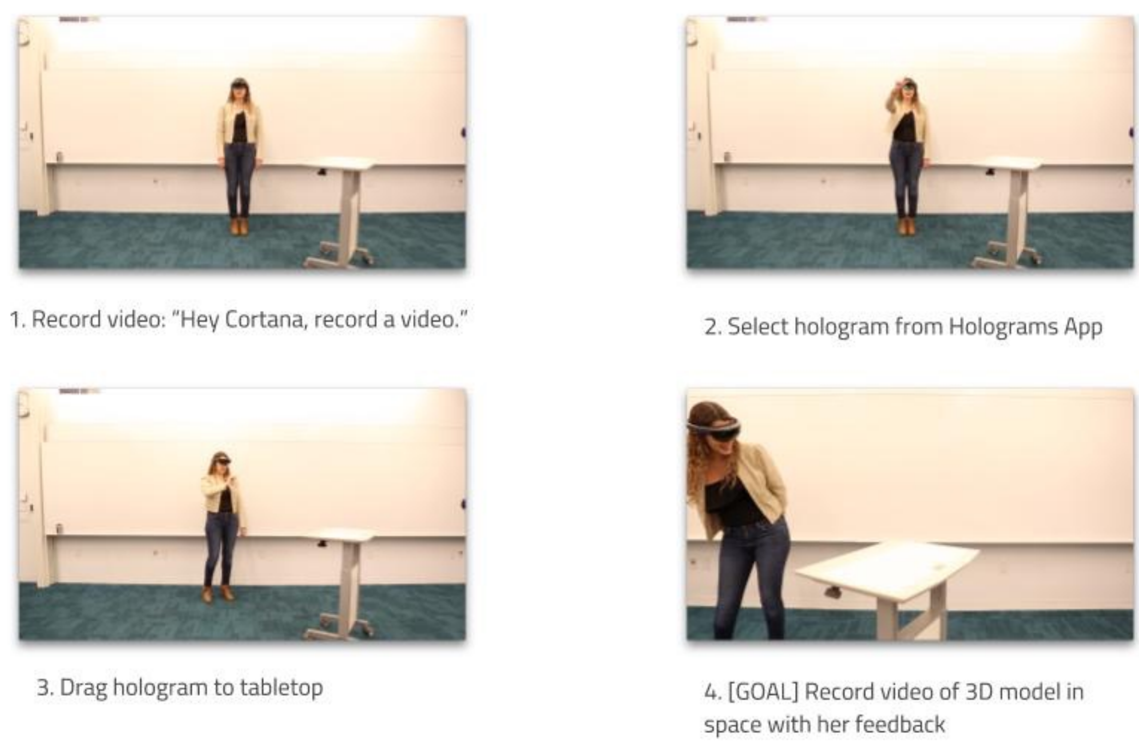


Figure 16. Scenario for the MR HMD case study.

hologram, placed it on a desk, resized it and was then able to inspect it from various angles.

As an observer I could not see the holograms she was interacting with. It was critical to get her POV video not only for the scenario but also for documentation, Figure 17. While the task interacting with a hologram was straightforward, recording a POV video (and later trying to download it from the HoloLens) proved to be the most challenging part of the scenario. The bloom gesture, which is used to access the Start menu, automatically stopped the recording of video. The user had to already be in the Holograms app and start recording by voice command, “Hey Cortana, record a video.” Cortana did not always recognize the voice command and would pull up search results in a web browser. The user had to repeat herself several times and attempt to reduce her

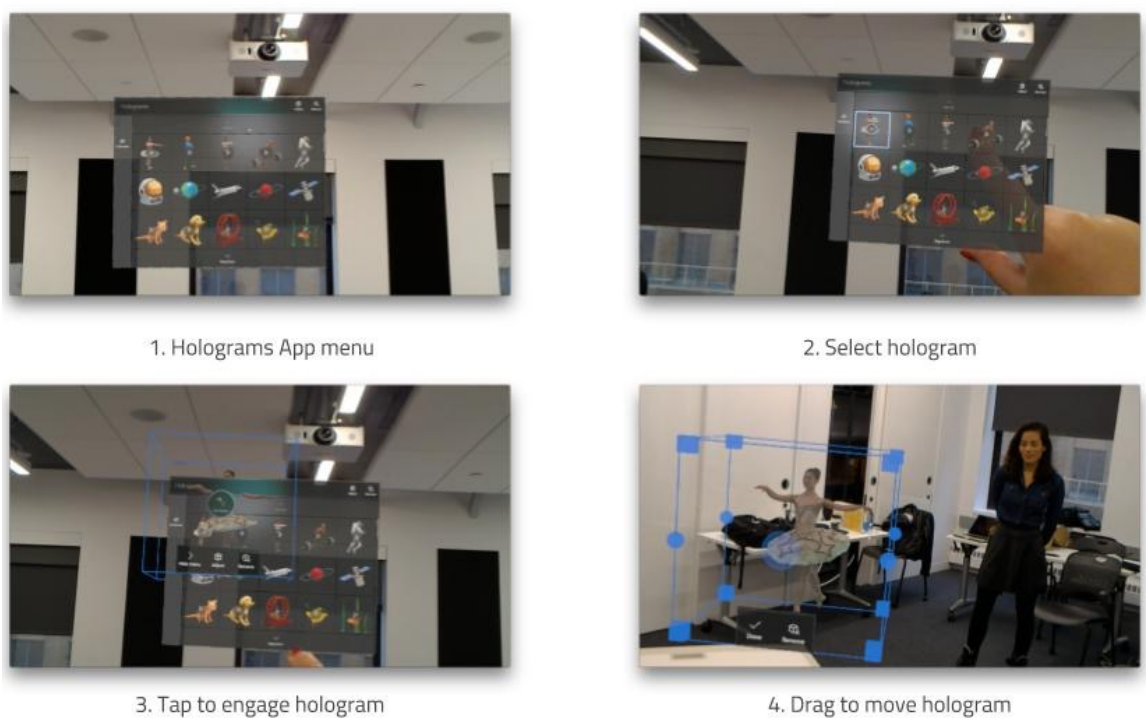


Figure 17. Documentation of user POV from MR HMD.

accent when the technology failed to recognize her voice speaking English as a second language.

The system provided little feedback on its status. This case study reflected some of the key concerns with sensing systems raised by Bellotti (415). We were unsure of whether it recognized the command, was processing the request, or recording the video. As an observer I saw a small white light illuminated in the front of the device a few times after the user gave the voice command. It was not clear to me what purpose it served, and because I watched her give the voice command I hypothesized it indicated to others that it was recording. What was of utmost importance was that the user could confirm that her command was understood. The user had to look all around her in search of any indication inside the HoloLens that confirmed it was recording. After several attempts she found UI indicating that it was recording in the corner of her FOV.

Analyzing the MR HMD case study was much easier with the v4 prototype of the Context Map in Figure 18. Using the tool felt more natural like a worksheet rather than a finished design deliverable. The updated language made it clearer which pieces of the scenario fit in each category and how they related to each other. Organizing my findings in the Context Map created a clear picture of the context within which the user was operating. and articulates everything required to enable this activity. Again, the Rules section provided valuable UX insights that could inform future design enhancements. These implicit rules included pronouncing English a certain way to be recognized by the system, staying within the spatially mapped area, and having the consent to take video from others in the room. Improvements to the software and hardware could include support for a wider range of English pronunciation and better indication to others of video recording.

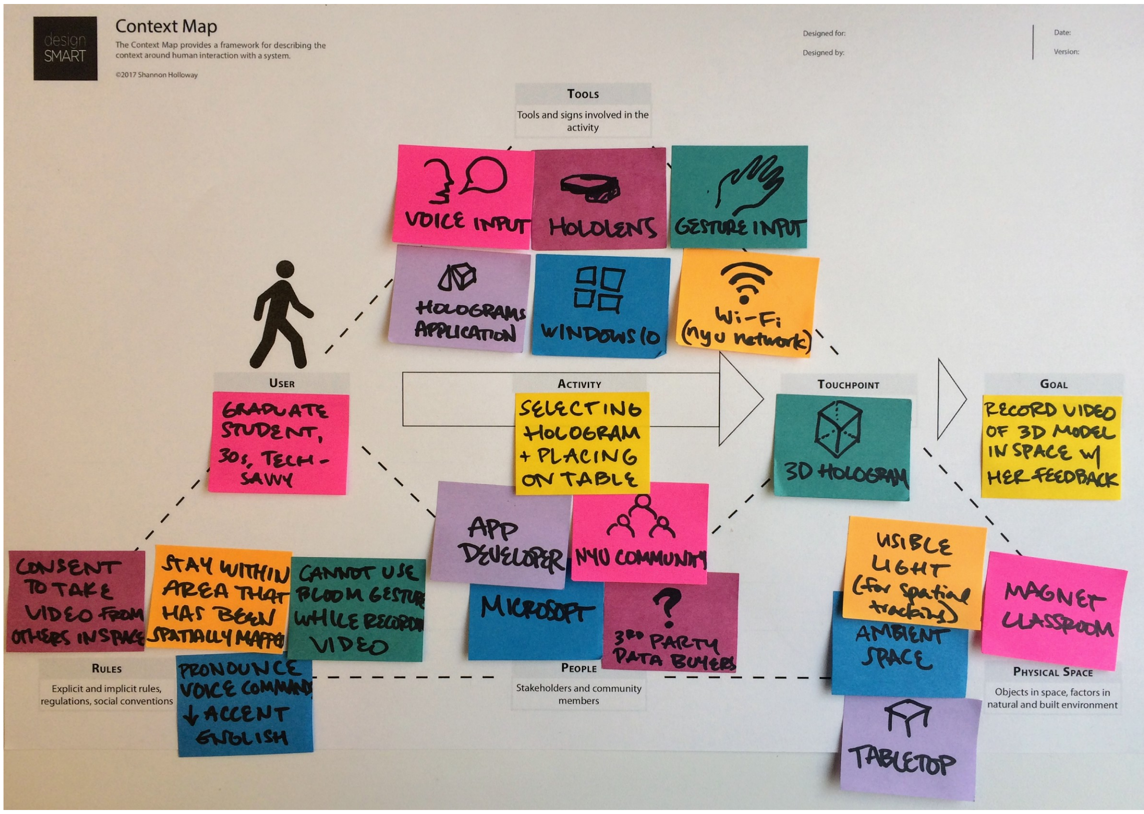


Figure 18. MR HMD case study in v4.

User Testing v4 with UX Design Students

I had the opportunity to test out my v4 prototype with 19 students in the graduate-level UX course at NYU Tandon School of Engineering. First I gave a brief overview on the need for considering a user's context in MR environments and introduced my proposed solution: the Context Map. The class happened to be midway through an MR design challenge partnered with Microsoft HoloLens acting as their client. I walked them through my HoloLens case study and how the Context Map provided a great way to structure my findings and inform the design process.

After the talk I handed out 11x17 prints of the Context Map to each student. I asked them to try using the Context Map with a HoloLens scenario they were already familiar with in class, Figure 19. The scenario is of a designer working at a desktop computer with a 3D CAD model of a motorcycle, then transferring it to a hologram and interacting with it in physical space (8ninths).

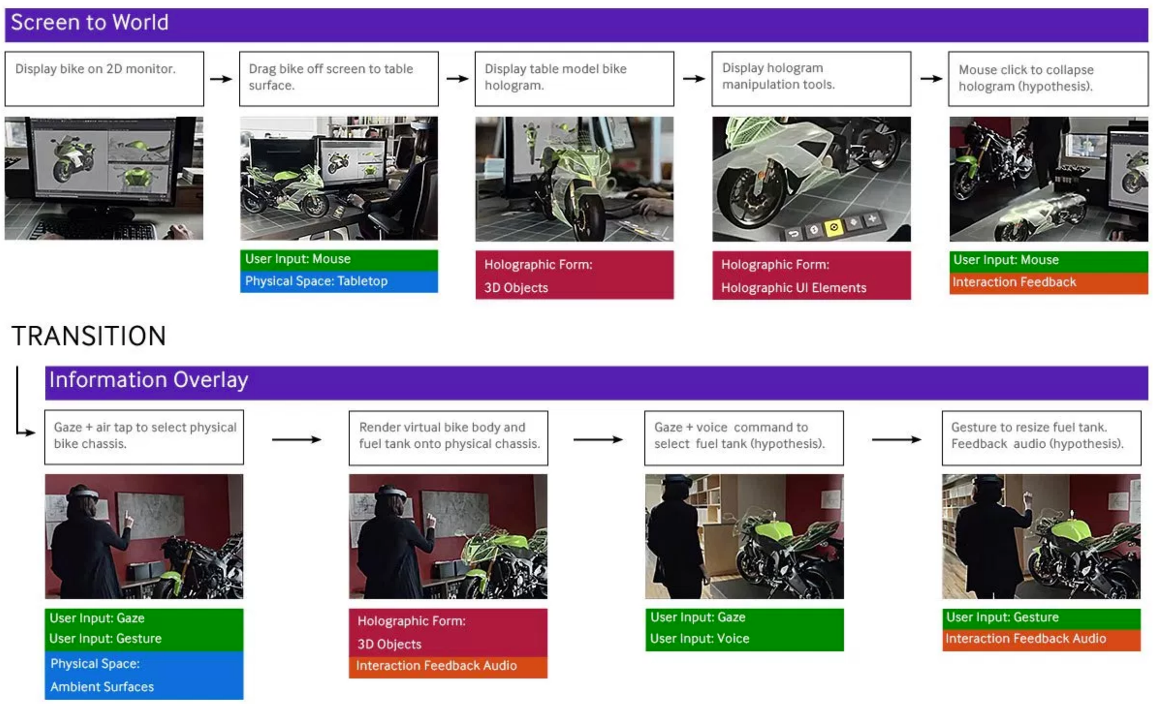


Figure 19. Scenario of motorcycle designer, 8ninths.

After the exercise we had a group discussion on their experience using the Context Map. The majority of users said they could see themselves using the Context Map for future projects. Some students said they wished their team had this tool at the beginning of their client project in order to make sure they considered all the contextual factors in the MR experience they designed. They had encountered problems with their design working with the user's physical space and believed the Context Map would have guided them to design around this earlier in the process. Some students also believed the Context Map would be useful for communicating with stakeholders and explaining their design decisions. Among those that did not see themselves using it, there was confusion about what information to put in each field. They wanted to see more case studies using the Context Map to see it in action and better understand how to use it. Some did not see a clear relationship between the Context Map and the scenario, which was presented in a user flow format and made sense to them in discrete and chronological steps. Others were confused about the language, namely the category named Rules and the inclusion of various user input modalities under Tools.

User testing provided some key findings for improvements to the Context Map. First, the Context Map was intimidating to new users. It was easier for experienced designers who were familiar with design tools from other fields such as service design. It was not clear how to translate the information provided in the scenario to the Context Map format. Second, the Context Map required more thorough onboarding/education before use. Many suggested providing more examples of the Context Map in action to see what types of information fit where. A few wanted to know more about the triangle format and the relationships between the contextual factors. Third, the Context Map proved to be useful for the research and planning phases of a project. The students' experience with designing MR experiences enabled them to recognize the value of this tool in the design process.

A Human-Centered Context of Use

I went back to the drawing board to reconceptualize my prototype from v4 into v5. The triangular structure inherited from the activity system was difficult for users to understand. The triangle depicted the relationships between the contextual factors and how each mediated the other, which is helpful for theory but not application. I restructured the hierarchy of contextual factors relative to the needs for the user experience, Figure 20.

Figure 20. Hierarchy and description of contextual factors.

At the base of the pyramid is Tools, which are system components involved in the activity. Tools represent the minimum system requirements for the interaction to take place, i.e. hardware, software, wi-fi, etc. The next level is Physical Space, the objects in the space as well as the natural and built environment. Physical Space is an important consideration for MR experiences because the digital and physical worlds are experienced by the user at the same time. This category includes some factors required for interaction to take place such as sufficient visible light for holograms to display and defined spaces for spatial tracking, but is also an area to take note of surfaces and furniture, the relationships of connected devices to each other, and other affordances and constraints in the user's physical environment.

The next level of the hierarchy is People, which includes stakeholders and community members. Identification of the relevant network of stakeholders and their relationships to the system and each other is an important step in requirements gathering (Sharp 4). This category considers secondary and tertiary users who are not interacting directly with the system and whose needs are often overlooked in the design process (Alsos & Svanæs 84). Considering these users will contribute to UX that supports collaboration and sharing or security and privacy as needed (Alsos & Svanæs 89). Included are parties involved in the background such as hardware and software providers, third-party data buyers and advertisers. The apex of the hierarchy is User Needs such as preferences and social norms. The previous title, Rules, caused confusion for users and failed to embody its prime importance. Also, many of the findings in that category pointed to implicit user needs and pain points.

Once I established the relationships of the contextual factors to each other, I sketched out ways to visualize them while focusing on the user journey. I looked at diagrams of ecosystems for inspiration on how to map out relationships in complex interdependent systems. The resulting diagram of user interaction in the context of use, Figure 21, provides a framework for describing the context in which a human interacts with a system. I separated User Input from the Tools category and placed it next to the figure of the user, interfacing with the Touchpoint of the system and pointing toward the user's Goal. Emanating from the user are rings of contextual factors in hierarchical order of their impact on the user's experience.

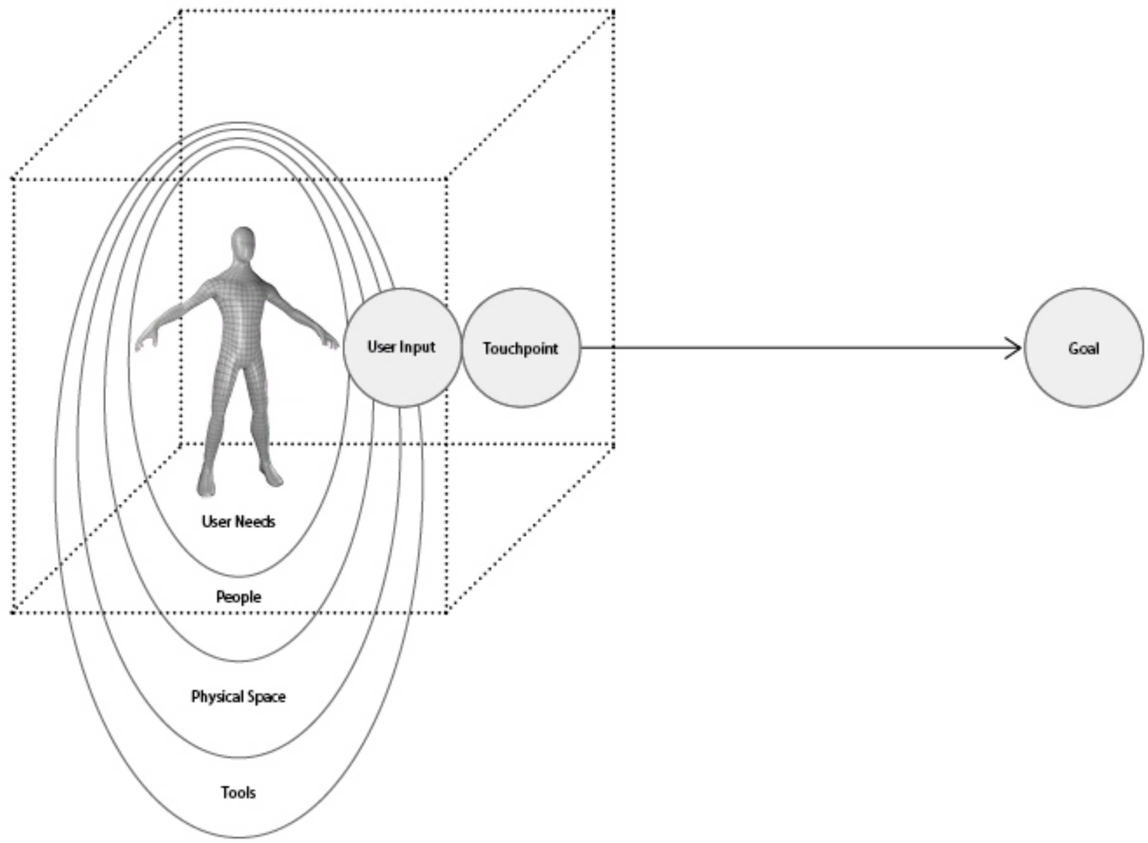


Figure 21. User interaction in the context of use.

Next, I created a new version of the Context Map. My goal with prototype v5, pictured in Figure 22, was to make this design tool as simple and effective as possible. The 8.5x11 worksheet format is more approachable and easier to fill out multiple worksheets for various contexts throughout a user journey. The focus is on the user

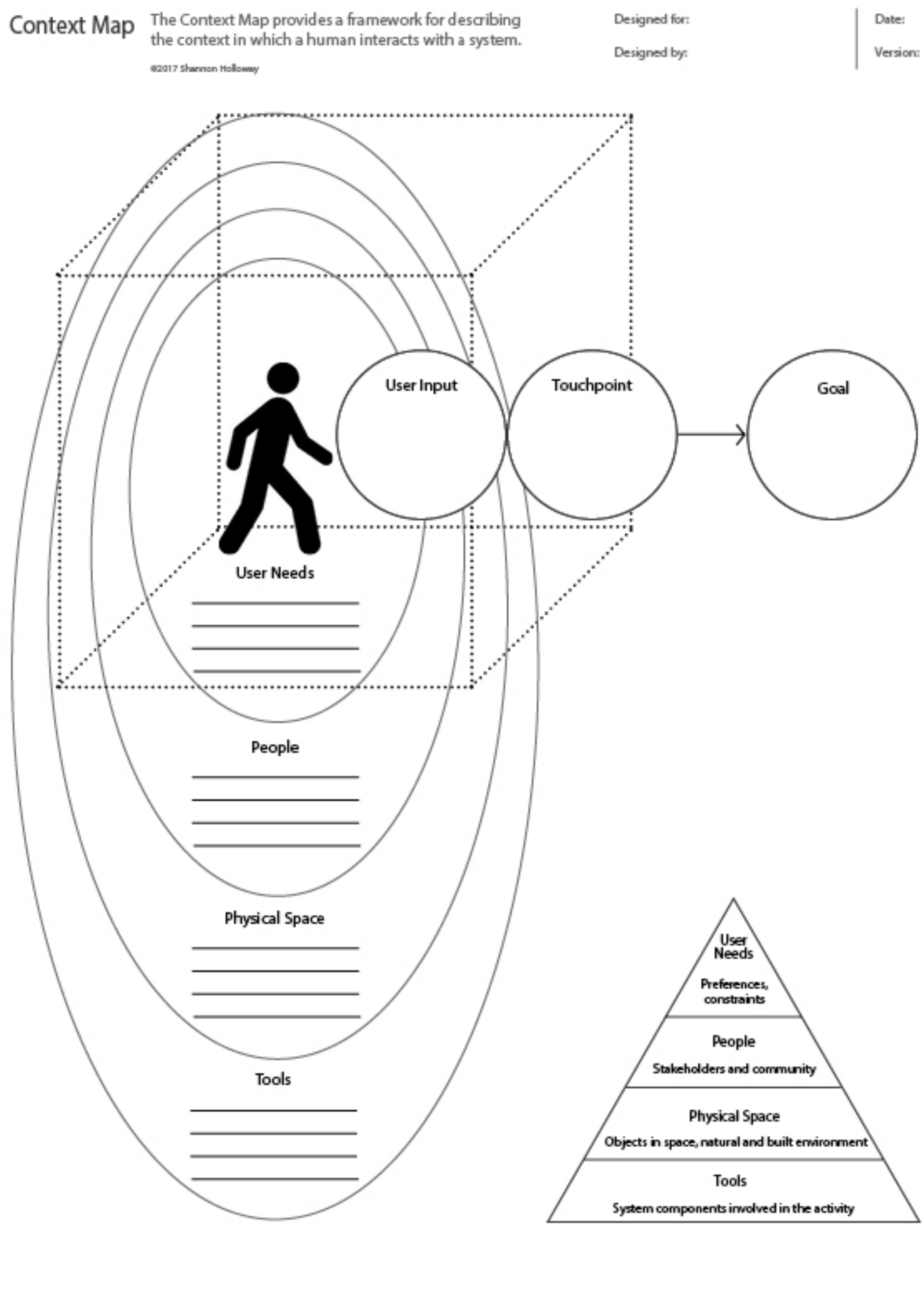


Figure 22. The Context Map, v5.

journey by featuring the User Needs, Touchpoint, and Goal at the top. The hierarchy of contextual factors and descriptions are in the bottom-right corner of the worksheet to guide the user.

I tested v5 of the Context Map with my MR HMD case study, Figure 23. The focus was clearly on the user journey and made it easier to read the document overall. Stacking the contextual factors around the user reinforced the reasoning behind the hierarchical order. The hierarchy and definitions in the corner were helpful reminders in the process. The 8.5x11 format made the tool more approachable and I could easily complete another one if it needed revision.

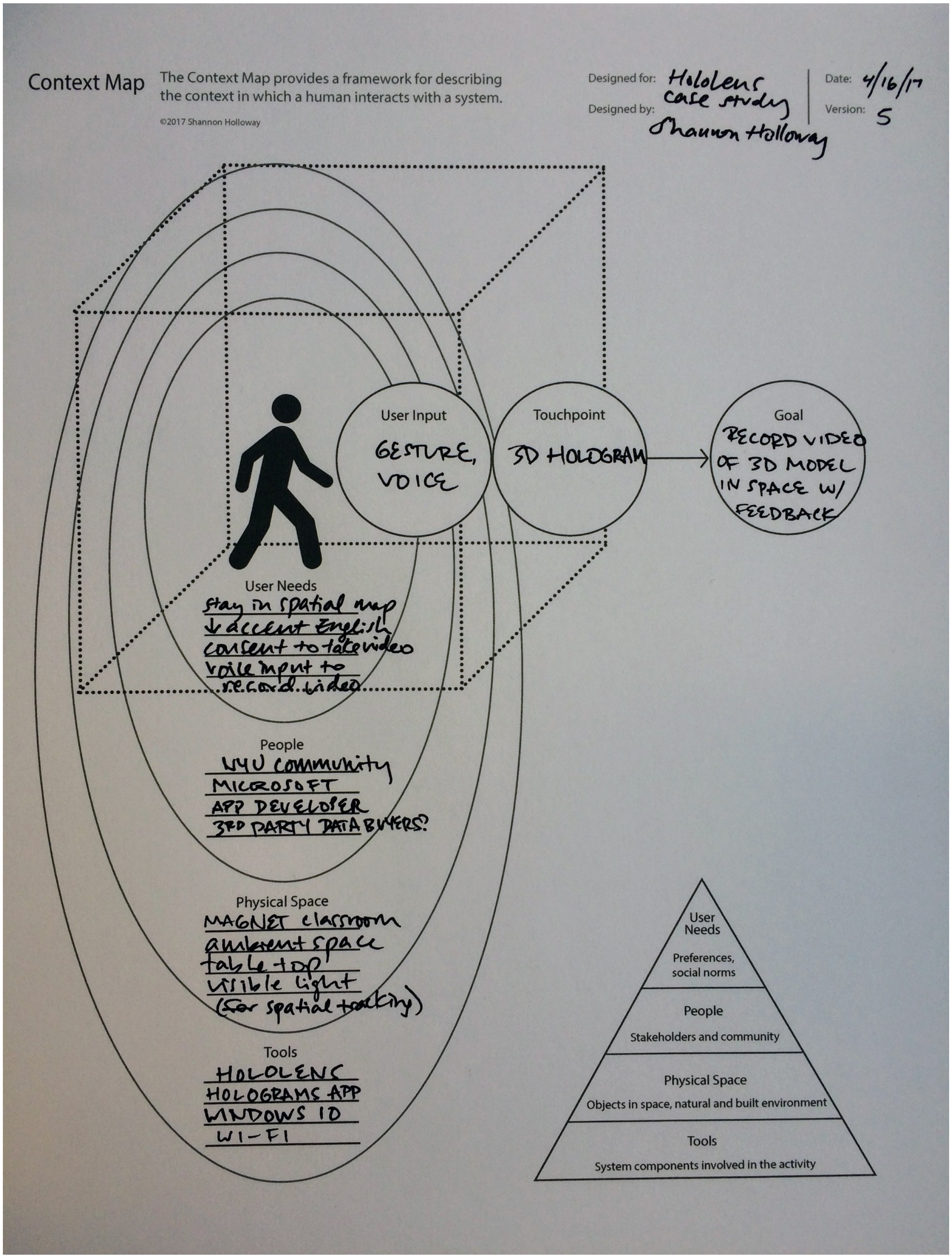


Figure 23. MR HMD case study in v5.

User Testing v5 with UX Design Students

I returned to the graduate-level UX course at NYU Tandon School of Engineering to user test v5 of the Context Map. First, I walked them through the hierarchy of contextual factors and descriptions. Then I showed them the diagram of user interaction in the context of use to provide the overall structure of the interaction. Afterward, I asked them to use the new version of the Context Map to analyze the same motorcycle designer scenario from the last round of testing. Once students completed the exercise they completed a brief survey, Appendix A.

The 9-question survey was designed to evaluate the Context Map and solicit student feedback. Questions 1-5 measured student comprehension and perceived usefulness of the Context Map. These multiple choice questions used a Likert scale to collect a range of responses and intensity of agreement or disagreement. Questions 6-8 were open response items about strengths and weaknesses of the Context Map. Finally Question 9 inquired about which field best described their background. This question asked students to check all that apply: Design, Engineering, Social Science, Other.

The survey results, Figure 24, show that students had a positive experience using v5 of the Context Map. While v4 was challenging for some students to translate the information in the scenario to the worksheet, v5 was easier to understand. 75% of respondents agreed or strongly agreed with the statement "I understood how to use the Context Map worksheet for the scenario." The Context Map was deemed useful in the design process by 69% of students. Overall, 62% of students reported that they would use the Context Map in their projects.

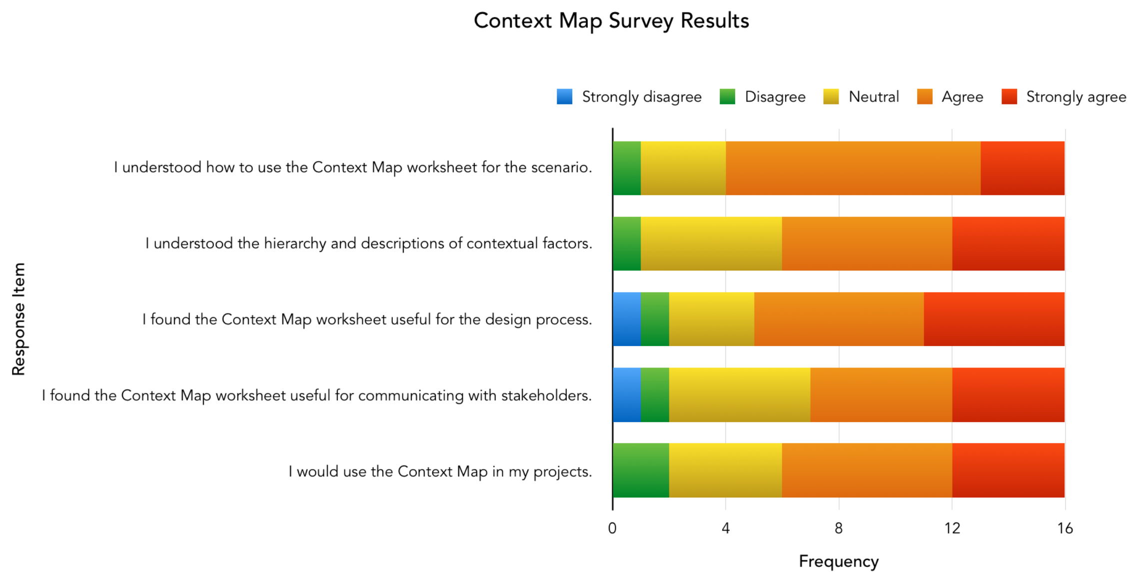


Figure 24. Survey results for multiple choice questions.

While there were few negative responses, some questions had a high number of neutral responses. When asked if they understood the hierarchy of contextual factors, 31% of students reported they were neutral. This sizeable number suggests a need for further explanation of the reasoning behind the hierarchical order relative to the user's experience. Answers to the open response items indicated changes to the terminology and descriptions as well as listing examples for each category would improve comprehension.

Students were confused about the role of stakeholders in the Context Map. 31% of students reported they were neutral about the Context Map's usefulness in communicating with stakeholders. This percentage, echoed by answers in the open response items, indicated students were unfamiliar with the term and/or had little experience working with stakeholders. Further, many students wrote about how they did not understand the involvement of other people at all:

- “I don't understand how/why the stakeholders and community fit into what the user is doing. The stakeholders are not the ones using the app, the user is. So why are they included in the functionality?”
- “Clarify People. What use does identifying stakeholders work with the app?”
- “I don't understand how stakeholder would get involved in this map.”
- “The wording of ‘People’ and ‘stakeholder’ doesn't intuitively make sense, and feels a bit disconnect to which design stage it could be used.”

These statements shed light on students’ mental model of direct one-to-one interaction between a user and system. Further explanation is needed for students to understand that the new range of input modalities in MR environments, regardless of the technologies enabling them, impact the people and environment in the context of use.

The survey results on the students’ backgrounds, Figure 25, were illuminating. Most students identified their background was in Design or both Design and Engineering, and positive responses correlated with these respondents. Negative responses correlated with those who identified their background was in Engineering. This finding points to a gap in reaching this particular audience. Further effort is needed to understand the engineering mental model and reasons why they disagreed with the terminology, logic, or visual representation of the Context Map.

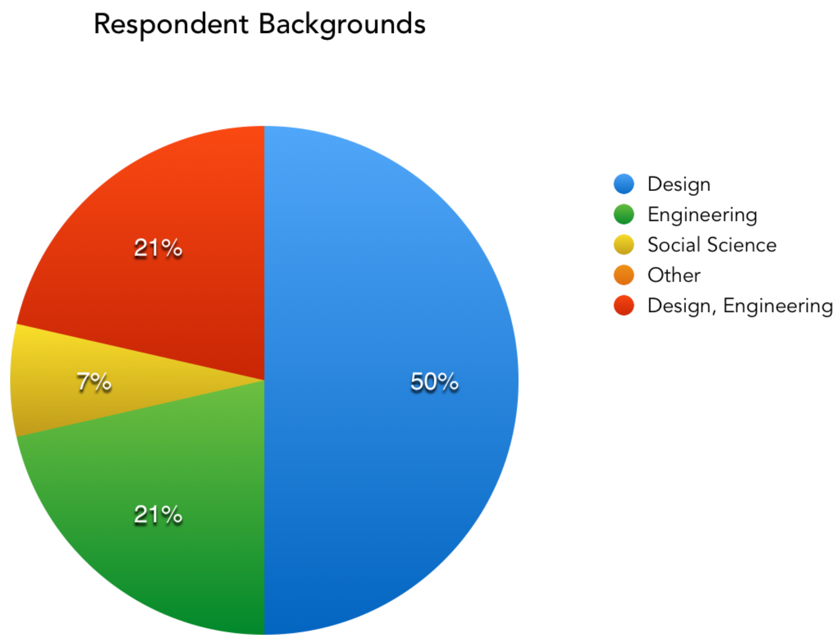


Figure 25. Survey results on respondent backgrounds.

CONCLUSION

In this thesis I researched and designed a method for HCD in MR environments. In MR environments, humans interact with real and virtual objects together in context. However, my research findings demonstrated that no existing methodologies effectively capture the user needs, people, space, and tools in a user's context to inform the design of MR environments. I developed a framework for describing the context within which a user interacts with a system. This framework proposes a hierarchy of contextual factors as they relate to the user experience.

My research informed the development of the Context Map, a lightweight tool for use in the design process. As demonstrated, the Context Map is an effective tool for understanding user context in the design of MR environments. This approach has been validated in two case studies in different MR environments. The tool can be applied in various MR projects regardless of the enabling technologies. The Context Map has proven value in the research synthesis, planning, and design phases of a project. It is hoped that use of this tool will improve UX outcomes which impact user acceptance of MR technologies and software project failures. Further, its use can aid in the design of more positive and holistic human interactions in MR environments. Arguably these everyday activities embedded in context are the site of our consciousness.

Further validation is needed for my framework and hierarchy of contextual factors. Input from both research and practice would identify contextual factors that are missing or need reinterpretation, and their hierarchical order as they relate to the user experience. Further research is needed on users of the Context Map. As the design of MR environments is an interdisciplinary endeavor, it is hoped that this tool is useful and accessible to people from a variety of disciplines and industries. The intended users of the Context Map are people involved in the design process including researchers, designers, engineers, and stakeholders. The tool has potential value in the design of software, hardware, services, immersive experiences, and architecture. Additional applications of the framework and the Context Map are needed to demonstrate their value in various project types and phases of the design process.

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APPENDIX A: THE CONTEXT MAP SURVEY

Context Map Survey

Please submit feedback regarding the Context Map and the design exercise you have just completed.

1. **I understood how to use the Context Map worksheet for the scenario.**
Mark only one oval.

	1	2	3	4	5	
Strongly disagree	◯	◯	◯	◯	◯	Strongly agree

2. **I understood the hierarchy and descriptions of contextual factors.**
Mark only one oval.

	1	2	3	4	5	
Strongly disagree	◯	◯	◯	◯	◯	Strongly agree

3. **I found the Context Map worksheet useful for the design process.**
Mark only one oval.

	1	2	3	4	5	
Strongly disagree	◯	◯	◯	◯	◯	Strongly agree

4. **I found the Context Map worksheet useful for communicating with stakeholders.**
Mark only one oval.

	1	2	3	4	5	
Strongly disagree	◯	◯	◯	◯	◯	Strongly agree

5. **I would use the Context Map in my projects.**
Mark only one oval.

	1	2	3	4	5	
Strongly disagree	◯	◯	◯	◯	◯	Strongly agree

6. **What aspects of the Context Map were most useful or valuable?**

7. What aspects of the Context Map were least useful or valuable?

8. How would you improve the Context Map?

9. Which of the following best describes your background?

Check all that apply.

- [ ] Design
- [ ] Engineering
- [ ] Social Science
- [ ] Other: ____________________