Delft University of Technology
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A MINOR TAXONOMY PROPOSAL FOR THE AMBIENT INTELLIGENT ENVIRONMENT (AmIE) DESIGN SPACE

A thesis submitted in partial fulfillment
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by

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SUMMARY

This research aims to create a minor taxonomy of the domain of Ambient Intelligent Environments (AmIE), sometimes simply called Ambient Intelligence (AmI). These refer to 'smart-,' 'intelligent-,' or 'assistive-' built environments including homes, schools, offices, museums, hospitals, libraries, stores, labs, prisons, warehouses, transport hubs, airports, parks, cities, etc. AmIE are often confused with (or described interchangeably as) 'ubiquitous-,' 'pervasive computing,' 'mobile computing,' or 'spatial computing;' as well as the Internet of Things (IoT) and building automation including HVAC automation. While AmIE comprise the aforementioned technologies, they specifically describe the paradigm in which these and other technologies (namely sensors, actuators, and processors) are outfitted in the built environment so that those places become sensitive and responsive to the presence, needs, wants, and preferences of their inhabitants. Given that AmIEs require an array of computing technologies to function, they are necessarily complex design-engineering systems that rely on some level of algorithmic taxonification and, as such, are vulnerable to perpetuating harm in so far as biases have been codified therein. This research engages this complexity and risk of harm perpetuation by utilizing Minor Theory (also 'minor theory') as a theoretical lens through which to begin to move towards values aligned taxonification of the vast AmIE design space. Through a series of sequential literature reviews, this work offers a jumping off point for the continued taxonification of the AmIE design space by 1) introducing and applying minor theory as a method for data analysis and by 2) proposing three thematic vectors to consider in codifying an AmIE a design space: attunement, embodiment, and anti-fragility.

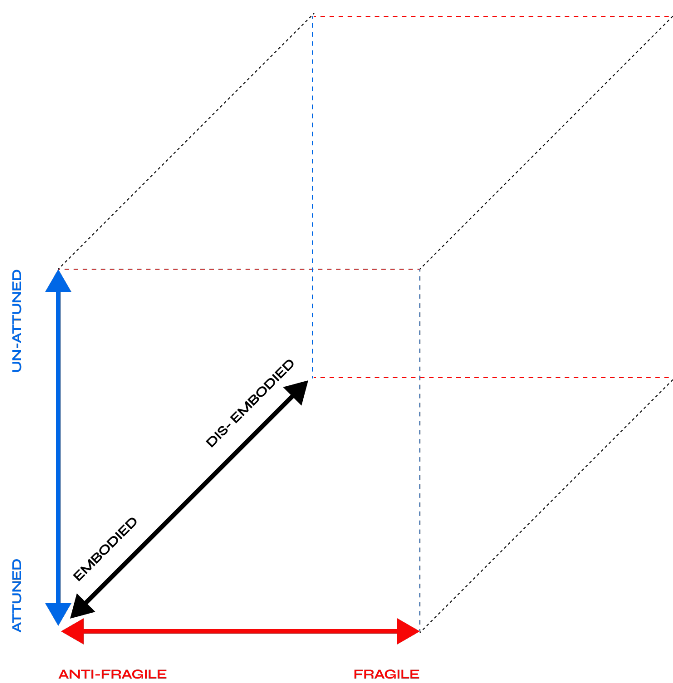

Figure 1 Visualization of how the three thematic vectors create a conceptual (as opposed to functional) design space.

For my mother.

Your poetic nature, advice on writing, and hope
that above all else I might always follow my passion
accompanied me every step of the way.

You are missed beyond words.

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Producing this work was made possible by the generous support of others and the constant companionship of Cobi without whom I may never have left my computer. Over the course of its five-month production, my singular topical focus was ambient intelligent environments. And for a topic I already loved and frequently discussed with anyone who had any interest at all on the topic, during the course of producing this thesis (across six cities in two continents) all of the people I met and talked with for more than five minutes inevitably indulged and engaged me in clarifying my thinking and sharing my excitement. I am deeply grateful for this support and curiosity (and am happy to report that I will continue to be in need of conversations like these as submitting this document marks the start of my doctoral studies journey).

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I also want to extend my acknowledgment to those supported me in defining, navigating, and accomplishing this work outside the boundaries of academic advising. To my godparents for letting me lodge with them while I wrote this thesis, for keeping the printer stocked with paper and the fridge stocked with snacks, and for discussing my work in detail as it solidified draft by draft. It inspires endless awe in me that our paths ever crossed, that you and my mother had the good sense to become beloved friends, so that I could be a part of your family. To my undergraduate co-thesis advisor, the late social psychologist, Dr. Ron Cohen, who always told me to tighten my research focus, I am still trying to fully integrate that lesson. To Don Sherefkin, my undergraduate architecture professor and co-thesis advisor, who instilled in me buildings are only accessible when they are accessible to everyone. To Brandon Harper who introduced me to the term 'ambient intelligent environments,' the professional ripples of this simple happenstance are felt to this day. To Clark Dodsworth who inspired me to be critical of outdated ideas that ambient intelligent environments must inherently have built-in sensors and actuators, and whose enthusiasm for the field is still palpable after working in it since the early days, your excitement makes me confident a career in this field will be full of compelling and inspirational challenges. To Eugene for selecting the font and Oskar for helping with the visuals.

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PREFACE

> **"Rather than the bracketing characteristic of phenomenology, or the denial of experience found in structuralism, Lefebvre wished to see how the structures, signs and codes of the everyday integrate with biographical life…In recent years there has been a noticeable shift from questions of temporality to those of spatiality. As Frederic Jameson asks, "why should landscape be any less dramatic than the event?" In his work, Lefebvre suggested that just as everyday life has been colonized by capitalism, so too has its location — social space. There is therefore work to be done on understanding space and how it is socially constructed and used. This is especially necessary given the increased importance of space in the modern age." (Elden & Philosophy Documentation Center, 2007)**

My very first memory is spatial.

I am two and a half and pressing my hands up against a floor-to-ceiling curtain window. Through the glass I can see straight across San Francisco's Sunset district, over Golden Gate Park, all the way to the Richmond. The outside light is dimming quickly as the winter sun sets to the West highlighting the twinkle of the streetlights dotting the horizon. This is always how the memory starts, me, hands up against the glass, the view ahead. And that's the only part of the memory that is cinematic. The rest of the memory is spatial; planar even, like architectural sectionals.

There is the plane of the window in front of me.
The plane of the chairs directly in front of the window.
The plane of the waiting area behind me; and beyond that
The plane of and array of columns delineating the circulation space for the elevator.
There is also the plane of a hallway somewhere to my left.

Navigating this memory is like using a joystick to pan the camera in a video game where the feeling that panning to view any given plane evokes is what is most notable. Looking out the window feels safe and generous, the uninterrupted view is all mine to admire and absorb undisturbed. Panning directly next to me, is my mother; I cannot see her, rather I know it is her by a particular sensation of comfort. Panning deeper into the waiting area, I feel the presences of others, and an awareness that I am not, in fact, in my own little world. It is at this plane that I am aware that the interior lighting gives off a muddy industrial orange glow, and that there are more planes further still from my perch like the circulation space. I start feel a worrying agitated bustle of new emergency room visitors entering behind me by the elevators. My worry grows as I pane finally to the hallway which starts behind me and to my left, I feel the medical staff in there and what I suppose must be a sense of dread about my impeding visit with the emergency room doctor.

And that is it, that is the memory: architectural and sensory.

Figure 2 Spatial memory of Robert H. Crede Ambulatory Care Center on UCSF's Parnassus Heights campus.

I feel as if I have always navigated the world through the lenses of architectural and the sensory. I have also gotten the distinct sense that not everyone else does. Thus, I have reasoned that perhaps I have some "innate" sensitivity which predisposes, nay, obliges me to see the world predominantly through these lenses. To this end, I have collected two leading explanations for how this sensitivity emerged.

First, a proposal that this sensitivity is both literal and literally-innate, my nature, if you will. Perhaps my sensitivity is in fact a sort of socio-spatial synesthesia that crosses the senses of perception of affect with perception of real-Euclidean geometry. As a temporal synesthete already, I am no stranger to conventionally separate senses being intimately and inseparably attached. In my case, time is inextricably connected to my visual field and perception of space. And this might be the sensitivity itself as research indicates that temporal synesthetes are more accurate in their perception of Euclidean geometry then the general population. On the other hand, it might have everything to do with how I was raised, the way I was nurtured. My mother was a psychologist with an uncanny capacity labeling people's affect and from the age of 5-11 we remodeled our home ensuring that I was consistently surrounded by floorplans and trips to the San Francisco's Department of Building Inspection's Permit Services Office. It doesn't get more concrete than that: I was seeped in buildings and behavior for the entirety of my youth.

If I were someone else, whether I have biological or cultural predisposition to space and affect might have remained a casual and fleeting inquiry. The unique thing about humans, they have unique interests. An interest in the relationship between space and affect: unique a special interest, "*did you know 'drunk-tank' pink-walls lead to agitation long-term?";* a conversation-starting party trick, *"when you enter a hotel room, do you choose the side of the bed nearest or farthest from the door?"*; a particular affinity for spaces that tickled a specific sensory experience in myself like the Elbphilharmonie in Hamburg *which kept me oscillating between feelings of bright awe and directional squishing*. Instead, and for whatever reason, for the last two decades my singular intellectual obsession has been understanding the science of the built-environment's effect on human experience.

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This obsession started in earnest as a high school student in the mid-late 2000s. During this time, any bookstore I passed required a quick skim for any books that might answer my question. My routine thumbing through the social science, the psychology, and finally the architecture books always left me empty handed, or with cousin concepts:

- The Situationist City by Simon Sadler (1999) (Sadler, 1998)
- Design of Everyday Things by Don Norman (1988) (Norman, 1998)

PREFACE

This was still the early days of the maturing-internet, where adults assured us teens that all knowledge could still be found at your local library, reminisced about printed copies of spark notes, and discouraged us to research off-line because it was, "lazy." This was early days of Twitter, LinkedIn, and Google Scholar, aka, where we now find and request niche-and pertinent content before we know the right place to look. Reddit and Quora emerge in this time as well, but it's still before the time that a post will receive enough engagement to yield meaningful answers. Which is all to say, in this temporal-landscape, I knew only about as much as the book-store clerks, the librarians, and adults in my life knew. And lucky for me, most of my parent's friends were architects or psychologists. They must have the answer. Unfortunately, whether it was because they didn't seem to see the link, they saw the link but didn't know where to point me, or, worst of all, never could imagine how serious my query was, for years I was left without the empirical evidence I sought.

That all changed on an after-school walk back home with my mother when we ducked into Bird and Beckett Books & Records in San Francisco's Glen Park neighborhood. I cannot recall what drove us into the set-back store that particular afternoon, but my mother and I, as always, slid into our respective section. She glid her way to the poetry whilst I did my procedural check through the overflowing redwood shelves: first social science, then psychology, and then architecture. And there it was.

There was nothing about its title that could have tipped me off, there is no knowing what insighted me to reach for the bulky and dense of the book with a soft matte yellow book jacket, A Pattern Language (Alexander et al., 1977). I remember everything about that moment, the sun flowing through the southwest windows, the weight of my pop-punk-checked messenger bag (my desperate attempt at coolness) dragging me down as my restlessness changed to patience (my mother could read as much poetry as she wished by my watch). It was in that time-warped afternoon that I first scanned the canonical architecture text written by a cohort of UC Berkeley faculty in the 1970s, Christopher Alexander, Murray Silverstein, and Sara Ishikawa. The pages were as thin as dictionary, and for over 1000 pages they juxtaposed social phenomenon with architectural designs with tiny chapters with titles like, "Dancing in the Street," "Raised Crossings," Corner Grocery, "Number of Stories," "Stair Seats."

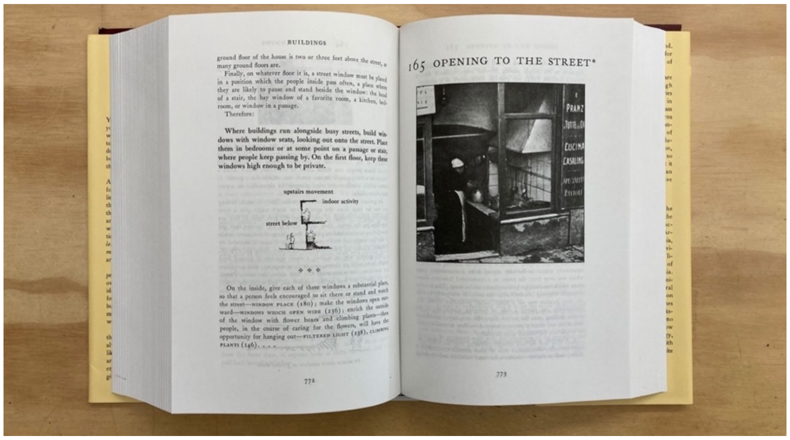

Figure 3 A page from A Pattern Language by Christopher Alexander, Murray Silverstein, and Sara Ishikawa

Finally. It felt like someone else got it.

Eventually, my mother swung by my perch, it was time to go home, *"this is what I mean!,"* I exclaimed in a book-store hush. It wasn't, well not exactly. The principle of relating built environment conditions to human experiences was spot on. But the "science," perhaps it wasn't as rigorous as I was truly seeking. Regardless, A Pattern Language is the intellectual inspiration on which my research and this work in particular rests: there are identifiable patterns between the built environment and human experience. My ambition, to surface identifiable patterns scientifically, to understand how to codify that science into ubiquitous computing technologies which turn traditional built-environments into ambient intelligent environments, to ensure such codification is done in a value-aligned way.

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The goal of terminology is to afford conversers access to shared mental models. When we lack shared terminology, we often lack the capacity to share a mental model. This is a phenomenon we all know well, we even share terms in the form of proverbs, idioms, and adages to invoke this phenomenon as a mental model: lost in translation, clear as mud, head-scratching. Simply, communicating in such a way that you are certain you are understood as you intend is hard. One way we have found to simplify this challenge is using shared terms which afford access to shared mental models on which understanding relies. In professional contexts, the value of relying on shared terminology cannot be understated (Drury et al., 2020; Garcia & Calantone, 2002) where knowing the correct terms is like having the right keys.

While I was desperate to address this topic of responsive environments from my earliest memories, the fastest way to stifle enthusiasm, is to give it no starting point and no history. While my thinking was isolated, it wasn't singular; thinkers were already asking (and answering) the questions I was asking, just using terms I couldn't yet fathom.

With the painful memory of searching for the right terms for over a decade, in addition to documenting my work, I aim to address the terminology relied on in this work and field for the uninitiated as we go along so that you may neither feel out of your depth, nor abandoned, as we move forward. So that, in the event that the young girl I once was happened upon such a text, she would be semantically up to speed by its end.

It took me the better part of fifteen years to acquire the set of conceptual keys that allowed me to access the work of others addressing the same mental models as myself. Why? Because, semantically, talking about 'space,' 'design,' 'technology,' and 'experience' is tricky. If I say, "I research how space effects humans," you might understand I study outer space and its effect human biology, for, which is far from what I do. If I say, "I research computational architecture," and you know a bit about building, design, and architecture you might understand I study designing buildings with computers programs like AutoCad or SolidWorks; whereas, if you are more familiar technology and engineering you might understand that I study the rules and methods for defining computing functionality as computer architects do. These understanding would, also, be incorrect.

It wasn't until I attended a conference before I returned to academia that I received the final key necessary to access the domain. There a Microsoft researcher, Brandon Harper, gave a keynote on ambient environments. He talked about the phenomenon of environments that responded to the mood of users, giving the example of a couple who lived together. One day, one of the partners returned to the apartment where the other partner already was enjoying their evening. Fun dance music was playing, and the whole vibe was altogether jovial. But the returning partner had just gotten some bad news and was in a less than jovial mood. Harper posed the challenge to the audience, "what is the ambient environment to do?" Does it alert the partner dancing through the house to temper their mood, or does it inform the returning partner that they will be entering a dance party? Or does it do something between the two, or even radically different? These were the design questions I too wanted to answer.

I'll never forget how specifically childish and giddy I felt when I complemented Brandon on his keynote afterwards. "How did you settle on that term?" I gawked. Which is to say, I behaved like he had made the key I sought, not that it might have already existed, and I simply hadn't acquired it yet. He replied graciously, didn't even let on that it was a term that had been around since the 1990s, and then spent the better part of an hour discussing the idea of a built environments that were responsive to the experience of the humans inhabiting them with me. In the most literal sense, this serendipity served to open a whole world of research and thinking to me. It brought me back into academia, and is why, when I introduce myself and my work I now say,

"I research alignment problems in the design space of ambient intelligent environments."

When I do this, of course, I understand that most listeners have little to no comprehension of what I am referring to. For while the phrase comprises common terms—"alignment," "problems," "design," "space," "ambient," "intelligent"—in this specific ordering they are uncommon jargon. So, even though its correct and succinct, I rarely introduce myself in this way, because, as we have established, without shared terms, we lack shared mental models. And without an existing mental model, your brain will attempt long-form-understanding:

- *"Alignment Problems"*
- *"Design Space"*
- *"Ambient Intelligent Environments"*

You notice there are two references to spatial concepts: 'space' and 'environments' which comprise two compound nouns: 'design space' and 'ambient intelligent environments.' Right-off-the-bat, you are certain that you've never heard of an 'ambient intelligent environment,' but you think it sounds computer-y. (You're right.) And since you definitely know what 'design' means, you don't realize until you have competed your initial polite and encourage nodding that 'design space' as a compound noun is also unfamiliar, much like 'alignment problems.' It is a well-established linguistic phenomenon to encourage the speaker by default, and in your well-rehearsed conversational turn taking you accidentally gas-lit the fact that while yes, each word singularly has meaning to you, together, you're not convinced you know what I do. Let's remedy that.

Ambient Intelligent Environments

The goal of ambient intelligent environments is to make the built environments we inhabit (invisibly) sensitive and responsive to inhabitants. In order to be responsive, fundamentally, ambient intelligent environments are computational built environments. Which is to say, that while there is an argument that any environment can be sensitive and responsive to an inhabitant's presence, needs, wants, and preferences, what makes an ambient intelligent environment different from any other built environment is that the sensitivity (and responsiveness) of the environment is driven by the automation and artificial intelligence of computing technologies. In this way, ambient intelligent environments necessarily leverage automation and artificial intelligence, and are thus, fundamentally, computational artifacts that rely on the mechanization of the built environment to articulate their computational awareness and decision making.

Figure 4 Visualization of sensing and actuating in an ambient intelligent environment.

Ambient intelligent environments' goal is for computing technologies to fall into the background. The field is colloquially called "zero UI," indicating that a fully ambient intelligent environments will have no visible interface. Instead, the human body, voice, and biometric data become the interface; all of which rely on algorithmic decision-making to instigate actuation in a user's ambient intelligent environment. In this way, the boundary between the tangible drifts imperceivably into the intangible. This is so both in the way the user experiences and engages the ambient intelligent environment, and in the way that the professionals conceptualize design solutions for the ambient intelligent environment. Let's look at an example. If the space you are inhabiting now, be it your living room, a form of transit, a public garden or recreation area were saturated in imperceptible computing technology, and those computer technologies change the lighting without your input, did you invoke that change? A true if a tree falls in the forest conundrum. The answer is not simple. The answer is also not no. Rather, in an ambient intelligent environment, the answer is yes, and. Which is to say, perhaps your stress levels were raising and the system had learned lower lighting supported you de-stress. It is this complexity which design spaces attempt to conceptualize.

Design Space

Design spaces are a type of taxonomy that help us not only label and order things, but also help us generate new ideas and evaluate existing ones. At their cores, and thus their name, design spaces are an invocation of the idea of space, area, domain, geometry, in other words, a multi-dimensional container. In so far as a design space is a multi-dimensional container, the container includes the full array of all possible variations of any given design, with any singular variation being a location in this container.

Say we are discussing the design space of driving and agree that driving has three parameters that effect the possibilities for driving: go, stop, steer, then each parameter gets an axis. With three parameters we are left with a 3D cartesian graph, where each variation of each parameter gets a unique point where each variation of each parameter intersects at a single point. Which, in theory, we can plot. When plotted, two- or three-dimensional design spaces are strong visual tools for evoking spatiality.

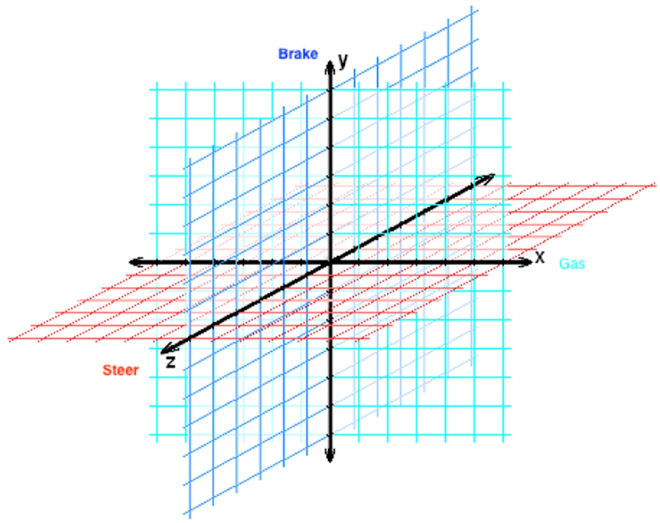

Figure 5 Cartesian mapping of three parameters

Alignment Problems

'Alignment' is a concept popularized by book, *'The Alignment Problem,'* which investigates the misalignment between algorithms and humans' values, intentions, instructions, and preferences (Christian, n.d.). The concept of alignment is proximal to goals of development engineering which is concerned with creating, testing, and evaluating "technological interventions designed to improve human and economic development within complex, low-resource settings," (UC Berkeley, 2022). Being aware that misalignment between computational design and humans is critical in ambient intelligent environments because of their reliance on machine learning. Despite the flourishing academic discussion on algorithmic decision-making, the domain of spatial computing is only now picking up visibility since the "metaverse" hype began last fall. Ambient intelligence, however, remains deeply under studied as a technology source vulnerable to misalignments, and questions like the following remain underexplored:

- *Whose needs values, intentions, instructions, preferences are prioritized when multiple users are in the same ambient intelligent spatial computing environment?*
- *In principle, policy should be technology-neutral to be future-proof. In the context of ambient intelligent spatial computing technologies, are there any technologies that justify technology-specific regulatory intervention?*

- *Finally, how do we ensure inclusive ambient intelligent spatial computing environments that do not discriminate based on either demographic or human factor status?*

It is my ambition in my work, of which this thesis is a major start to this goal, to perform systematic evaluations into questions like these; to better understand what is appropriate, reasonable, just, and ethical in the paradigm of ambient intelligent environments, e.g., address what I call the Spatial Alignment Problem (SAP). An example of what I mean by this is conducting scientific research to credibly answer questions such as: *how does ceiling height affect productivity, and under what conditions is it reasonable to intervene by changing the ceiling height in order to change the user/s productivity?*

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I introduce my passion for this work because I am called to it. The following work is my first extended contribution to this topic, but also a mere fraction of what I am thinking about, have been thinking about, for as long as I can remember. I can't be sure my proclivity for the topic is biological or social (or neither) it really doesn't matter, as it is here to stay. What matters is my passion and curiosity for this domain, my eagerness to learn as much as I possibly can, contribute in ways that afford meaningful and salient and scientifically significant experiences in the built environment.

I am gladdened that the delivery of this document to the Technical University of Delft coincides with the start of my doctoral work at the University of California, Berkeley. The spatiality of returning to where I grew up to pursue the topic which grew me up is not lost on me. For anyone reading this who knows me, please turn to the acknowledgements. For anyone who does not, I hope you allow yourself to always be curious and discerning about the built environment around you; and if this topic calls you as it calls me, I will be glad to connect.

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1. INTRODUCTION

Ambient intelligent environments (AmIE) are computational design-engineering systems (also called 'cyber-physical systems') that function through a vast array of **sensors** gathering data, **processors** processing data, and **actuators** acting on data in the built environment. Through this saturation of technological artifacts—both digital (processors and data) and physical (sensors and actuators)—AmIEs transform the real Euclidean space around inhabitants into agentive spaces that are sensitive and responsive to inhabitants' presence, needs, wants, and preferences. Additionally, this technological array transforms not only the built environment (and objects therein) but also inhabitants' bodies themselves into interfaces through which to interact with the AmIE.

In its comprehensiveness, the AmIE paradigm opens a vast landscape of novel design possibilities for the traditionally static built environment. Current grocery store AmIEs, for example, allow shoppers to shop and checkout without going to a teller or self-scanning their own items. Instead of barcode scanning, AmIE grocery stores leverage an array of sensors to track individual shoppers and the items they take off (and put back on) the shelves, processors to accurately add (and remove) items from their virtual shopping cart for billing, and actuators to allow for entry once banking information has been verified and exit after virtual purchase has been completed. In the future, AmIEs could become even more complex. Take, for example, the ceiling in a conference room might rise (actuation) after the biometric data of the inhabitants (sensing) indicated people were getting tired and ceiling height changes was a known factor in contributing to overall interaction on the team (processing). Or perhaps, in a less functional example, a few weeks in advance of an adult-child coming home to visit their parents in their smart home a hologram of a book the adult-child is reading might appear on the parent's coffee table (actuation) after the adult-child told their own smart own smart home that they would love to discuss the book with their parents when they visit (sensing) and the two smart homes had all of the necessary consent agreements to share such information between them (processing). The possibilities are endless, defined only by the limits of science.

Typically, the discussed scientific limitations of AmIEs are about the capacity of the technologies themselves; i.e., *can the sensor be more precise?*, *can the actuator be more compact?*, *can the processor work without internet?* There is less discussion about the nearly incomprehensible vastness of the possible constituent elements of the AmIE design space. Which is to say, in addition to the important scientific questions around refining the technologies which enable AmIEs, there are equally important scientific questions about conceptualizing all of the constituent elements of an AmIE. This ambition to identify all possible elements resembles the work of codifying all the chemical elements in a periodic table or the work of codifying all the genetic information of an organism in a double helix. What these two examples highlight is that some scientific knowledge is contrived, like the periodic table, while other scientific knowledge is elemental, like the double helix. Despite this difference, both examples are understood as theoretically sound comprehensive scientific knowledge. In this way, as mapped elemental codifications, the periodic table and double helix support scientists align so that they know what they are talking about, what they should focus on, what has already been addressed, and what still needs more attention. While architecture has a long scholastic history, comprehensive scientific codification of the domain has not been the fields' primary concern. As such, science codifying the built environment in so far as it is a neuro-socio-phenomenon is lacking. Which is to say, there is no existing theory akin to the periodic table or double helix that affords those creating or studying built environments to understand how variations in built environments effect specific biological and social responses. In a non-AmIE built environment this lack has proven relatively inconsequential. As outlined in the examples of the AmIE store, conference room, and homes, AmIEs necessarily require codification about how things (should, could, might) interact. In this way, a lack of existing codified ground truth about built environments is a significant scientific limitation to the field of AmIE.

The heralding in of AmIE necessarily invites with it a deeper understanding of how spatial variations in built environment effect inhabitants. For the first time in recorded science, compressive codification of the built environment as neuro-socio-phenomenon has, though inadvertently, commenced. While there is no lack of ethnographic and anthropological research on built environment as neuro-socio-phenomenon, AmIE ushers in the first ever possibility of continuous, longitudinal observation at scale. It is this scale which presents an opportunity to produce rigorous theory codifying (all) the elements of built environments as effectors of changes to human biology and experience. However, because such a codification does not yet exist, in the interim, proposing theory on the constituent parts of the AmIE design space is necessary to further any future ambitions of more comprehensive scientific codification. This work seeks to address this emerging opportunity space by proposing thematic vectors of the AmIE design space in support of design-engineering researchers working towards systematic agreement of the constituent parts of AmIEs with special attention paid to:

- AmIEs newness as a limiting factor in domain-specific best practices, theories, methods, tools, processes, etc.
- AmIEs complexity as multi-agent design-engineering paradigms

Understandably, given AmIEs are a relatively new design-engineering paradigm only conceptually formalized in the 1990s with few existing examples, domain-specific tools are limited. However, unlike prior design-engineering domains, the field of AmIE is emerging at a time where design-engineering research has fully matured. Which is to say, the scientific study of domain-specific design-engineering best practices, theories, methods, tools, processes is well established. In this way, AmIE research is uniquely situated to learn from previous design-engineering research and doesn't need to re-invent the wheel. Previous research has indicated that this is already happening (Ballestas et al., 2021; Zimmerman & Forlizzi, 2014), which at a first glance is encouraging. However, AmIEs are fundamentally unlike almost all other design-engineering paradigms in so far as the levels of complexity they must manage is orders of magnitude beyond near design-engineering paradigms like mobile user interface design, product ergonomics, or service design. For this reason, unexamined re-tooling of best practices, theories, methods, tools, processes, etc. from other domains is likely un- or under- equipped for the uniquely complex AmIE design space. Luckily, because of the maturity of the design-engineering field, AmIE-specific theories and methods are inevitable, and as AmIE-specific tools emerge so too might formerly-unimaginable design solutions. It is in the interest of supporting design-engineers and design-engineering researchers in the unique challenges faced in creating AmIEs, including the identification of novel opportunities, that this work seeks to support by proposing thematic vectors that underscore the complexity of AmIEs.

This complexity is mediated by the fact that AmIEs are computational design-engineering systems that rely on an array of machine automation and machine learning. On the one hand, this mediation is one of adding additional levels of complexity in that all possible interactions in an AmIE must be codified so that a computational agent can act. Which is to say, as discussed above, the built environment is complex in and of itself and adding a machine agent which can make changes to the built environment only increases that complexity. On the other hand, the act of codifying all possible interactions in an AmIE is also an act of simplification in so far as the boundaries become defined. Scilicet, defined boundaries indicate that there is some agreement about what constituent parts exist within the frame, and therefore also imply what is outside of the domain. Regardless of how complex, AmIEs are complex, and their complexity extends to their reliance on machine automation and machine learning. This dependance is at once exciting and worrying.

As established, AmIEs rely on an array of sensors, processors, and actuators. In other words, AmIEs are data producing and data distilling systems. The exciting opportunity, as mentioned above, is that there is the possibility to understand how human biology and behavior is effected by changes in built environment conditions as articulated by AmIEs. AmIEs rely on sensors in the form of a watches, motion sensors, shoe inserts, stool-collecting toilets, infrared cameras, augmented reality glasses, etc. to draw conclusions about what is happening therein. Sensors, thus, produce data from biometric data (e.g., hormone levels, heart rate, temperature) to spatial data (e.g., location in space, time spent in motion or at rest) to frequency data (e.g., how often a particular object is looked at or how often the volume is changed) to ambient data (e.g., humidity or air quality) and beyond. Theoretically, AmIEs rely on a constant stream of such sensor-acquired data for a processor to make real-time continuous adjustments. Simply, this is a lot of data. It is the role of design-engineers to afford inhabitants of AmIEs an array of services based on correlations that are found in this data, e.g., motion sensor under bed triggers morning routine (lights on, coffee start, news read aloud) on weekdays after 6am. There is also another, more latent, possibility when such a vast array of data is present: discovery of formerly never considered correlations (e.g., turning head slightly to the left frequently while in conversation is correlated with changes in stress hormones and intervening with turning the color of the lights slightly more towards red tones re-levels stress indicators). This is where the worrying side of such a comprehensive and constant stream of data shows itself.

In computer science there has been an increasing critique about how data is acquired and processed. When the outcome of such data acquisition and sequential processing goes awry, especially when that outcome perpetuates harm, scholars suggest there is an 'alignment problem.' Alignment problems were conceptually popularized by the book, *'The Alignment Problem,'* which investigates the misalignment between algorithms and humans' values, intentions, instructions, and preferences (Christian, n.d.). However, there is little discussion in the literature around alignment problems specific to AmIEs, which take data acquisition and processing to a whole new scale. This work introduces minor theory as a theoretical lens through which to negotiate the opportunities and challenges that come with fundamental dependance on machine automation and machine learning in AmIEs so that AmIEs discover and support aligned experiences, i.e., increasing spatial alignments, as well as center harm reduction i.e., avoid spatial alignment problems.

2. BACKGROUND

To align specialists from an array of backgrounds, in addition to clarifying the prior work on which this work relies, this section also aims to introduce core topical work in domains on which this research relies—computing wave history (Sec. 2.1), mechanical and software engineering (Sec. 2.2), design-engineering (Sec. 2.3), and minor theory (Sec. 2.4)—as well as solidify terminology as used in this work.

2.1 Ambient Intelligent Environments, Precursors

Discussions of AmIE typically situate the paradigm as an out-growth of the ubiquitous computing wave. The wave model of computing history affords the most succinct explanation of the history of AmIE emerging as a computing paradigm.

2.1.1 Computing Waves

Computing waves are used to invoke a history of computing innovation. They are based on Kondratiev's Waves of Innovation, which start at the beginning of the First Industrial Revolution with the invention of the steam engine in the 1780s. Kondratiev's Waves of Innovation were proposed by Soviet economist Nikolai Kondratiev in his book, '*The Major Economic Cycles.'* Therein, he proposed a cycle-like economic phenomenon of waves that consist of alternating peaks and troughs of sectoral growth which occur in roughly fifty-year increments. Critics of the eponymous K-Waves say the whole concept is apophenia, that the waves are a recognition of patterns that might not even exist. Despite the controversy, K-Waves made a big dent in the imagination of technologists and have been leveraged to explain the rapid growth of technological innovation, namely, in the conceptualization of computing waves.

Since the mid-90s, computing waves have been used as a way of describing the three largest innovation cycles in computing. While there are some discrepancies in the titling of each of the three (sometimes four) computing waves, there is consistency in terms of what each wave is meant to describe. Namely, each wave describes a discreet computing type as a direct relation to the number single users it is designed to serve.

- **Mainframe Computing** (One Computer, Many Users)
- **Sever Computing** (Many Computers, Many Users)
- **Desktop Computing** (One Computer, One User)
- **Ubiquitous Computing** (Many Computers, One Users)

Table 1 Computing Waves

WAVE 1 **Mainframe Computing**	WAVE 2 **Desktop Computing**	WAVE 2.5 **Server Computing***	WAVE 3 **Ubiquitous Computing**
refers to mainframe computers, i.e., single computers serving many simultaneous users.	refers to desktop or personal computers, i.e., single computers serving a single simultaneous user.	refers to server computers, i.e., many computers many simultaneous users. (*typically omitted in wave discussions)	refers to a ubiquity of many smaller computers, i.e., many computers serving a single simultaneous user.

2.1.2 Ubiquitous Computing (UbiComp)

The term ubiquitous computing is attributed to former Xerox CTO, Marc Weiser who defined the term for the first time in his paper, 'The Computer of the 21st Century' (Weiser, 1991). In the intervening two decades since Weiser proposed the term, computing waves and their subtypes have codified further, and ubiquitous computing has come to refer a ubiquity of many smaller computers which serve a single simultaneous user. In this sense, UbiComp has three sub-types: mobile, pervasive, and spatial computing.

Table 2 Ubiquitous Computing Sub-Types

Mobile Computing	**Pervasive Computing**	**Spatial Computing**
UbiComp with mobility but without (inherent) exteroception is Mobile Computing. *When computational-exteroception is present, Mobile Computing transforms to Spatial Computing*.	UbiComp without mobility and without (inherent) exteroception is Pervasive Computing. *When computational-exteroception is present, Pervasive Computing transforms to Spatial Computing*.	UbiComp with or without mobility but with inherent exteroception is Spatial Computing.

Confusingly, the boundaries between the three UbiComp sub-types are not as rigid as the boundaries between the computing wave types. Instead, UbiComp sub-types are distinct from one another based on both their mobility and their computational-exteroception[1]. Which is to say, mobile computing and pervasive computing are distinct from one another based on the fact that mobile computing is inherently mobile (e.g., a mobile phone or a smart watch) and pervasive computing is not inherently mobile (e.g., a CCTV camera or a smart fridge). Here begins the porousness of the UbiComp subtype boundaries: while a smart fridge and CCTV camera are technically movable, they are not exactly mobile, but when a CCTV camera is in the form of a GoPro on a helmet of a traffic officer, the device might be considered a type of pervasive computing. And when a CCTV camera is embedded in a drone, it then can be considered a type of spatial computing.

2.1.3 Spatial Computing (SComp)

It could be argued that Spatial computing (SComp) is not a distinct subtype of UbiComp, but rather an expression of UbiComp's subtypes pervasive and mobile computing. Said another way, SComp is any kind of UbiComp that leverages exteroceptive computing (through either deterministic or nondeterministic means[2]) to track (events in) a real Euclidean space.

Table 3 Computing Waves and Subtypes

WAVE 1 Mainframe Computing	WAVE 2 Desktop Computing	WAVE 2.5 Server Computing	WAVE 3 Ubiquitous Computing				
			Mobile UbiComp	Pervasive UbiComp	Spatial UbiComp		
					Automobile SComp	Mobile SComp	Immobile SComp

In this way, SComp can be further divided, based on mobility, into three subtypes: automobile, mobile, and immobile. The shared characteristic of autonomously mobile SComp is the ability to navigate successfully (i.e., move without incurring or causing unintentional physical harm for

[1] Look to section 2.2 for a discussion of computational-exteroception.
[2] Look to section 2.2 for a discussion of determinist and nondeterministic methods in computing.

extended periods without human intervention). Whereas the shared characteristic of mobile SComp is size (i.e., it can be moved but doesn't move itself) and the shared characteristic of immobile SComp is omnipresence (i.e., it cannot be moved, rather, it is built-in or contiguous and thus, fixed).

Table 4 Spatial Computing Sub-Types

Automobile SComp	Mobile SComp	Immobile SComp
SComp artifacts which can navigate unsupervised through real Euclidean space. *This is the simplest of the three SComp sub-types to conceptualize, as they have the most concrete shared form-types, namely vehicles and robots.*	SComp artifacts which can be moved through real Euclidean space, but such a movement is reliant on another human or machine actor. *This is where most consumer SComp artifacts are found, namely, smart connected devices and extended reality devices.*	SComp artifacts which are either too large to move or are immobile by virtue of being digital. *Immobile SComp comprises building automation, ambient intelligent environments, the internet of things and the spatial web.*

Complicating matters further, when both deterministic *and* nondeterministic computing is applied to track a real Euclidean space, SComp possesses ambient intelligence (AmI).

2.2 Computational-Exteroception

In biology, exteroception is a sensitivity to any form of sensation that results from stimuli located outside the body through, e.g., vision, hearing, touch or pressure, heat, cold, pain, smell, and taste. (Colman, 2009). In computing, exteroception, similarly, refers to computational sensitivity of the Euclidean environment beyond the computer. Computational exteroception is the shared feature of SComp and is made possible by deterministic and/or nondeterministic computational methods. Namely, SComp relies on an array of automation and machine learning, which, when used in tandem, is known as ambient intelligence (AmI), the namesake of AmIE.

Table 5 Differences Between Automation, Autonomy, Machine Learning, and Ambient Intelligence

Automation	Autonomy	Machine Learning *(aka Artificial Intelligence)*	Ambient Intelligence
Process which produces <u>deterministic</u> outcomes.	*State which relies on <u>deterministic</u> and <u>nondeterministic</u> processes.*	*Process which produces deterministic and nondeterministic outcomes*	*Exteroceptive-computing process which produces <u>deterministic</u> and <u>nondeterministic</u> outcomes*

2.2.1 Deterministic Computation, Automation

Deterministic computing is the defining feature of automation, e.g., the act of using machines to perform well-defined tasks that, rather than replace human labor, typically change the nature of human's contribution from operator to supervisor. Automation uses fixed sets of rules to produce deterministic results that a result is produced deterministically from an input. Said another way, given the same starting state, automated systems always produce the same output. Automation should not be confused with autonomy. Autonomous computing artifacts can perform (selected, specific) tasks independently and adaptively, which is to say they can theoretically operate under some degree of unanticipated scenarios. Automated computing artifacts are deterministic, whereas autonomous computing artifacts are not inherently deterministic. Automation is a process while autonomy is a state that relies on nondeterministic computing.

2.2.2 Nondeterministic Computation, Machine Learning

Given the same starting state, nondeterministic computing, unlike deterministic computing, can exhibit different outcomes. It is the capacity for delivering an array of possible nondeterministic outcome that is the defining feature of machine learning (ML), aka artificial intelligence (AI). In other words, in addition to leveraging deterministic computing, it also leverages nondeterministic computing. In this sense, ML is the act of using fixed sets of rules to produce deterministic and nondeterministic results, results that can adapt the fixed sets of rules automatically or manually, which allows ML to perform tasks across an array of loosely-defined to well-defined tasks. Whereas automation is most successful when tasks to be performed by machine computing are well-defined.

Importantly, ML is not intelligent in the biological or human sense. Rather, ML, in that it relies on nondeterministic computing, mustn't always produce the same result, instead it is self-adaptive. However, ML can simulate biological intelligence in its relationship to comprehension. Said another way. ML can refer to one of two goal-states

1. *The ML actually understands.*
2. *The ML does not understand, but simulates understanding.*

While conceptually these two states are drastically different from one another, they both apply nondeterministic computing. And it is this application of nondeterministic computing which makes them both ML. The idea that a nondeterministic computing artifact understands in the sense that humans do, is called strong AI (Jajal, 2020; Wooldridge, 2020). This kind of ML does not yet exist (Russell, 2019) but can be seen in media speculations like the humanoid robot, Ava, in the film Ex Machina (Garland, 2015; Pedersen, 2016). The idea that employing deterministic and nondeterministic computing to perform tasks historically performed by humans and/or simulate understanding, is called weak AI (Jajal, 2020; Wooldridge, 2020). This is the kind of ML that is in use today and does things humans once did that automation alone cannot. Increasingly, weak AI also does that which humans could never do which automation also cannot. Some argue there is also a third category, Artificial Superintelligence, where machine "intelligence" categorically exceeds human intelligence in "virtually all domains" (Bostrom, 2014). Herein, ML categorically refers to weak AI. When ML leverages computational exteroception, it is called ambient intelligence (AmI).

Table 6 Machine Learning Goal States

Weak AI *(aka Artificial Narrow Intelligence (ANI)*	*Strong AI (aka Artificial General Intelligence (AGI))*	*Artificial Superintelligence*
Is machine "intelligence" which simulates being in likeness to human intelligence.	Is machine "intelligence" in line with human intelligence.	Is machine "intelligence" categorically exceeds human intelligence.

2.2.3 Ambient Intelligence (AmI)

Ambient intelligence (AmI) is a type of ML that is unique to computational-exteroception. AmI is, as such, the defining property of SComp in that it leverages deterministic *and* nondeterministic computing to track (events in) a real Euclidean space. Confusingly, when the term was initially proposed in the 1990s, it was used to refer to what now is predominantly distinguished as ambient intelligent environments (AmIE).

2.3 Ambient Intelligent Environments: Sensors, Actuators, Processors

Because the field is still relatively new, semantic best practices are still being defined. This can be seen in the migrating away from the ambient intelligence (AmI) to ambient intelligent environments (AmIE). When it was first proposed, AmI was the term to refer to the paradigm where the built environment is computationally sensitive and responsive to inhabitants' presence, needs, wants, preferences. After nearly two decades of research, the term AmI has been mostly (but not completely) abandoned in favor of adding a spatial qualifier e.g., (ambient) intelligent *environment* or smart *space*. For this reason, this work refers to the paradigm as AmIE and AmI as the exteroceptive ML that the AmIE paradigm relies on.

2.3.2 Ambient Intelligent Environments (AmIE)

At their most fundamental, AmIEs are a type of built environment. Which is to say, that while the argument can be made that any environment can be sensitive and responsive to our presence, needs, wants, preferences, what makes an AmIE different from any other built environment is that the sensitivity (and responsiveness) of the environment is facilitated by the exteroceptive computing. In this way, AmIE necessarily leverage ML, and are thus, fundamentally, computational artifacts. To enact their sensitivity to inhabitants, AmIE are also, fundamentally, mechanical artifacts. For this reason, AmIE are considered cyber-physical systems that comprise sensors, actuators, and processors.

2.3.2 Actuators

Actuators are devices able to produce mechanical work as a response to external stimuli, i.e., work is produced as a response to an electrical input, temperature or pH variation, among others (Lanceros-Méndez et al., 2018). Said another way, at the most theoretical physics level, an actuator is matter or non-ionizing radiation that is changed by having a force placed on it. In the case of a door, for example, an actuator might be hinge, or a track, or rotator, that is, a mechanism that translates the force of pulling or pushing into the resulting opening or closing of the door. Which is to say, an actuator, is a discreet concept from that which leads to a force being exerted and is also discreet from detecting an exertion, that is the job of sensors.

2.3.3 Sensors

Sensors are devices capable of measuring physical phenomena in their (immediate) environments for the explicit purpose of converting that measurement into data which can be interpreted by a processor. A scale is a sensor that measured weight (aka gravitational force), a thermometer is a sensor that measures heat (aka non-ionizing radiation), a security camera is a sensor that measures visible light (aka non-ionizing radiation), a smart home speaker often has a sensor that measures sound waves in the form of voice commands (aka non-ionizing radiation). In exploring an array of sensors, it becomes clear that sensors, like actuators, are discreet concepts from the way that any given measurement is processed, that is the job of processors.

2.3.4 Processors

Processors translate input-data gathered by sensors that measure physical phenomena into output-data needed by actuators that enact a force to modify physical phenomena. In AmIE, processors comprise and array of deterministic and nondeterministic methods to process input and output data.

2.4 Design Engineering

Design-engineering (also, 'design engineering' or 'engineering design') refers to the efforts of engineers to develop and deploy both conceptual and tangible work, i.e., engineer and design. (Robinson, 2010, 2012; 2005). It is disciplinarily comprehensive and extends to the engineering fields of industrial engineering, electrical engineering, mechanical engineering, chemical engineering, aeronautical engineering, and civil-, structural-, or architectural- engineering. The term has become especially popularized as a way of addressing the collaborative work of designers and engineers (in any field) by the American Society of Mechanical Engineer's annual eponymous 'International **Design Engineering**[3] Technical Conferences & Computers and Information in Engineering' conference (IDETC/CIE)

[3] Emphasis my own.

2. BACKGROUND

Typically, design-engineering research falls under the umbrella of one of two fields: human-computer interaction (HCI) or design theory and methodology (DTM). Researchers in these fields seek to understand how different methods of design-engineering and different artifacts of design-engineering effect an array of corollaries they are trying to better understand.

2.4.1 Domain Specific Design-Engineering

Both HCI and DTM scholars produce design-engineering knowledge in the form of tools, methods, frameworks, processes, case studies, and theories. In recent decades, a particular sub-focus in design-engineering is on centering the user leading to the two domain-specific HCI/DTM sub-fields: user experience design (UX) and user interface design (UI). UX/UI focus specifically on how an end-user will respond to a given design-engineering artifact. However, much of this scholarship is focused on tangible and graphical user interfaces, meaning that the field of AmIE is left with few domain-specific tools. Given the UX/UI opportunity landscape dramatically differs in AmIE from, say, a web browser (a well-researched UX/UI domain) from a more tangible artifact, theorists are now discussing a need for similar research like that conducted in UX/UI design and user interface design research for the context where there is no interface or limited interface:

> *"As an evolving applied science criterion, Ambient Intelligence is taken to the next level by considering behavioural and humane aspects into day-to-day applications such as traffic, education and smart homes etc. Although recent progress has indicated significant breakthroughs in computational and cognitive directions, the Human-Computer-Interaction dimension is not effectively applied. Interaction principles such as accessibility, usability and learnability from the user acceptance aspect are not significantly explored." (Ravulakollu et al., 2021, p. 1)*

2.4.2 Design-Engineers

A design-engineer, in any field, comprises an array of designers and engineers who are responsible for the design-engineering life cycle. The terms are linked as an acknowledgement of the fact that design-engineering professionals often work on a spectrum of engineering and design where the delineation between where one domain starts and the other stops is not clear cut. Additionally, it is an acknowledgement that artifacts made by designers often also comprise elements made by engineers, and vice versa. Ultimately, whether a design or engineering specialist, design-engineers are responsible for defining, researching, creating, implementing, and evaluating their artifacts.

In the field of AmIE, 'who' the design-engineer is additionally complicated by the reliance on ML agents gleaning live use-data. Like in other design-engineering domains where automation and ML are leveraged, there are, at least two design-engineer (types) in an AmIE: the human design-engineer and the computational design-engineer.[4] In the context of design-engineering AmIE, there is also a third design-engineer: the user/s. As an inhabitant of an AmIE, the act of merely existing in effect to inform the articulation of the environmental conditions. In this way the user, whether actively-intentional or passively-unintentional, becomes a design-engineer. This presents a unique opportunity to AmIE, but also an additional level of complexity to consider and manage.

Table 7 Design-Engineers in AmIE

Human design-engineer	Computational design-engineer	User design-engineer
Professionals who design and engineer AmIEs.	Computational agents that sense and actuate articulation in AmIEs.	Inhabitants of AmIE who inform the articulation of AmIE through implicit and explicit enactments.

The professional skill set of human design-engineers of AmIE typically falls into one of three categories, where the former two are more computational focused and the latter is more spatially focused: computer science and electrical engineering research, mechanical engineering and industrial design-engineering research, environmental design and engineering research. These three fields comprise a wide array of engineer and designer types including, but not limited to software engineers, mechanical engineers, product designers, experience designers, interiors designers, architects, and civil engineers. In showcasing this array of design-engineers, it

[4] In this sense, design-engineer is very close, if not overlapping, with the concept of agent.

becomes apparent design-engineering AmIE relies on a wide array of professional expertise and necessarily requires a level of interdisciplinarity.

Table 8 Human Design-Engineer Professional Landscape

<table>
<tr><td rowspan="4">(typically) Spatial Computing Design-Engineers</td><td colspan="7">Computer Science and Electrical Engineering Research</td></tr>
<tr><td colspan="2">Machine Learning Engineers</td><td colspan="3">Software Engineers</td><td colspan="2">Electrical Engineers</td></tr>
<tr><td colspan="7">Mechanical Engineering and Industrial Design-Engineering Research</td></tr>
<tr><td>Mechanical Engineers</td><td>Industrial Engineers</td><td>Hardware Designers</td><td>Product Designers</td><td>Interface Designers</td><td>Service Designers</td><td>Experience Designers</td></tr>
<tr><td rowspan="2">(typically) Spatial Design-Engineers</td><td colspan="7">Environmental Design and Engineering Research</td></tr>
<tr><td colspan="2">Interior Designers</td><td colspan="2">(Landscape) Architects</td><td colspan="2">Civil Engineers</td><td>Urban Planners</td></tr>
</table>

Computational design-engineers which are ML agents who effect the process of design-engineering in-situ, continuously, and in real-time. Arguably, computational design-engineers have the largest active and long-term role in AmIE design-engineering in so far as they are (constantly) aware and adjusting systems that have the capacity to learn over time and adjust in an increasing array of ways. In this way, computational design-engineers are, effectively, ML agents. Calling them computational design-engineers, however, highlights the association with the role the ML agent in an AmIE has in creating novel design-engineering conditions based on real-time data that human design-engineers may have never specifically envisioned or design-engineered for.

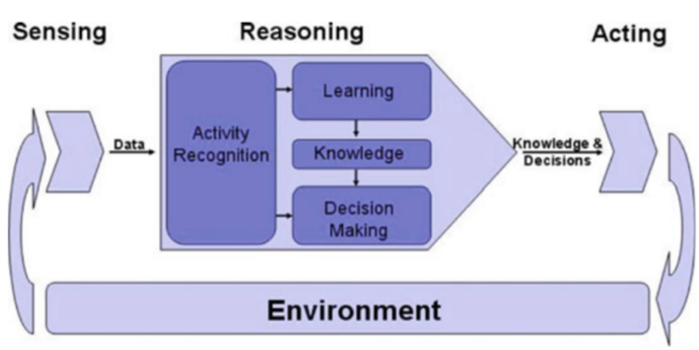

Figure 6 Visualization of how an ambient intelligent environment is design-engineered (Aztiria et al., 2010)

User design-engineers are design-engineers by complicity—unintentional complicity, unaware complicity, and aware-complicity. Given AmIE adjust based on the actions, interactions, indications, of the users, users are in effect co-creating the AmIE design-engineering conditions. Thus, they are the third design-engineer type in an AmIE, in so far as they are both the instigator of exteroceptive computing in that their actions are tracked and that they have agency which can override, supplement, or self-adjust the AmIE.

2.4.1 Design Space

A design space is a taxonomical sub-type used in the field of design-engineering where taxonomical hierarchy can occur on multiple cartesian dimensions. First proposed in 1989 as a design-engineering tool, design spaces allow for precise cartesian locating of discreet design variations (Lomas et al., 2021). In this way, a design space is a multi-dimensional container, where within the dimensionality, all possible variations of any given design can be located (with any singular variation being a location in this container). Or as the author of the first formal definition of a design space, Richard Fox, described it,

> *"a design space...[is where] each Cartesian coordinate axis represents a design variable, and thus a point in this space...represents a design."(Lomas et al., 2021, p. 226)*

In other words, a design space is the "space of possible options" (Maclean et al., 2004, p. 9) for any given design mapped to cartesian coordinates, where all dimensions reflect a type of variable a design-engineer can tweak. Which means, the more adjustable dimensions of a design, the more complicated once any more than three parameters are defined.

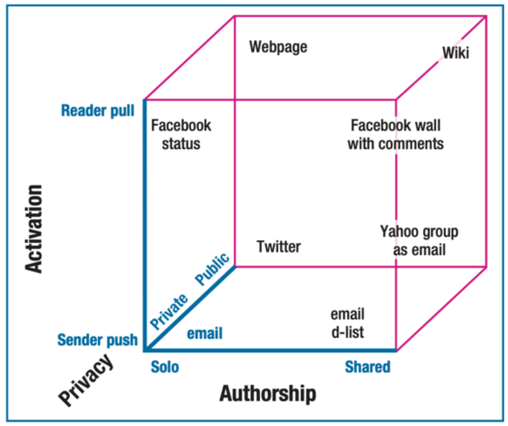

FIGURE 1. A small design space for Web information sharing. This representation selects three decisions about information sharing and shows how they correspond to some common applications.

Figure 7 Example of a Cartesian design space (Shaw, 2012)

When there are more than three dimensions in a design space, the cartesian coordinates are typically visualized conceptually. Take for example a paper that discusses the design space of driver-based automotive user interfaces (Kern & Schmidt, 2009) where three vector clusters were found to define the design space: input, output, and position of input or output. Each of these vector clusters comprised an array of vectors. The position cluster comprised 7 vectors, 4 of which had a single variation, while 3 of had two variations. In the position cluster alone there are 10 vectors, visualizing a ten-dimensional space is in a cartesian coordinate visualization is, in a word, challenging. And more importantly, not specifically helpful for the goal of conceptualizing a design space. Instead, researchers turn to two-dimensional visualizations of multi-dimensional design spaces to communicate design spaces, if they visualize it at all.

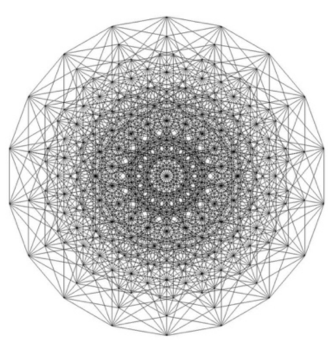

Figure 8 Cartesian mapping of a 10-dimensional space

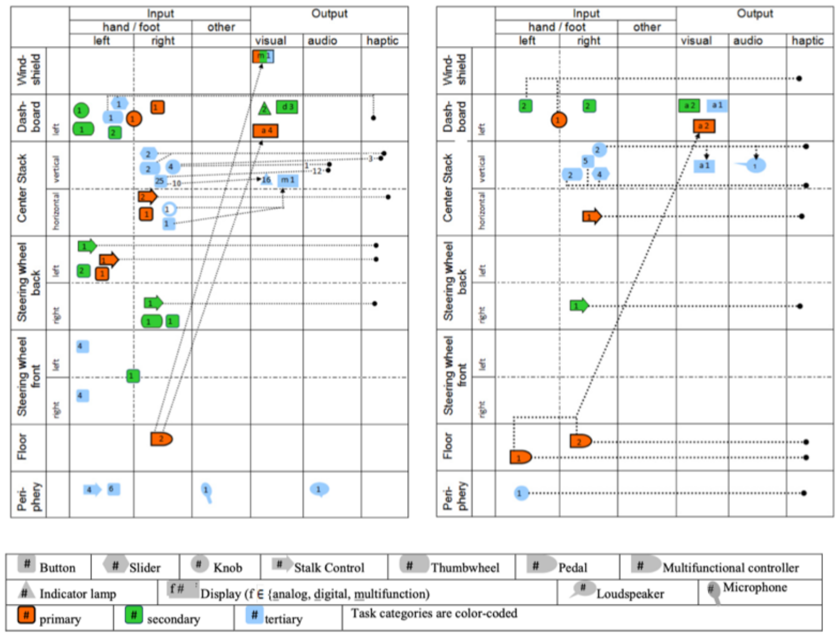

Figure 9 Visualization of the design space of an automobile (Kern & Schmidt, 2009)

2.4.1 Design Space, a Taxonomy Type

However, a design space is visualized, or not, they are a kind of taxonomy. Taxonomies are artifacts for classification (Petzold et al., 2013). They are intended to make abstractions tangible in support of engagement and meaning derivation. To create a taxonomy is to practice the act of taking what has been seen and named (classifying) and contrasting it with other things that have been seen and named. This act of contrasting between items (ordering) is what differentiates a taxonomy from a classification; e.g., taxonomies describe relationships between items or groups of items (i.e., order) whereas classifications simply sort items (i.e., classify).

Design spaces afford something quite atypical as a taxonomy: a mechanism for generating and evaluating ideas, a "framework for systematically considering design alternatives, for recognizing interactions and trade-offs among decisions, and for comparing designs" (Shaw, 2012, p. 50). While not all taxonomies are design spaces, all design spaces are taxonomies. As such, they are vulnerable to the trappings of any other type of taxonomy.

Namely, in so far as taxonomies describe relationships between items or groups of items (i.e., ordering) and name items and groups of items (i.e., classifying), they are also effected by the rigidity such an act imposes. In other words, getting a taxonomy "right" is complicated. Complicated because it requires imposition of a relational hierarchy between items, (i.e., ordering) and imposition of a name for what has been seen (i.e., classifying) and therefore also delineates what constitutes a boundary between alike and non-alike items. In this way we find two challenges in any taxonomy, imposing hierarchies and defining boundaries which this work addresses by introducing and using minor theory to produce a design space of AmIE that is cognizant of these vulnerabilities of taxonification.

2.5 Minor Theory

Minor theory was first proposed by human geographer Cindy Katz who built off the work of film theorist Tom Gunning who wrote an article on 'minor cinema' which, "provided a backdoor—perhaps a 'minor' door—to Deleuze and Guattari's '*Kafka: Towards a Minor Literature*'" (Katz, 2017, p. 596). Therein, Katz was struck by Deleuze and Guattari's "disavowal of mastery and embrace of marginality—a marginality that recognizes and relates to all that it edges *and* all of its edges" (Katz, 2017, p. 596). Said another way, Katz built upon Gunning, Deleuze, and Guattari's assertion that literature and cinema are political, and proposed minor theory as a critical theory research method,

> *"'minor' research strives to change theory and practice simultaneously, and … can be conjoined with the critical and transformative concerns of Marxism, feminism, antiracism, and queer theory to pry apart conventional geographies and produce renegade cartographies of change." (Katz, 1996, p. 488)*

There are two ways in which minor theory supports the needs of this work in producing domain-specific AmIE theory cognizant of spatial alignment. (And thus, affords the field of design engineering a new theoretical tool.) First, minor theory stresses the impossibility of exhaustibility. Instead, it presses theorists to maintain sensitivity to the vastness of their domain and maintain humility whilst producing theory so that hubris may not befall their work. In this way, minor theory can be seen as a champion of the scientific method, believing that theory is improved through systematically seeking to replicate, contest, deviate, and build upon existing theory. Thus, while perhaps a taxonomy, such as this, will never be 'complete,' it will also never near completion without advancing continuous theoretical contributions. Second, in addition to its valuing of empiricism, minor theory stresses the inclusion of historically excluded and marginalized voices. This is where minor theory gets its name. Namely, in its contrast to major, or dominant, perspectives taking precedence over minor, or non-dominant, perspectives. In this way, minor theory also affords the inclusion of scholarship focused on ensuring value alignment in our societies, inter-personal worlds, and interactions with technology.

Herein, special focus is paid to looking through the lens of scholarship which seeks to understand social value-aliment for those typically marginalized (feminist-, queer-, post-colonial- and anti -racist, -ableist, -ageist, -classist theory) and scholarship which seeks to make sense of the future (post-humanist-, post/cyborg-, cybernetics- theory, and futures studies). In no way is this research a full survey on any of the aforementioned theories. Rather, in the words of the preeminent scholar of minor theory, Cindi Katz, the aim of keeping such minor theories top of mind is to press the array of theories "through the pores of the other so that any production of theory cascades in an endless transformative becoming." (Katz, 1996, p. 490). Ultimately, minor theory, is a theoretical contrasting of dominant theoretical and social positions through a critical, minor, lens.

3. METHOD

This work centers on a mixed method study that builds upon prior published (Ballestas et al., 2021) and unpublished research I conducted while a graduate student at the Technical University of Delft between 2020 and 2022. Mixed methods studies comprise two or more research strategies within a single study (Creswell & Creswell, 2017; Tashakkori et al., 2003)(Creswell & Creswell, 2017). Research Strategies, or methods, in a mixed method study can be implemented concurrently or sequentially. In this work, three methods were employed: exploratory literature review (Meade et al., n.d.); review of and subsequent Grounded Theory (Charmaz, 2014) analysis of gray literature (Garousi et al., 2016) in the form of expert interview transcripts (Meade et al., n.d.); systematic literature review (Kitchenham & Charters, 2007) and corresponding Grounded Theory analysis (Charmaz, 2014).

The strategies used were employed in relatively sequential manner, though the Grounded Theory analysis of the data from the gray literature review and the data from the systematic literature review were mostly concurrent and in certain ways, integrated. Ultimately, the three methods were constructed to propose a taxonomy of the design space of AmIEs with a focus on using review of relevant literature to surface the conceptual elements of that design space. In total, over 700 pieces of literature and 21 expert interview transcripts were reviewed to address the two main questions that guided this research: *What are the conceptual elements (interaction space, inputs, and outputs) reported in the literature which define the design space of AmIE?* and *how can we look at these elements through a critical lens?*

3.1 Exploratory Literature Review

An exploratory literature review (Meade et al., n.d.) served as the preliminary study in the mixed methods design of this research and comprised a survey of publications in the fields of design-engineering, critical theory, and ambient intelligence in order to identify and synthesize thematic focuses and challenges of codifying AmIE design spaces.

3. METHOD

Exploratory literature reviews are a good way of preparing for a systematic literature review like the one conducted hereafter. In this way, an exploratory literature and a systematic literature review differ most in how they handle the data collected and reviewed. In the most reductive sense, an exploratory literature review mustn't review all collected data in the precisely the same way. In other words, an exploratory literature review is a non-, or rather, less- systematic method to discovering literature and evaluating it than a systematic literature review which treats all data in the same way.

Given the dual focus of this review (i.e., to deepen my understanding of the field of ambient intelligence research as well as gain a critical lens through which to ultimately evaluate the field), two literature review methods were employed: a *scoping review* and a *critical review* (Paré & Kitsiou, 2017). Scoping reviews help to orient to the relative scale of the exiting published literature on the topic; and in this exploratory review, a scoping review was used to orient to the literature on ambient intelligence (later clarified to ambient intelligent environments). Critical reviews help to understand the issues in a given topic area, including the "strengths, weaknesses, contradictions, controversies, inconsistencies" (Paré & Kitsiou, 2017); and in this exploratory review, a critical review of critical theory literature and design-engineering literature helped situate the aim of producing a taxonomy that was mindful or criticality.

Table 9 Types of Literature Reviews (Paré & Kitsiou, 2017)

Review type: *Overarching goal*	**Search strategy**	**Appraisal method**	**Analysis and synthesis**
Scoping review: *Aims to provide an initial indication of potential size and scope of the extant research literature. May be conducted to identify nature and extent of research evidence, including ongoing research, with a view to determine the value of undertaking a full systematic review.*	Comprehensive search using an iterative process that is guided by a requirement to identify all relevant literature (published and unpublished) suitable for answering the central research question regardless of study design. Uses explicit inclusion and exclusion criteria.	No formal quality or risk of bias assessment of included primary studies is required.	Uses analytic frameworks or thematic construction in order to present a narrative account of existing literature, as well as numerical analysis of the extent, nature and distribution of the studies included in the review.
Critical review: *Aims to provide a critical evaluation and interpretive analysis of existing literature on a particular topic of interest to reveal strengths, weaknesses, contradictions, controversies, inconsistencies, and/or other important issues with respect to theories, hypotheses, research methods or results.*	Seeks to identify a representative number of articles that make the sample illustrative of the larger group of works in the field of study. May or may not include comprehensive searching.	No formal quality or risk of bias assessment of included primary studies is required.	Can apply a variety of analysis methods that can be grouped as either positivist (e.g., content analysis and frequencies) or interpretivist (e.g., meta-ethnography, critical interpretive synthesis) according to the epistemological position.

3. METHOD

To identify the literature reviewed in the exploratory phase of this work, three main searches were conducted using Google Scholar as the search engine or starting from reference texts provided by my advisors. In total, more that 500 documents were reviewed in the exploratory literature review, of which around 250 documents were surveyed in depth (bibliography of reviewed documents found in the Appendix).

3.1.1 Design Engineering and Design Spaces (Scoping Literature Review)

The initial seedlings of this work were informed by Kern and Schmidt's article, 'Design space for driver-based automotive user interfaces' (Kern & Schmidt, 2009). Therein, they proposed a design space of the interaction area of a car, naming three interaction zones, and a plethora of inputs and outputs found in the interaction of driving a car. It was this design space triad that I also saw in ambient intelligent environments—namely, sensors, actuators, and data processors. In this way, Kern and Schmidt's paper informed the goal of creating a design space for ambient intelligence as my master's thesis. For this reason, I began this research by conducting an exploratory literature review into 'design spaces.'

Additionally, design engineering is the term used by the Technical University of Delft's department in which my research resides: The Faculty of Industrial **Design-Engineering** (IDE), and the term of the conference where the breadth of my research to date has been published, 'ASME International **Design Engineering** Technical Conferences & Computers and Information in Engineering Conference.' For this reason, I have used the compound term 'design-engineering' by default in the past, and sought herein to deepen the contextualization of the term and its subtypes human-computer interaction (HCI) and design theory and methodology (DTM). Thus, clarify the concept of design-engineering, I referenced texts shared with me by my advisors and others found independently. (See Appendix 1.A for full bibliography of this exploratory literature review.)

3.1.2 Critical Theory (Critical Literature Review)

3. METHOD

Given the goal of producing a design space that addressed spatial alignment was central to this work, before engaging in a systematic literature review, I had to define a theoretical lens through which to evaluate the literature. To do so, a very non-procedural search ensued. The search was emergent and snowballed in a nonlinear way, meaning in retrospect the best way to describe the search would be to list the texts that became central to my thinking (Appendix 1.B). Through the review of critical theory literature, I discovered the theoretical lens of 'minor theory.'

3.1.3 Ambient Intelligent Environments (AmIE)(Scoping Literature Review)

Given that the concept of 'ambient intelligent environments' originated with the concept of 'ambient intelligence,' which, theoretically, is synonymous with 'ambient intelligent environments,' and the fact that the concept termed in such a way did not arrive until the 1990s, three searches conducted were conducted on Google Scholar to reference [1] core historical work in the field (i.e., search "ambient intelligence" [all time]), [2] core recent work in the field (i.e., search "ambient intelligence" [since 2020]), and [3] core surveys in the field (i.e., search "ambient intelligence" and "survey" [all time]) (Appendix 2.A, 2.B, 2.C).

3.2 Grey Literature Review

Grey (also gray) literature is unpublished research or information produced outside of traditional publishing and distribution channels sometimes referred to as "literature that 'falls through the cracks'"(Merrigan & McKimmie, 2002) or as "little literature"(Schmidmaier, 1986). While first proposed as a literature type in 1978 (Hopewell et al., 2007), debate has ensued about what constitutes as grey, scholars seem wary of agreeing on the formal inclusion or exclusion criteria of grey literature. However, they seem to be agreed that it is "not 'white' (available and cataloged), and that is not 'black' (not available, unknown, or not obtainable)." A recent survey outlines the following types of documents have been argued to fall into the category of grey literature (Rucinski, 2015):

- academic courseware
- academic and government reports
- blog posts

- conference proceedings
- corporate documents
- datasets
- discussion papers
- in-house journals and newsletters
- institutional or association reports and bulletins
- lecture notes
- maps
- presentations
- personal communications
- pre-prints
- product catalogs
- social media updates
- surveys
- technical reports
- trade association publications
- tweets
- unpublished manuscripts
- websites of universities, major libraries, government agencies, nongovernmental organizations
- working papers

The value of grey literature, is in the opportunity to review information that might better reflect the "state of practice" (Garousi et al., 2016). Advocates of this perspective argue for a multivocal literature review(Garousi et al., 2016), which references grey literature in addition to published literature in a systematic literature review. In this way, the grey literature review described in this section is a component of the systematic literature review that will be described in the next section. The goals of the grey literature review described in this section were two-fold*: to triangulate search terms for the systematic literature review* and *to aid in the Grounded Theory analysis*.

3.2.1 Interview Transcripts

Transcripts from unpublished research I conducted as a member of the People in Transit Lab at the Technical University of Delft between 2020 and 2022 were reviewed. The interviews were centered on gathering data from industry spatial computing practitioners to understand the process practitioners took to create spatial computing artifacts and how the definition of artifact might necessarily change based on the role of the practitioner.

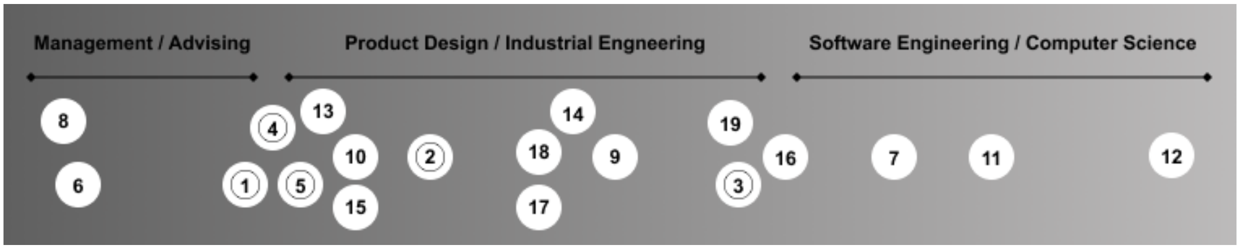

Figure 10. Participants' number and professional domain

The study included 19 design-engineers (see Table 10) in varying roles who are tasked with some type of spatial computing artifact creation. The sample size was consistent with other qualitative studies (Creswell & Creswell, 2017; Lee et al., 2020; Patton, 2014; *Quantitative, Qualitative, and Mixed Research Methods in Engineering Education - Borrego - 2009 - Journal of Engineering Education - Wiley Online Library*, n.d.) and allowed for the level of both breadth and depth necessary to answer our research question. Participants were either recruited directly from existing professional networks or through snowball sampling (*Snowball Sampling: Problems and Techniques of Chain Referral Sampling - Patrick Biernacki, Dan Waldorf, 1981*, n.d.). For inclusion in the research, potential participants had to be in a professional role where they were tasked with the engineering, design, or management of spatial computing artifacts.

Participants worked in large (greater than 50), medium (less than 50), and small (less than 10) companies in North America or Europe. Together, the 19 experts have a combined working experience of 240+ years, or an average of 12.6+ years.

Table 10 Expertise and Practice Domain of Participants **Experience measured in five-year increments*

Role	Gender	Experience*	Company	SComp Type
(1) Founder	M	10+	Startup	XR
(2) Senior Designer	M	5+	Major Tech	XR, AmI
(3) Research Director	M	10+	Startup	XR
(4) Head of Design	M	15+	Major Tech	XR, AmI
(5) Head of Design	M	25+	Major Tech	XR, AmI
(6) Project Manager	M	5+	Government	AmI
(7) TTS Language Engineer	F	0+	Major Tech	AmI
(8) Advisor	M	25+	Self-Employed	XR, AmI
(9) Principle UX Designer	M	15+	Major Tech	AmI
(10) UX Consultant	F	0+	Major Tech	XR

(11) Senior Deep Learning Researcher	M	5+	Major Tech	XR, AmI
(12) Staff Engineer	M	10+	Major Tech	XR, AmI
(13) Advisor	M	15+	Self-Employed	XR
(14) Founder	M	5+	Startup	XR
(15) CEO	M	15+	Startup	XR
(16) Director of Integration	M	25+	Startup	XR, AmI
(17) Research Design Manager	F	30+	Major Tech	XR, AmI
(18) CEO	F	5+	Startup	XR
(19) Co-Founder	M	20+	Startup	XR

3.3 Systematic Literature Review

The purpose of a systematic literature review is to provide a thorough and consistent overview of all the material that is selected for review. Additionally, the search criteria in a systematic literature review should be concise and informed in its objective of surfacing all related literature deemed relevant to the research objective. Often, systematic literature reviews aim to be fully comprehensive. In the case of this research, the number of documents that were surfacing before refining the scope of the reviewed catalogs (above 40k documents) greatly exceeded the capacity of this thesis. Thus, after the exploratory literature review, and with support from grey literature, the scope of the systematic literature review was defined in terms of both search terms and catalogs of review.

Table 11 Systematic Literature Review (Paré & Kitsiou, 2017)

Review type: *Overarching goal*	**Search strategy**	**Appraisal method**	**Analysis and synthesis**
Systematic review: *Aims to aggregate, critically appraise, and synthesize in a single source all empirical evidence that meet a set of pre-specified eligibility criteria in order to answer in depth a clearly formulated research question to support evidence-based decision-making*	Exhaustive literature search of multiple sources and databases using highly sensitive and structured strategies to identify all available studies (published and unpublished) within resource limits that are eligible for inclusion. Uses a priori inclusion and exclusion criteria.	Two different quality assessments must be addressed in systematic reviews: (a) risk of bias in included studies, and (b) quality of evidence by outcome of interest. Both assessments require the use of validated instruments (e.g., Cochrane criteria and GRADE system).	Two different types of analyses and syntheses methods can be used: 1. Meta-analysis (statistical pooling of study results), and 2. Qualitative/ narrative: use of vote counting, content analysis, frameworks, classification schemes, and/or tabulations.

3. METHOD

Systematic literature reviews are based on an explicit a priori review methodology that aims to be as unprejudicial as possible (Higgins & Green, 2008). To support in this objective, they often comprise three phases: collection, analysis, and synthesis (Tranfield et al., 2003). Data collection and analysis will be presented here, while synthesis can be found in Section 6.1.

3.3.1 Data Collection

Data collection consisted of three main steps (see Figure 11). It was proceeded by the exploratory literature where searches of Google Scholar ("ambient intelligence," "ambient intelligent environment," and "ambient intelligence survey") and a review of gray literature of expert transcripts, helped in refining the search string and databases to foster relevance. This extended search was undertaken to capture the various terms that could be used for ambient intelligent environments, the chosen terms were surfaced. Given the focus on the design space of AmIE, in addition to the array of title search terms designated to surface papers on the topic of ambient intelligent environments, the search term "design" was added to search in the abstract to extract papers that were in some way focused on the design of AmIE.

To further narrow down the scope and maintain centrality to the domain of engineering-design with a focus on human-computer interaction (HCI) and design, theory, and methods (DTM) literature, two main publishing catalogs were chosen. Namely, the digital catalog of one of the largest US-based DTM conferences, the American Society of Mechanical Engineers International Design Engineering Technical Conferences & Computers and Information in Engineering Conference, and the digital catalog of one of the largest US-based HCI conferences, the Association for Computing Machinery's CHI Conference on Human Factors in Computing Systems. Given the field is relatively new and no papers were found before 1991, no search dates were included. Terms search for in the title included: "ambient intelligence," OR "ambient intelligent," OR "ambient intelligent environment," OR "ambient intelligence environment," OR "building automation," OR "intelligent environment," OR "smart home," OR "smart office," OR "smart school" OR "smart factory," "smart environment," OR "smart space," OR "ubiquitous computing," OR "pervasive computing," OR "persistent computing," "ambient computing," OR "natural computing," OR "embodied computing," OR "immersive computing," OR "context computing." Additionally, the catalogs were searched for titles which had one of the proceeding terms when "design" was also found in the abstract. The search surfaced 235 documents which were immediately collated immediately excluding six documents for being a duplicate, a workshop proposal, in a language other than English, a keynote address, or unfindable. Thereafter a multi-step vetting process ensued prior to analysis of 229 documents (Appendix 3.B) and synthesis of 43 documents (Appendix 3.C).

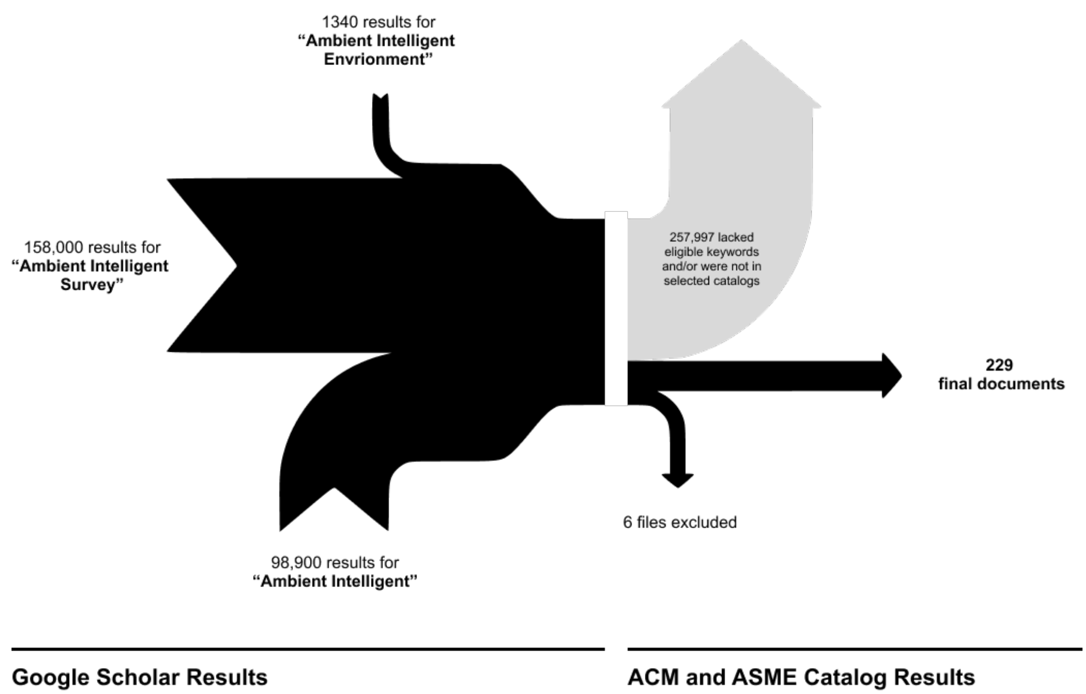

Figure 11 Visualization of data surfacing journey.

3.3.3 Data Analysis and Synthesis

During data analysis, papers surfaced in the data collection phase were pruned for relevance and main themes were annotated. Data analysis was conducted on 229 of the 235 resulting articles described above (6 papers could not be located). The process began with descriptive analysis and ended with a final round of document exclusion. During this analysis phase, all paper's abstracts were read as a means of evaluating whether the paper indicated that it would, "speak to elements of the design space of ambient intelligent environments." At this point papers were annotated "yes," "no," or "maybe." Papers designated "yes" and "maybe" proceeded to be read (the introduction) a second time. The reading of the introduction included “yes,” “maybe,” and “no” designations. All papers designated “yes” (n=43) in this round were considered relevant for data synthesis.

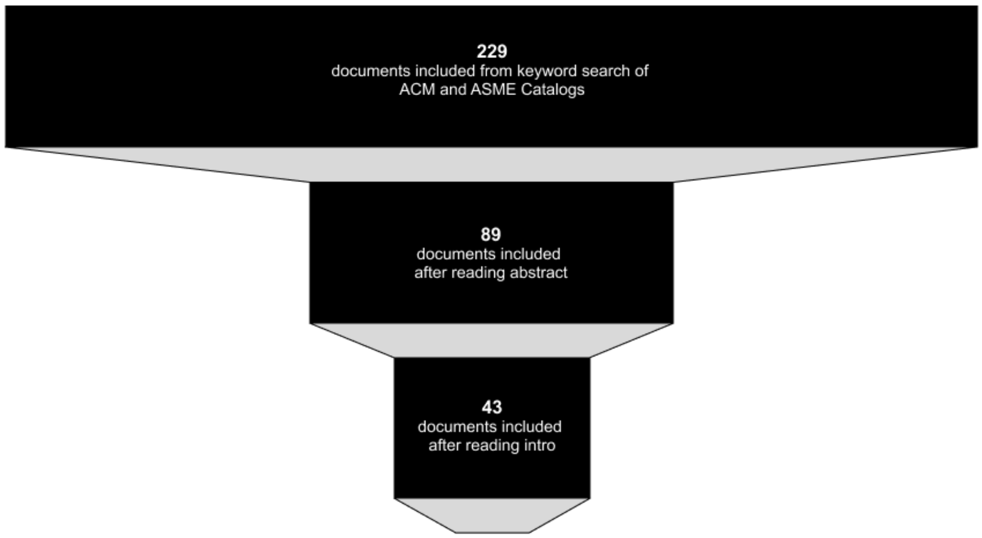

Figure 12Visualization of how many papers were excluded in each round.

Descriptive analysis involved handwriting a note describing what the abstract indicated the paper would be about. During this process, themes emerged supporting the development of thematic codes to cluster the arising conceptual elements of AmIEs. Over the course of two rounds, the entire starting selection of 235 papers was whittled down through an emerging principle of exclusion based on themes discovered in the literature. For example, papers on middleware and energy consumption were ultimately excluded because no new themes were indicated in the abstracts between papers. Papers that spoke directly to conceptual elements of AmIEs or were noteworthy from a minor theory perspective, were also included in the final data selection. Before the synthesis of the 43 papers, and given the theoretical lens of minor theory, data that addressed minor theory ideas or took a minor theory perspective (n=14) were coded: MT.

In the data synthesis phase, all 43 papers designated for inclusion in the final literature review were coded using the Grounded Theory method. The aim of the coding was to surface elemental concepts of the design space of AmIE. Codes like: “energy and environment,” “privacy and security,” “multi-user," "multi-device," were ultimately clustered into the larger code: "design space elements." Whereas initial codes like "design principles" and "design methods" were coded into a larger code: "design-engineering theory." Thereafter, data from the "design space elements" cluster were re-clustered thematically until three final clusters comprising 21 total elements were organized.

4. FINDINGS: Exploratory Literature Review

4.1 Design Engineering and Design Spaces

The literature referenced to deepen understanding of design-engineering and design spaces covers in total 9 different sources, 5 conferences and 4 journals between 1979 and 2021. The investigated conference proceedings were from:

- **(CHI)** ACM SIGCHI Conference Human Factors in Computing Systems
- **(ESPRIT)** The European Strategic Program for Research and Development in Information Technology
- **(AutoUI)** ACM SIGCHI Conference on Automotive User Interfaces and Interactive Vehicular Applications

While the investigated journals include the following:

- **(CoDesign)** International Journal of CoCreation in Design and the Arts, Taylor & Francis
- Design Issues, MIT Press
- Design Studies, Elsevier
- IEEE Software, IEEE Computer Society
- **(PACM HCI)** Proceedings of the ACM on Human-Computer Interaction, Association for Computing Machinery

4.1 Critical Theory

The literature referenced to deepen understanding of critical theory as it relates to and geography, topology, and taxonomy including 6 online sources (magazine articles, newspaper articles, and blog posts), 2 book chapters, 19 books from 15 publishers between 1988 and 2016, 2 book chapters from 2 book publishers between 2011 and 2018, and 53 journal articles from 31 journals between 1991 and 2013. The investigated books and book chapters were from:

- Blackwell
- Bloomberg Publishing
- Clarendon Press

- Columbia University Press
- Cornell University Press
- Duke University Press
- Indiana University Press
- MIT Press
- Orion
- PM Press
- Princeton University Press
- Routledge
- Springer
- University of California Press
- Utah State University
- Willey

While the investigated journals include the following:

- (ACME) ACME: An International Journal for Critical Geographies; Free Journal Network
- Annals of the Association of American Geographers; Taylor & Francis
- Area; Wiley-Blackwell
- British Journal of Educational Studies; Taylor & Francis
- Contemporary Sociology; SAGE Journals
- cultural geographies; SAGE Journals
- Die Philosophin; Edition Diskord
- Educational Philosophy and Theory; Taylor & Francis
- Environment and Planning A: Economy and Space; SAGE Journals
- Environment and Planning D: Society and Space; SAGE Journals
- Forum Qualitative Sozialforschung / Forum: Qualitative Social Research; Free University of Berlin
- Geoforum; Elsevier
- Geografiska Annaler: Series B, Human Geography; Taylor & Francis
- Geography Compass; Wiley-Blackwell
- Information, Communication & Society; Taylor & Francis
- International Journal of Disaster Risk Reduction; Elsevier
- International Journal of Urban and Regional Research; Wiley-Blackwell
- Journal of Geography in Higher Education; Taylor & Francis
- Journal of Global Ethics; Taylor & Francis
- M/C Journal; Open Access
- Nature Chemistryl Nature Portfolio
- (Prof. Geogr.) The Professional Geographer; Taylor & Francis
- PS: Political Science & Politics; Cambridge University Press

- Qualitative Research; SAGE Journals
- Review of Education, Pedagogy, and Cultural Studies; Taylor & Francis
- Signs: Journal of Women in Culture and Society; University of Chicago Press
- Social & Cultural Geography; Taylor & Francis
- Studies in Iconography; Medieval Institute Publications and Princeton University's Index of Medieval Art.
- The Journal of Higher Education; Taylor & Francis
- Theory and Practice in Language Studies; Academy Publication
- Transactions of the Institute of British Geographers; Wiley-Blackwell

4.3 Ambient Intelligent Environments (AmIE)

The three Google Scholar searches conducted to gain a deeper understanding of the thematic discussions in the literature on ‘ambient intelligence’ and ‘ambient intelligent environments’ turned up 180 articles, of which 162 were locatable, and 9 were duplicates[5], leaving 153 total documents for review.

4.3.1 Ambient Intelligence, All Time.

Searching "ambient intelligence" [all time] on Google Scholar returned 99,300 results. Of that, the first 10 pages were referenced—a total of 100 documents of which a total of 98 were located and reviewed (Appendix 2.A). The 98 documents came from 26 different publishing sources, including 8 conferences and 18 journals, and were published between 2003 and 2021. The investigated conference proceedings were from:

- **(ICCHP)** International Conference, Computers Helping People with Special Needs
- **(AmI)** European Conference on Ambient Intelligence
- **(AVI)** Advanced Visual Interfaces
- **(EUSAI)** European Symposium on Ambient Intelligence
- **(EPIA)** European Progress in Artificial Intelligence

[5] Of the 9 articles which were duplicates, 5 were found in the first ten pages of AmI [all time] and AmI Survey [all time] (Acampora et al., 2013; Augusto, 2008; Aztiria et al., 2010; Bikakis et al., 2008; Sadri, 2011) and 4 were found in the first five pages of AmI (since 2020) and AmI Survey (all time) (Dunne et al., 2021; Haque et al., 2020; Martinez-Martin et al., 2021; Park et al., 2020).

- **(ESAI)** European Symposium on Ambient Intelligence
- **(ICSE)** International Conference on Software Engineering
- **(ICSOFT)** International Conference on Software Technologies
- **(ISLPED)** The International Symposium on Low Power Electronics and Design
- **(UAHCI)** International Conference on Universal Access in Human-Computer Interaction

While the investigated journals include the following:

- ACM Computing Surveys
- Artificial Intelligence Review
- Computer Science and Information Systems
- CyberPsychology & Behavior
- Ethics and Information Technology
- IBM Systems Journal
- IEEE Transactions on Systems, Man, and Cybernetics - Part A: Systems and Humans
- IEEE MultiMedia
- IEEE Intelligent Systems
- Information, Communication & Society
- Journal of Ambient Intelligence and Humanized Computing
- Journal of Ambient Intelligence and Smart Environments
- Journal of Biomedical Informatics
- Journal of Universal Computer Science
- Microelectronics Journal
- Pervasive and Mobile Computing
- Proceedings of the IEEE
- Telematics and Informatics

4.3.1 Ambient Intelligence, Since 2022.

Searching "ambient intelligence" [since 2022] on Google Scholar returned 17,100 results. Of that, the first 5 pages were referenced—a total of 50 documents of which a total of 49 were located and reviewed (Appendix 2.B). The 49 documents came from 23 different publishing sources, including 5 conferences and 18 journals, and were published between 2020 and 2022. The investigated conference proceedings were from:

- **(BWCCA)** International Conference on Broad-Band Wireless Computing, Communication and Applications
- **(ICCSA)** International Conference on Computational Science and Applications
- **(IE)** International Conference on Intelligent Environments
- **(INTERACT)** Human-Computer Interaction
- **(ISMAR)** IEEE International Symposium on Mixed and Augmented Reality

While the investigated journals include the following:

- ACM Computing Surveys
- Advances in Human-Computer Interaction
- Aggression and Violent Behavior
- arXiv:2106.05100 [cs]
- Electronics
- Engineering Proceedings
- Expert Systems with Applications
- Human-centric Computing and Information Sciences
- IEEE Access
- IEEE Transactions on Mobile Computing
- Information
- International Journal of Computational Science and Engineering
- International Journal of Human–Computer Interaction
- JAMA
- Journal of Ambient Intelligence and Humanized Computing
- Journal of Ambient Intelligence and Smart Environments
- Nature
- The Journal of Supercomputing

4.3.3 Ambient Intelligence and Survey, All time.

Searching "ambient intelligence" "survey" [since 2022] on Google Scholar returned 40,300 results. Of that, the first 3 pages were referenced—a total of 30 documents of which a total of 28 were located and reviewed (Appendix 2.C). The 28 documents came from 14 different publishing sources, including 4 conferences and 10 journals, and were published between 2005 and 2021. The investigated conference proceedings were from:

4. FINDINGS: Exploratory Literature Review

- **(AISB)** Artificial Societies for Ambient Intelligence, Artificial Intelligence and Simulation of Behaviour
- **(ICACCA)** International Conference on Advances in Computing, Communication & Automation
- **(ICSCAN)** IEEE International Conference on System, Computation, Automation and Networking
- **(I2MTC)** IEEE International Instrumentation and Measurement Technology Conference

While the investigated journals include the following:

- Artificial Intelligence Review
- Journal of Ambient Intelligence and Smart Environments
- Proceedings of the IEEE
- IEEE Journal of Biomedical and Health Informatics
- Universal Access in the Information Society
- The Lancet Digital Health
- Enterprise and Work Innovation Studies
- International Journal of Computer Science & Engineering Survey
- Digital Policy, Regulation and Governance
- Journal of Ambient Intelligence and Smart Environments

5. FINDINGS: Grey Literature Review

5.1 Interview Transcripts

During the interviews, a total of 11 terms were used to refer to computing with exteroception. The 3 most common terms were ‘spatial’ (74 mentions), ‘ambient’ (12 mentions), and ‘immersive’ (9 mentions). While not all spatial computing practitioners actively work on all identified spatial computing artifacts, their descriptions of what comprises a spatial computing artifact within their role, facilitated identification of three main spatial computing artifact categories within which all spatial computing artifacts fall: immobile, mobile, and autonomously mobile.

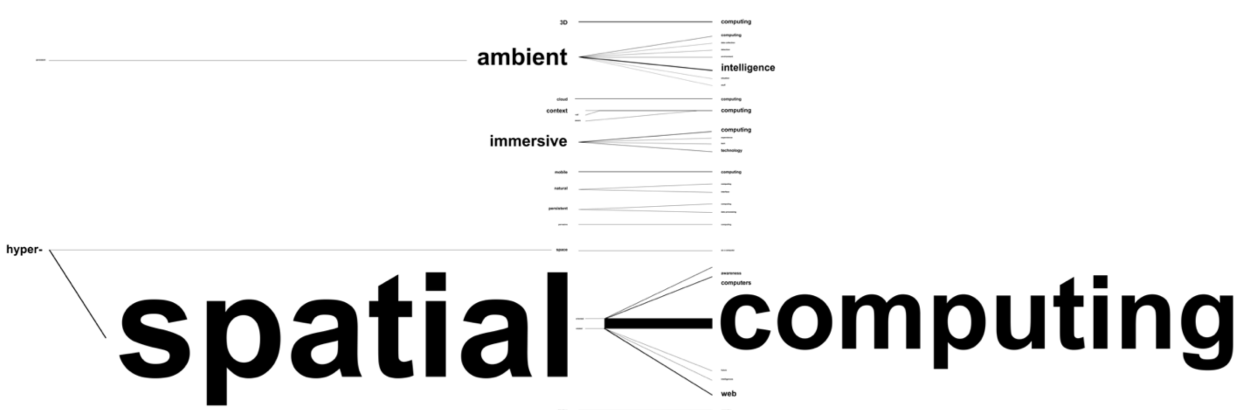

Figure 13. Term (sets). Relative scale indicates frequency of use..

Participants’ discussions of what their role comprises, as well as their definitions of spatial computing artifacts they create as a part of their role, supported proposal of the updated and simplified definition of spatial computing (the definition used in this work) which built on a prior definition of spatial computing proposed in a prior work[6] synthesized existing definitions.

[6] “We define Spatial Computing (SComp) as computing where interaction with a machine works by the machine (1) understanding the physical world and the biological, virtual, and mechanical subjects that move through it; (2) knowing and (3) communicating the subjects’ (selected) relations to places in that world—and the subjects’ quantifiable experiences within it; and (4) navigating through those places (whilst leveraging other artifacts therein).” (Ballestas et al., 2021).

5. FINDINGS: Grey Literature Review

The data clearly indicated that in addition to necessarily tracking a real Euclidean space, spatial computing was almost always tracking an array of events therein. Namely, events between subjects and/or objects. While human subjects are currently the focus within industry, other biological, virtual, and mechanical subjects can be tracked by spatial computing. Spatial computing can also track both real physical objects and virtual-"physical" objects.

Table 12 Types of Spatial Computing and Product Examples

Auto-Mobile	Mobile	Im-Mobile
Autonomous Vehicles Autonomous Aircraft ... • *Unmanned aerial vehicle, UAV (aka drones), Air Taxis, Personal Air Vehicles.* Autonomous Cars ... • *Autonomous vehicle, AV (aka self-driving car, driverless car, or robotic car (robo-car)); Shared autonomous vehicles (aka self-driving taxi/bus or driverless taxi/bus); Autonomous guided vehicles (AGV).* Autonomous Water Vehicles ... • *Autonomous surface vehicles, Unmanned surface vehicles, Autonomous underwater vehicle*	**Smart Connected Products**[7] Smart Home (aka IoT Devices) ... • *Speakers, Cameras, Lights, Sensors, Appliances, Etc.* Wearables ... • *Watches, Rings, Clothes, Etc.* Intelligent Virtual (Voice) Assistant ... • *Siri/Alexa/Google/etc.*	**Built Environments** Building automation... • *Speakers, Cameras, Lights, Sensors, HVAC, Etc.* Ambient Intelligent Environments... • *Sensors, Actuators*
Autonomous Robots • *Autonomous robotic vacuum, Autonomous robotic lawnmowers, Autonomous delivery robot, Autonomous manufacturing robot*	**Extended Reality Devices** Virtual Reality ... • *Headsets, Controllers, Other accessories.* Augmented Reality ... • *Eyewear, Screens, Other accessories.*	**IoT / Spatial Web** (Decentralized) network protocol

6. FINDINGS: Systematic Literature Review

The literature referenced in the systematic literature review covered in total 235 from 19 different sources, including 17 conferences and 2 journals between 2002 and 2020. The sources were from two publishing catalogs, where 4 were from the ASME Digital Catalog (Appendix 3.B), while the remaining 39 were from the ACM Digital Catalog (Appendix 3.C).

The investigated conference proceedings were from:

- **(AIAM)** International Conference on Artificial Intelligence and Advanced Manufacturing
- **(ASME IDETC-CIE)** International Design Engineering Technical Conferences & Computers and Information in Engineering Conference
- **(C&C)** Creativity & Cognition
- **(CHI)** ACM SIGCHI Conference on Human Factors in Computing Systems
- **(DIS)** Conference on Designing Interactive Systems
- **(EICE)** International Conference on Electronics, Information and Communication Engineering
- **(FabLearn)** Conference on Creativity and Making in Education
- **(HAI)** International Conference on Human-Agent Interaction
- **(ICIT)** International Conference on Information Technology: IoT and Smart City
- **(ICSIM)** International Conference on Software Engineering and Information Management
- **(ISCSIC)** International Symposium on Computer Science and Intelligent Control
- **(iiWAS)** International Conference on Information Integration and Web-based Applications
- **(Middleware)** International Middleware Conference
- **(MUM)** International Conference on Mobile and Ubiquitous Multimedia
- **(NordiCHI)** Nordic Conference on Human-Computer Interaction
- & Services
- **(SAICSIT)** South African Institute of Computer Scientists and Information Technologists
- **(UbiComp)** ACM International Joint Conference on Pervasive and Ubiquitous Computing

While the investigated journals include the following:

- **(TOCHI)** ACM Transactions on Computer-Human Interaction
- **(IMWUT)** Proceedings of the ACM on Interactive, Mobile, Wearable and Ubiquitous Technologies

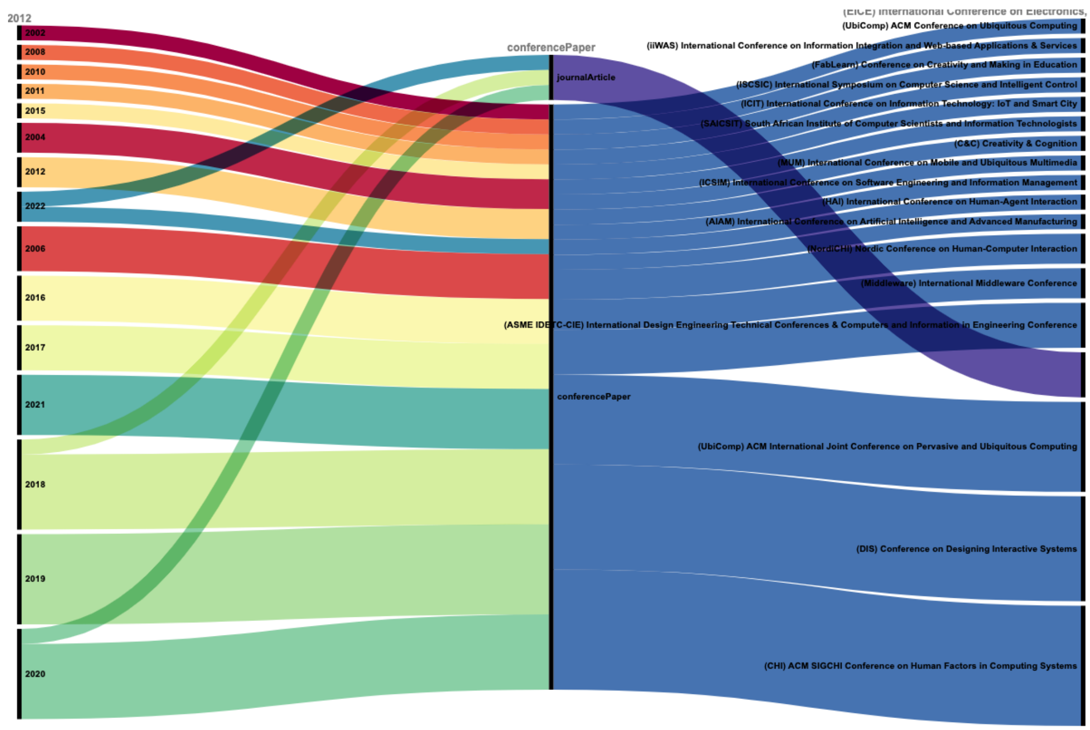

Figure 14 Visualization of data of final 43 papers reference by year, paper type, and publishing venue.

Terminology was clarified during this review. Findings showed that AmI was often used with a spatial qualifier such as "space" or "environment" (See Table 14) and for this reason this work uses AmIE where others might simply use AmI.

Table 13 Terminology: Ambient Intelligence (AmI)

Authors	Terms	Quote
(Luyten et al., 2005)	Ambient Intelligence /AmI	*"This work is … aimed at solving a set of key challenges in the area of Ambient Intelligence (AmI), where personal devices will form an extension of each user's environment, running mobile services adapted to the user and his context."*
(Obermair et al., 2006a)	Ambient Intelligence /AmI	*"Ambient intelligence (AmI) originated from the developments of ubiquitous computing, natural interaction and intelligent systems. The vision of AmI describes the pervasion of the everyday world with digital technology which is able to adapt to the presence and actions of users."*
(Wakkary et al., 2005)	Ambient Intelligence	*"Ambient intelligence computing is the embedding of computer technologies and sensors in architectural environments that combined with artificial intelligence, respond to and reason about human actions and behaviours within the environment."*

The review found that when authors deviated from AmI, they still used the qualifier of "intelligence" and in this way reinforce the centrality of ML in AmIE. This phenomenon also helped reinforce that

AmI, apparently, was not suitable in and of itself to refer to the spatiality implied by explicitly naming “environment” in AmIE.

Table 14 Terminology: Ambient Intelligent Environment (AmIE)

Authors	Term	Quote
(Cabitza et al., 2015)	Ambient intelligence environments	*“In this paper we propose a novel conceptual framework for the design and continuous evolution of ambient intelligence environments.”*
(Garg & Cui, 2022)	Intelligent environments	*“While many argue for developing end-user-driven systems that provide agency to the user (user-centric), others support the idea that intelligent environments should be driven by autonomous agents (agent-centric), and yet others set of scholars has emphasized the importance of understanding how agency can be negotiated between users and objects such as IoT devices.”*
(Ho et al., 2019)	Intelligent environments	*“Intelligent environments refer to environments that can monitor their own state and the state of their inhabitants with the purpose of improving the experience within that environment [17,27]. A smart home refers to the application of intelligent environments in the domain of traditional homes,*
(Luyten et al., 2005)	Ambient intelligent environments	*“While this can be considered as a step toward the ubiquitous computing vision Mark Weiser predicted [24], there still exists a large gap between the actual tasks a user should be able to perform and the user interfaces exposed caused mainly by two missing pieces: the lack of a taskcentered user interface design approach on the one hand and the lack of support for distributable user interfaces in ambient intelligent environments on the other hand.”*
(Novotny & Bauer, 2017)	Intelligent environments	*Weiser’s vision of intelligent environments, where technology is ubiquitous, pervading everyday life, but disappears into the background Weiser [28]. Based upon Weiser’s vision, the community works towards the seamless integration of information and services into real-life, everyday systems [4]. While the community refers to these intelligent system environments with different names, such as “context-aware”, “adaptive”, “situated”, “ambient”, etc., we hereafter refer to them as “context-aware systems”. The major research fields, researching, designing, and investigating such context-aware systems are “pervasive computing” or “ubiquitous computing”.*
(Wakkary et al., 2005)	Ambient intelligent spaces	*“Ambient intelligent spaces lend themselves extremely well to physical and group play. .. [the] goal of this project is to understand to what degree physical play and game structures such as puzzles can support groups of participants as they learn to manipulate an ambient intelligent space.”*

During the second phase of data analysis in the systematic literature review after the introduction of 89 papers was read, the final 43 papers selected for inclusion were given a special label (MT) based on a reading of the title, abstract, and introduction for inclusion of any minor theory themes. A total of 14 papers were given an MT label with the specific minor themes:

- abuse (Leitão, 2019)
- age (Katterfeldt & Dittert, 2018)
- collaboration (Eccles & Groth, 2004)

- collective intelligence (Obermair et al., 2006b)
- comprehension (Poole et al., 2008)
- consent (Luger, 2012)
- folk culture (Chen et al., 2019)
- gender (Katterfeldt & Dittert, 2018; Strengers et al., 2019)
- love (Yang & Neustaedter, 2020)
- multi-species (Minami et al., 2007)
- ownership (Salovaara et al., 2021)
- play (Wakkary et al., 2005)
- pleasure (Strengers et al., 2019)
- socio technical system (Cabitza et al., 2015)
- tech literacy (Chalhoub et al., 2020)

6.1 Data Synthesis

These minor theory themes supported the eventual clustering of data coded into three umbrella categories which together account for all of the identified elements: attunement, embodiment, and anti-fragility. Data clustered under the overarching thematic code "attune," predominantly describe the elements of the AmIE design space that support processor-enacted articulation based on a contextualized understanding of situational goals within the AmIE. Data clustered under the overarching thematic code "embodied," predominantly describe the elements of the AmIE design space that involve interaction with the AmIE as a system and with the AmIE's constituent parts. Finally, data clustered under the overarching thematic code "anti-fragile," predominantly describe the elements of the AmIE design space that support varied, stable, and equitable access to an AmIE.

Table 15 Overarching Thematic Cluster Codes and Sub-Cluster Codes

Ambient Intelligent Environments are ATTUNED through contextualizing the situational goal.	Ambient Intelligent Environments are EMBODIED through interactions with intelligent hardware / software.	Ambient Intelligent Environments are ANTI-FRAGILE through secure fault-tolerant accessibility.
A1 Situation	E1 Interactions	AF1 Fault-Tolerance
A2 Goal	E2 Hardware	AF2 Secure
A3 Context	E3 Intelligence	AF3 Access

6.1.1 Attunement

To be attuned, an AmIE must understand the situation (A1 Situation) wherein an array of goals exists (A2 Goals) all the while remining mindful of the context (A3 Context).

Table 16 Attuned Codes (A1, A2, A3)

Ambient Intelligent Environments are ATTUNED through contextualizing the situational goal.		
A1 Situation is :	A2 Goal is :	A3 Context is:
One user – More than one user	Discreet – Compound	Second – Millennium
Non-Conflict – Conflict	Crosswise – Longitudinal	Following – Proceeding
Non-Urgent – Urgent	Functional – Non-Functional	Personal – Cultural

A1: Situation. Data coded 'situation' refers to the number of users needing accommodation from the space, the numbers of conflicts present in the space, and the array of urgency levels of accommodations needed from the space.

When it comes to multi-user accommodations. Design-engineers must consider that the moment more than one user is being considered as a user, there will be inherent conflicts. In this way, AmIE are more akin to shared spaces than they are to personal devices. It is this sharedness that is a fundamental consideration to ensure the 'situation' is understood.

Table 17 Attuned A1 (One User – More Than One User)

Authors	Quote
(Garg & Cui, 2022)	*"the current designs of IoT devices do not support shared use by multiple users, besides enabling users to create multiple profiles. One issue that designers need to be cognizant of is how smart technology in shared spaces entrenches, extends, or equalizes power among co-users."*
(Obermair et al., 2006a)	*"Researchers have identified features such as three-dimensional environments, cross-platform support, and multi-inhabitant support as research requirements…The participant also mentioned that managing multiple inhabitants was the most difficult task to implement."*
(Jakobi et al., 2018)	*"Randall et al. [72], provided an early ethnographic account of using and living with smart home technology where they found that control in the smart home was not merely a technological, but also a social matter in multi-person households…These findings point to another challenge of smart home technology when it is being used by multiple users: What should users be able to see about each other's activities in the home and how can privacy demands be respected by designing adequate mechanisms, such as access control"*
(Jang et al., 2017)	*"Most smart home devices have multiple users with different expectations from the same device"*

Conflict is inevitable in any environment, and thus is something that will be dealt with in an AmIE, and should therefore be explicitly codified and managed. Managing conflict, thus, is one of the primary concerns of AmIE design-engineering. Conflict can exist at the intra-level user, that is to say a user's goals can be in conflict with their own goals; e.g., pick up child from daycare at 4pm vs. stay at meeting until 4pm. Conflict can also exist at the inter-user level, where different users have conflicting goals; e.g., user one wants to use kitchen for cooking while user 2 wants to use kitchen for a zoom interview. Conflict can also exist at the inter-group level, which is to say that different groups of users have different goals from the same space; e.g., nursing staff have different goals then their patients.

Conflicts are not always explicit, or goal related, rather, conflicts are often implicit, cultural, and emerging, which makes them identifiers of the situation rather than the goal. Understanding the situation can support in design-engineering for contextualized goal accomplishment.

Table 18 Attuned A1 (No Conflict – Conflict)

Authors	Quote
(Davidoff et al., 2006a)	*"A smart home may need to face, interpret and react to a situation where goals conflict and the situation may still be valid."*
(Obermair et al., 2006a)	*"Putnam and Poole (as cited in [42], p. 2), defined "conflict" as "the interaction of interdependent people who perceive opposition of goals, aims, and values, and who see the other party as potentially interfering with the realization of these goals... [This] definition highlights three general characteristics of conflict: interaction, interdependence, and incompatible goals." The political theory of agonism focuses on the positive aspects of certain forms of conflict, as it allows for pluralism and seeks to show how people might accept the existence of conflict and channel it positively [79]. Deutsh[36] also perceived conflict to have a positive impact, in terms of improving one's understanding, fostering creativity, and leading to positive change. Scholars have also tried to classify conflicts into different categories. For example, Al-Bin Ali [3] used technical recognizability as a metric to divide conflicts into explicit conflicts, which a system can directly identify by examining behaviors, and implicit conflicts, which are grounded in "hidden factors" such as users' moods and intentions[82]."*
(Davidoff et al., 2006a)	*A smart home system that allows its inhabitants to feel in control of their information will need to be able to blend elements across contexts, media and individuals and aggregate them into a unified model of what is happening. A smart home that supports this principle would support planning tasks and maintenance of routines everywhere the family goes, monitor and react to family activity in and out of the house and be able to leverage all available artifacts that the family uses.*

Urgency is a lesser discussed but central concept of AmIE, i.e., how urgent is the articulation needed of the environment? Urgency in the literature was used synonymously with the idea of the need to know. But in terms of understanding the situation, can be understood more complexly, it is the relative need for agency from any agent in an AmIE, machine or otherwise. This is to say, should a machine agent be passive, active, or proactive; should a human agent be passive, active, or proactive; and are any of the agents already passive, active, or proactive in their need to know. Knowing this affords a deeper sense of the situation. Said another way, a gardener at a smart botanical garden might not need the greenhouse to start blinking brightly when a new shipment of dirt arrives, unless they need that dirt ASAP, whereas a nurse may indeed want a ward to blink brightly near to the location a patient is experiencing cardiac distress.

Table 19 Attuned A1 (Non-Urgent – Urgent)

Authors	Quote
(Voit et al., 2018)	*"We assume that most of the provided notifications of smart home appliances will inform the users about home tasks that are important for the users but non-urgent, such as unloading the washing machine or changing the robotic vacuum cleaner bags."*
(Voit et al., 2020)	*"Should non-urgent smart home notifications appear immediately?... High-urgency notifications are more accepted than non-urgent ones [44, 45]; medium-urgency notifications were accepted when they were unobtrusive [45]. In contrast, low-urgency notifications are not accepted [45]. Low-urgent notifications should be delayed until the urgency increases or dismissed if the urgency does not increase."*
(Cabitza et al., 2015)	*"If father Luigi gets a text message containing 'urgent', switch off the TV, warn the patient of the next appointment of a possible delay and show the route to reach the message sender's house"*
(Jakobi et al., 2017)	*"As a result, participants quickly imagined a classification of urgent messages that should be pushed and others that should not interrupt or distract users from what they were doing."*
(Garg & Cui, 2022)	*"(e.g., establishing priorities for activities based on social hierarchy, such as parents versus children or household members versus visitors, or based on urgency)"*

A2: Goal Data coded 'goal' refers to the intended use of the AmIE. Goals can be discreet or comprise an array, they can be momentary or longitudinal, and finally, they can be functional or non-functional. Goals are the objectives of agents of any kind. In taking a human-centered perspective, goals in AmIE are those of the human inhabitants. However, it is important to stay mindful to the fact that machine agents can also be understood to have 'goals.'

Discreet goals are the simplest to understand, e.g., I want to listen to music, now. However, often, goals are more ambiguous, which is to say, compound, e.g., I want to graduate. For the first example, turning on any music would, theoretically, satisfy that particular goal. Whereas the second goal requires an array of things to happen for that goal to be fulfilled.

Table 20 Attuned A2 (Discreet – Compound)

Authors	Quote
(Davidoff et al., 2006a)	*"Families often select activities based on long-term goals such as preparing their kids for a successful career or increasing the chance of college admission to selective schools."*
(Chiang et al., 2020)	*"[Participant 14], for example, said 'as long as it turns [the appliance] on for me, it is enough, I don't care much about how confident it is.' Similarly, [Participant 9] commented, 'to achieve my goal [turning on specific appliances], I don't need it to say what it has predicted.'"*

Goals are further complicated by their temporality. Goals can be immediate, like the music example, or longer term, like keeping a fridge stocked.

Table 21 Attuned A2 (Crosswise – Longitudinal)

Authors	Quote
(Ardekani et al., 2017)	*"The smart-home applications themselves operate on streams of events generated by the sensors such as a temperature or motion sensor, actuate, or control, physical entities such as light bulbs and door locks, and create workflows to automate everyday tasks such as ordering groceries."*
(Davidoff et al., 2006a)	*"Families often select activities based on long-term goals such as preparing their kids for a successful career or increasing the chance of college admission to selective schools."*

Finally, goals can be functional or non-functional. (Major or minor, if you will.) Functional goals are goals that are classically utilitarian, e.g., turn up the lights because focused work is happening. Whereas non-functional goals are non-utilitarian, be that social, aesthetic, emotional, pleasure oriented, etc. An example of a non-functional goal might be to project an ethereal scene for pure amusement and nothing else[8].

Table 22 Attuned A2 (Functional – Non-Functional)

Authors	Quote
(Jang et al., 2017)	*Device goals. Functionality: The user expects the device to cater to their functional needs. For example, a smart lock lets them enter their house or room, a smart coffee maker makes coffee according to their preference, and a smart home assistant allows them to control other smart devices, respond to queries or make purchases. The user should be able to easily specify their functional needs on the device. For current devices, this step is done via a smartphone application on the primary user's phone*
(Poole et al., 2008)	*Evaluations of ubiquitous computing systems have typically examined the functional aspects of these technologies. A system's success has historically been judged based on factors such as performance, utility, or usability. All of these aspects of a technology are essential components to its ultimate success or failure; a technology that neglects performance, utility, and usability is unlikely to be adopted.*
(Salovaara et al., 2021)	*however, we also discovered the previously overlooked use category of social automation. Research has not actively attended to social applications because its predominant emphasis has been on smart-home automation employed to utilitarian and aesthetic ends.*

A3: Context Data coded 'context' refers to the cultural, seasonal, and temporal elements of an AmIE.

AmIE are ongoing systems; they exist now, in a week, and in a year. Data from the analysis showed that users of AmIE expect that an AmIE is self-aware of these "seasonal" changes. But there are also deviations from routine, it might rain unexpectedly, there might be a surprise party. In this way an AmIE must be responsive to an immediate need, e.g., heating the store now, and also a more seasonal need, e.g., keeping the humidity down in summer, but also when taking a shower.

Table 23 Attuned A3 (Momentary – Infinite)

Authors	Quote

[8] One might argue such a goal is functional in so far as it might promote calm or rest which have the function of reducing stress; this argument is a minor theory argument. That is to say, arguing such non-utilitarian needs being met serves a function is a minor perspective to hold.

(Chiang et al., 2020)	*"For example, P14 said, "once the season changes, since I won't need AC during wintertime, smart homes could have a different setting that asks me whether I would like to set turning on the TV as the primary task."*
(Obermair et al., 2006a)	*"Even if routines could be specified entirely beforehand, people both intentionally and necessarily deviate from routines. Some deviation is seasonally mandated, such as children participating in soccer in the fall, and in basketball in the winter. Some deviation occurs due to exceptions – Mom wants to get a surprise gift for her daughter. Many routines are substantially improvisational, representing constantly shifting targets."*
(Jakobi et al., 2017)	*"One-time and temporal home awareness demands. During summer, in particular, a set of temporal or seasonal information demands became apparent. With longer daylight and higher temperatures during the summer season there was simply less to be managed in the house and interest in checking the temperature for heating was less sought. During the summer, however, a two-person household with cats for example wanted to check the room temperature while they were abroad:"[..] We could control if it was too hot for the cats at home." (two-person household)"*
(Luria et al., 2017)	*"When a user would move the slider, the temperature would immediately adjust."*

As AmIE are systems with agents that pass action between themselves and their users, these actions are necessarily sequential. This adds a layer of complexity to understanding a given context, it is always changing. Which is to say, in addition to actions being sequential, they are also conditional on one another. In this way, context is a complex temporal object.

Table 24 Attuned A3 (Following – Proceeding)

Authors	Quote
(Voit et al., 2020)	*"All in all, the interviews revealed that users required a high degree of context-awareness. They expected that a smart plant system would reflect their complex routines and socio-temporal conditions and constraints."*
(Garg & Cui, 2022)	*"Given that context is an interactional problem i.e., that the relevance of contextual features is dynamically defined for individual users by their activities [39], the question one can then ask is how design can help."*
(Luyten et al., 2005)	*"Because the execution of a task depends strongly on the situation or context of use, the consequences of a context change on the execution of a task specification should be communicated with the task designer during the design process."*
(Mennicken et al., 2016)	*"Hamill and Harper [9] drew analogies between HCI and historic master-servant interaction to inform the design of speech-based interfaces in smart homes. Their work was mostly concerned about the nature of how instructions were expressed and they identified that a lack of contextual information in the instructions of the mistresses to the servants was often the cause of ambiguities and misunderstandings; due to the nature of the historic relationship the servant could not ask for clarification. In a butler-like smart home, people might expect the same reserved behavior from the agent interface. However, a role in which the home could reasonably ask back with clarifying questions might be more promising, eventually lead to less."*

Context is also deeply social, in this way, AmIE must understand if any given context is a personal or social one. In a public space, like a subway, for example, it is easy to assume that the context is predominantly cultural, like getting up to allow a pregnant or disabled person a seat. As AmIEs have to opportunity to blur this line, understanding the array of personal and cultural contextual orientation is important.

Table 25 Attuned A3 (Personal – Cultural)

Authors	Quote
(Garg & Cui, 2022)	*"Supporting Social Context-Based Data Collection and Inter-Member Privacy. Our participants suggested that data collection should be adapted to the social contexts in which the devices are situated. They defined social context in terms of location of use (e.g., private or communal spaces), user(s), co-located activities, and the presence of others during use."*
(Leitão, 2019)	*"Involving users who experience a system under extreme conditions, such as victims of IPA, can contribute to informing the design of smart home privacy and security mechanisms [13,48]. Importantly, not only for this audience but for other non-traditional households (e.g., house shares and multi-family households), in which trust between household members may not be a given."*
(Prange et al., 2022)	*Authentication for smart homes should consider the various roles and relationships [13, 35] and be seamlessly integrated [15]. For instance, authentication for voice assistants should be natural, unobtrusive, and adapt to the context (e.g., presence of bystanders) [28].'"*
(Prange et al., 2022)	*"[participants] suggested adapting to context by, e.g., not reading the [security] questions out loud in case of bystanders being present.'"*
(Reig et al., 2021)	*"A few participants commented on speakers' limited functionality or a general dislike of using voice interaction in certain contexts, e.g., when home alone"*

6.1.2 Embodiment

To be embodied, an AmIE must allow for an array of interactions (E1 Interactions) across an array of technologies (E2 Hardware) and leveraging an array of technological capacities (E3 Intelligence).

Table 26 Embodied Codes (E1, E2, E3)

Ambient Intelligent Environments are EMBODIED through interactions with intelligent hardware / software.		
E1 Interactions are:	E2 Hardware is :	E3 Intelligence is :
Directions – Corrections	Sovereign – Subject	Predicting – Inquiring
Active – Passive	Tangible – Ambient	Assuming – Learning

E1: Interaction. Data coded 'interaction' referred to type of user interaction with the AmIE Systems.

The latent opportunity in an AmIE is that there is the opportunity for the system to make an environmental change without alerting the user. When this goes wrong, e.g., the lights are too bright, then a user may desire to correct that. Similarly, there may be things that are not anticipated by an AmIE system which a user may want to directly request. In this way, interactions are directions or corrections.

Table 27 Embodied E1 (Directions – Corrections)

Authors	Quote
(Chiang et al., 2020)	*"As frictions caused by false predictions may be unavoidable, especially in the early stage of adopting an SHRA. Below, we present how our participants assessed and corrected automated actions caused by the SHRA's false predictions, and their suggestions for system improvement… Less serious, but still troublesome, was manually turning off appliances that had been turned on due to incorrect prediction: "If the system turns on the wrong device, I have to go there just to shut it down" (P12). The SHRA asking permission could not only prevent such trouble, but also give users the opportunity to coordinate while answering, as P6 explained: "If the system told me it was turning the AC on for me, then I could go and close the window""*
(Garg & Cui, 2022)	*"It's good that device takes over such tasks, as it helps me to achieve my health goals faster, but it should also allow me to see how my actions led the device to infer my preferences, and so forth. If I notice something that I do not agree with, that way I can correct it. But more importantly, if I see it give a good learning pattern over an extended period of time, I will start to blindly rely on the device.'"*
(Jakobi et al., 2017)	*"Fearing unintended system behavior or that they might have somehow configured it incorrectly, they wanted to understand what the system was doing and assess whether it was behaving as intended."*
(Liu et al., 2020)	*"…actual applications, developers can replace this type of gesture with other ones to enhance the user's experience when calling repeated instructions quickly."*

Not all directions and corrections must be delivered in the same way. Agents can make decisions with no explicit direction or correction; this would be a passive interaction. Whereas when a user explicitly directs or corrects an agent, an active interaction can be found.

Table 28 Embodied E1 (Passive – Active)

Authors	Quote
Grey lit	*"Issues of having an active user versus passive [are] substantial...[For example, a checkout-less smart store is] measuring where you're at [but in] more of an active position, because [by] entering that space and you know...that you are now being observed...And how that's communicated to someone [is] incredibly important...It comes down to the active or passive, and notifying the users [is] incredibly important." - Participant 0*
(Garg & Cui, 2022)	*"While this article does not argue for nor adopt any one particular position regarding the symmetry of agency between the user and the object, it is motivated by the common thread in these theories that both human (users) and non-human actors (devices/objects) have the ability to act and affect one another and IoT devices, many of which are designed and used in home today, have increasing agency, sensing and acting autonomously—i.e., making decisions independently"*
(Luger, 2012)	*"The human agency involved in the act of consenting to the disclosure of personal information, whether explicit or implied, "is the primary means for individuals to exercise their autonomy and to protect their privacy"*
(Mennicken et al., 2016)	*"Should a smart home have a proactive or passive personality? Should it try to socialize with inhabitants? What personality traits do people consider desirable or undesirable? To learn more about this design space, we created two variants of a usage scenario of a domestic routine in a smart home to demonstrate different personality trait combinations."*
(Poole et al., 2008)	*"The exact capabilities of a tag can vary; at the minimum, a tag contains an antenna and a semiconductor chip encased in forms that can be smaller than 1cm in size. Tags can be either active or passive. Active tags require a power source. Passive tags do not have their own power source, but are powered by electromagnetic waves emitted from readers."*
(Wakkary et al., 2005)	*"The system is a "passive" system, meaning that the markers do not send a signal that identifies the marker's identification. This is in contrast to an "active" system where markers can be tracked based on a signal it sends to the system either through a blinking rate or through an electromagnetic signal."*

E2: Hardware. Data coded 'hardware' referred to the types of tangible technologies leveraged to interact with an AmIE.

Hardware can be any kind of spatial computing technology, which is to say, it can be auto-mobile, mobile, or immobile. In this way, while there is a favoring of the idea of embedded hardware in the early AmIE visions, technologies that allow for AmIE to exist can be of any scale. Examples of sovereign hardware are wearables and mobile phones, while subject hardware are those on loan from a provider, like a Wi-Fi hub. In addition to scale, data also shows that the ownership of the device is something that can be considered.

Table 29 Embodied E2 (Sovereign – Subject)

Authors	Quote
(Crabtree et al., 2006)	*The level of mobility that we have observed in these examples challenges normal modes of field study. However, we have also seen that the ubiquitous computing technologies themselves, with their concern to support mobile users, can be directly exploited to support the process of description and analysis. In some cases, existing elements of the system – as recorded in system logs – provide the necessary resources for study. In other cases, we might seek to add further facilities into the system to support description and analysis. For example, adding additional sensors (such as accelerometers) to handheld devices, or making more use of their built-in microphones and cameras would provide additional resources for analysis.*
(Prange et al., 2022)	*"Smart homes are typically multi-device, but also multi-user environments. Devices are naturally shared [38] among owners and other inhabitants, but also visitors [13]. Visitors are users who do not live in the smart home (hence, are not the owners of the devices), but might be present in the environment and potentially interact with the devices [1, 9, 22, 24, 37]. Examples include, but are not limited to, remote living family members and friends, but also (foreign) subtenants or maintenance workers."*

Hardware affords an array of interactions in so far as users can interact with hardware tangibly or ambiently. Sensors that are not meant to be noticed are ambient, whereas sensors that are meant to be noticed and engaged are tangible.

Table 30 Embodied E2 (Tangible – Ambient)

Authors	Quote
(Leitão, 2019)	*"Even though dystopian in nature, the product reflects the capabilities of spyware embedded in a tangible artefact, aiming to aid participants in more fully understanding the abstract capabilities of such covert software."*
(Luria et al., 2017)	*"In the past, comparisons have been made between other non-robotic modalities for smart-home control [8, 34], while social robots and tangible interfaces were compared to screen interfaces in other contexts of the domestic space, e.g., game play [57], education [62], and weight-loss coaching [32]. However, we do not know of a comparison between a social robot and traditional interfaces in the context of smart-home control."*
(Newman et al., 2002)	*"These users were consistent about grouping by location when searching for things like the projector control and the PowerPoint Viewer (in other words, components with a physical embodiment or effects that would be tangible in a particular space), and grouping by owner when searching for files."*
(Jakobi et al., 2018)	*"Suggested solutions largely focused on technologies that were already being used in daily activities, such as smartphone push notifications or a widget on the phone's home screen, or having a dedicated ambient display in the kitchen or the hallway that could just display system conditions,"*
(Wakkary et al., 2005)	*"Recent projects have investigated the play space of responsive environments and tangible computing utilizing sensors, audio, and visual displays."*
(Chuang et al., 2015)	*"Among those ideas, some were tangible smart products that could detect the environmental information and proactively help to improve the indoor quality."*

E3: Intelligence. Data coded 'intelligence' referred to both human and machine intelligence, which both can predict or inquire, assume or learn.

Prediction, in a machine intelligence sense, is a mathematical best guess. To increase the accuracy of the prediction inquiring can be leveraged. Data revealed that users anticipate that predictive machine behaviors are more intelligent, whereas when the machine inquires directly, there is the perception that the machine is less intelligent.

Table 31 Embodied E3 (Predicting – Inquiring)

Authors	Quote
(Ho et al., 2019)	*F score is typically used when the labels of data are imbalanced [2,21]. It is mentioned that the ratio of performed activities for each inhabitant is typically not similar and therefore it is good to assume that labels are imbalanced [2]."*
(Newman et al., 2002)	*"For example, we augmented the functionality of the templates to increase the "intelligence" with which components could be filtered, by allowing the inclusion of constraints based on variables such as "owned by the current user" or "locations near me." In addition, we added assumptions about the ability of the browser to make certain filtering decisions by default, such as restricting the scope of the components shown to those in nearby locations or within a certain administrative boundary."*
(Chiang et al., 2020)	*"Such prediction-based systems would require effective communication, not only because constant user feedback is crucial to making their predictions more accurate[28], but also because users who lack knowledge of machine learning are likely to have unrealistic expectations of what such systems can do and how long their learning phases will take [15]."*
(Davidoff et al., 2006b)	*"The interviews covered both predictable days, like weekdays and weekends, predictable exceptions like business trips and holidays, and unpredictable exceptions such as sick days or miss-the-bus days."*

Prediction in a human intelligence sense is better understood as assuming. Assumptions in an AmIE are made about the AmIE itself and about the myriad of activities that happen therein. Where assumptions fail, learning supports. While the inhabitants must learn about the AmIE, the AmIE must also learn about the inhabitants. In this way, many types of intelligence (human and machine) are being collaboratively negotiated in an AmIE.

Table 32 Embodied E3 (Assuming – Learning)

Authors	Quote
(Chalhoub et al., 2020)	*"Our results also give an example of a common communication problem in multi-stakeholder teams where security de- sign happens. As Flechais and Sasse [16] report, in the absence of day-to-day communication between stakeholders, the number of implicit assumptions made increases… The larger the number of stakeholders, the more assumptions will be made."*
(Garg & Cui, 2022)	*"This means that, while an agent can make initial assumptions about the various aspects of social context described above and learn to improve its adaptations, the design should expose its seams [54, 113] to reveal any complexities, ambiguities, and inconsistencies that affect its ability to re-configure itself to suit the user's idiosyncratic preferences and the continually manifested, redefined, and negotiated context."*
(Cabitza et al., 2015)	*"For instance, literature work concentrate on learning user profiles [12], extraction of recurrent behavior patterns [2], combination of temporal and probabilistic reasoning [1], agent- based architectures [36]."*
(Chiang et al., 2020)	*"However, if they knew the SHRA was "still learning" a specific pattern, the participants preferred it to ask for permissions. And, regardless of confidence, some participants doubted that an SHRA could ever accurately recognize their specific intentions, from among the wide array of possibilities"*

6.1.3 Antifragility

To be antifragile, an AmIE must be fault-tolerant (AF1 Fault-Tolerant) in an array of configurations (AF2 Software) for an array of users and in their varied experiences (AF3 Access).

Table 33 Anti-Fragility Codes (AF1, AF2, AF3)

Ambient Intelligent Environments are ANTI-FRAGILE through secure fault-tolerant accessibility.		
AF1 Fault-Tolerance is:	AF2 Secure is:	AF3 Access is:
Online – Offline	Safe – Un-Safe	Singular – Varied
Local – Cloud	Private – Public	Equitable – Un-Equitable

AF1: Fault-Tolerant. Data coded 'fault-tolerant' referred to the capacity for an AmIE to continue functioning under an array of failure scenarios.

Given that AmIE are computational artifacts, they are also (typically) electronic artifacts, which often also connect to the internet. This presents a challenge should the power go out or the internet go down.

Table 34 Anti-Fragility AF1 (Online – Offline)

Authors	Quote
(Ardekani et al., 2017)	*"Smart homes, unlike data centers, are rarely managed by a professional system administrator, and are especially susceptible to errors in management, configuration and device failures. Furthermore, failures are also harder to recover from due to lack of redundant infrastructure and expertise. Conventional distributed system techniques cannot always be applied in a home since many underlying assumptions (e.g., majority of replicas are not faulty) cannot always be guaranteed."*
(Garg & Cui, 2022)	*"The participants were especially concerned about the negative consequences and safety issues that emerge when a device malfunctions or fails to operate. In such cases, the participants included a manual override (or a "kill switch," as participant P15 termed it) in their designs of devices."*
(Jakobi et al., 2018)	*"The lack of overview provided by the default home log widget also severely limited the possibility of finding patterns in observed system failures."*
(Jung & Jin, 2018)	*"Figure 2 shows real-time free-length monitoring systems for checking total production and failure rate. This systems consists of an IoT device connected to the spring free-length sorter, a server including a server program and a database, and a user GUI program."*

Similarly, as computational artifacts dependent on information processing, data management must happen somewhere. Somewhere locally, e.g., a personal device, or somewhere else, e.g., the cloud (aka an off-location server).

Table 35 Anti-Fragility AF1 (Local – Cloud)

Authors	Quote
(Ardekani et al., 2017)	*"The vast majority of existing smart–home solutions are cloud centric wherein applications run in the cloud, and need to frequently communicate with in-home devices. Therefore, data from sensors and appliances needs to be sent to the cloud, and the results of computations, including actuation."*
(Jakobi et al., 2017)	*"Additionally, households had to register with their email addresses to gain access to the vendor's cloud portal."*
(Jakobi et al., 2018)	*"The system1 used in our study was a commercially available off-the-shelf system, which incorporated a range of features common in DIY smart home products. The system was based on Zwave and relied on a coordinating hardware gateway that managed the connection for remote access and data upload. Measurements and rule sets were both uploaded into the vendor's cloud, which allowed for complete remote control of the system."*
(Jang et al., 2017)	*"Users may be concerned about a microphone or cam- era that is constantly recording and feeding information to the cloud, even though the devices may be using the micro- phone and camera feed only for voice and face recognition respectively. Also, the feed is typically sent to the cloud, so an external adversary could obtain the recordings when they are sent to the cloud or from the user's account in the cloud."*

AF2: Secure. Data coded 'secure' referred to the capacity for an AmIE to facilitate safe and contextually private and public behaviors.

Safety is deeply subjective, and yet it is a clear goal and expectation of AmIE. Meaning, neither what is safe nor unsafe is clear cut, and as the context or inhabitant changes, so too might that which is safe.

Table 36 Anti-Fragility AF2 (Safe – Un-Safe)

Authors	Quote
--	*"However, even within traditional online environments, the use of such mechanisms for informing and securing consent are problematic."*
(Chuang et al., 2015)	*"The females would turn on most of the lights. When they moved around, he would turn off the lights but the females would keep the lights on. When we discussed this observation with them, Participants A and C told us that for the females, it made them feel safer and more peaceful at home."*
(Strengers et al., 2019)	*"David also monitored his pets during the day via a livestream camera in the laundry (where he had installed a television for their entertainment). He described coming home one day because "one of the dogs…got a toy stuck in the doggy door and they couldn't get in or out". David's intentions were caring rather than sinister – he wanted to check up on whether his children were doing their homework and his pets were safe and happy."*
(Leitão, 2019)	*"Recent work has also investigated the specific misuse of digital technologies to monitor, stalk, and harass victims of intimate partner abuse (IPA) [18,25,26,31,40,54]. In England and Wales, 27.1% of women, and 13.2% of men experience domestic abuse [44]. It is estimated that around 48% of these cases include technology-facilitated forms of abuse [51]."*

Similarly, privacy is not a fixed concept. Data showed more nuance that is typically attributed to the idea of privacy. Namely, ideas of what is private versus what is public shift between contexts and between inhabitants.

Table 36 Anti-Fragility AF2 (Private – Public)

Authors	Quote
(Ma et al., 2019)	*"With Blockchain, single point of failure can be eliminated as all the participating nodes will take part in the transaction recording and validating."*
(Garg & Cui, 2022)	*"Based on their own experiences of using IoT devices and other technologies in the home (e.g., televisions, smart phones, desktop computers), the participants expected conflicts to emerge more frequently in the public spaces, as they are "jointly-owned by family members" (P13). Family members often have equal authority to decide how a technology will be used in such spaces, which often leads to conflicts arising from different opinions."*

(Mennicken et al., 2016)	*"Gockley et al. [7] who studied people's reactions to a personality exhibiting robot in a public setting, found that differently designed personalities affect the amount, frequency, and duration of interactions."*
(Newman et al., 2002)	*"First, both the user interface and the under- lying system must allow users to assess what devices and services are available ("there is a printer here; I can access this video projector from my PDA"); determine what their capabilities are ("this is a format conversion service; there is a display here that can show video"); understand their relationship to one another and to the physical and social environment ("this printer is nearby but, it is 'owned' by a user and is not considered public"); and be able to predict likely outcomes from interaction ("the video projector is currently in use by another person")."*

AF3: Accessible. Data coded 'accessible' referred to the need for AmIE to be accessible in a myriad of ways for a myriad of people.

Data clarified that accessing an AmIE and its respective services must be possible across an array of access points. Single point failures are likely when single access points are given. Which is to say, AmIEs will need to consider when singular versus varied modes of access are appropriate.

Table 37 Anti-Fragility AF3 (Singular – Varied)

Authors	Quote
(Jang et al., 2017)	*"Authentication methods may not always work according to the developer's expectation. Using Bluetooth scans to sense if a user's smartphone is close by makes it convenient to unlock doors using smart locks, however, it assumes that only the authorized user will have access to the device."*
(Reig et al., 2021)	*"We conducted an online study and found that while people currently use smart home technologies as single-function tools, they envision a future where these technologies both improve these functions and interact in more complex ways."*
(Crabtree et al., 2006)	*"It also means that ubiquitous computing distributes interaction across a burgeoning array of different applications and devices, some online, some mobile, each exploiting different mechanisms of interaction."*

Reviewed literature revealed concerns from both researchers and users that AmIEs should afford equitable experiences. Equity is not always clear cut, like safety. But unlike equality, implies more explicit ethical and moral adjustments to increase the equality of experience across contexts and inhabitants.

Table 38 Anti-Fragility AF3 (Equitable – Un-Equitable)

Authors	Quote
(Garg & Cui, 2022)	*"Rogers voiced several ethical and social concerns concerning Weiser's vision of calm computing and raised questions such as "How do designers decide which activities should be left for humans to control and which are acceptable and valuable for the environment to take over responsibility for?"*
(Luger, 2012)	*"Existing literature related to consent derives of multiple contributing disciplines (e.g.,law, computer science, psychology, bioethics, sociology, policy studies) casting consent as a conceptually complex and multifaceted issue. However, even without the additional challenges posed by ubicomp, these perspectives are siloed, disparate, epistemologically distinct and often highly theoretical rather than applied and as such are not immediately useful to the design community."*
(Pierce, 2019)	*"This fourth industrial revolution will transform how we live, work, create, and play—and yet (of course), it carries with it a dizzying array of ethical dilemmas, societal anxieties, and practical growing pains. A similar tale is told of AI (artificial intelligence), one that is at once exuberant and cautionary. This design research project sets out to explore tensions in the twin unfolding stories of IoT and AI, and their confluences within the emerging smart home consumer product landscape. This work proceeds with sensitivity and concern for a cluster of top-of-mind issues for academics, media pundits, and policymakers alike that includes digital privacy, security, trust, accountability, and fairness."*
(Strengers et al., 2019)	*"However, while these householders had confidence in their own knowledge, skills and ethics, they also expressed concerns for the security and privacy of other less aware or capable households. For example, some participants were concerned that smart home technologies could be used to invade other household members' privacy or lock them out of critical services and access points to the property (case studies 2&4)."*

7. TAKEAWAYS

The three literature reviews afforded two main takeaways: triangulation of constituent elements of the AmIE design space and semantic clarification of the field. Through applying minor theory as a method of data synthesis of the final data selection in the systematic literature review, the intended ambition of producing a functional design space where all variations of a design could be located as a given point in the design space was found to be out of scope. However, thematic vectors that define qualities a minor taxonomy of AmIE might include were identified. In this way, this work makes three contributions to the field of design-engineering research and practice:

1. Suggests best practice terminology.
2. Forwards a comprehensive array of constituent elements of the AmIE design space,
3. Presents data synthesis through a minor theory lens (i.e., proposes attunement, embodiment, and anti-fragility as necessary conditions for an alignment problem aware AmIE).

7.1 Terminology

Competing definitions of 'ubiquitous computing,' 'pervasive computing,' 'mobile computing,' 'spatial computing,' 'ambient intelligence,' 'ambient intelligent environments,' and 'design engineering,' were surfaced through review of literature surfaced in the exploratory, grey, and systematic literature review. Synthesis of these terms led to the proposal of best-practice terms as defined in the Background. Despite this contribution, this work is a drop in the bucket in terms of research published in this field. Thus, what this inconsistent use of terminology underscores is that at the very least there is lack of agreement about what terms mean, and at worst, indicates that there is intra-term knowledge loss. In a particular glaring example from the systematic literature review, the challenge of semantic precision is further complicated when even within academia, even when written by the same authors, even in the same paper terminological use is inconsistent,

> *"…in this paper we use the terms end-user programming and smart home control interchangeably…" (Davidoff et al., 2006a)*

Additionally, a specific review of terminology used by practioners in industry, as found in the grey literature, revealed that the semantic disconnect between practice and academic publication is vast. The immediate implications of these findings are clear, there are no clear best practices or consistent standards of use for terms related to this field. This invariably has and will continue to present challenges for inter-academic, inter-industry, and inter-industry/academic research alignment.

This challenge was apparent in the difference between key authors and publications represented in the exploratory literature review versus the systematic literature review. In the more comprehensive exploratory review where 156700 documents were surfaced of which 165 documents were reviewed, there was a group of consistently referenced authors and publication venues. Surprisingly, in the systematic literature review, very few of these authors and publication venues surfaced even though many of documents from the exploratory literature review were from the ACM catalog. Another interesting finding from the systematic literature review is that search of the ASME catalog had surfaced relatively few results compared to ACM. A large portion of the reviewed ASME document used the term 'cyber-physical system' synonymously with how this work defines AmIE. It is anomalies like this which indicate terminology is critical to surfacing the correct literature. This is certainly true for the ASME and ACM catalogs, which had vastly different result amounts and types based on the same search parameters. These findings might also reflect a greater divide in knowledge assimilation between the two fields.

The review of the gray literature more specifically showed that practitioners use terminology much differently than academic publications, namely in two ways: colloquialisms and industry jargon. Review of the transcripts revealed that people are, naturally, conversational. It was this colloquial setting that led to a certain level of expectable semantic imprecision. Participant 1, for example, used a total of seven terms when asked what they use "to identify your work." Likely because the function of language is different between spoken speech in industry and written words in academia, transcripts revealed not only favoring of terms,

> *"I originally liked 'mixed reality,' but 'spatial computing' sounds a little cooler. [but] if I pick one of those, I immediately caveat it with like, it's kind of like 'VR,' kind of like 'AR'*

> … *I'm having to explain more what it is because 'mixed reality' sounds like you're on drugs and 'spatial computing' sounds like you're in hardware development.*
> *Participant 12, for example "And what's really interesting, too, in the artificially intelligence-, within the ambient environment* ***thing****…"*
>
> – Participant 8 explaining what term they would use to describe their work at a "at a cocktail party"

but also more generally, in so far as a lot of the concepts used in academia are simply unknown or unused in practice. Participant 12, for example "And what's really interesting, too, in the *artificially intelligence-*, within the *ambient environment* ***thing****…*" This interchangeable inconsistency or terms invariably creates a gap between academia and industry. Additionally, these examples highlight another looming challenge of terminological inconsistency, the comprehension of the end user.

Data reviewed in the systematic literature review underscored how this semantic challenge extended to lay people end-users. In one exemplar, from a study where 20 "not tech savvy" participants who participated in a mixed methods lab study on user-system communication in AmIEs participants had a wide array of interpretations of a term that is used commonly in both industry and academia, (machine) confidence:

> *"When prompted to describe what confidence meant, the participants used an array of broadly similar terms such as probability, possibility, likelihood, accuracy, certainty, and strength of association. Other interesting interpretations included "how sensitive the system is" (P6), "what the system knows/thinks I want to do" (P13, P18), "prediction of my own confidence in doing it" (P10), and "a kind of desire or urge to do some- thing" (P19). (Chiang et al., 2020, p. 5)*

This is not altogether a problem, in fact, the systematic literature review also indicated academics' awareness that academic terminology is often not suited to normative expressions of day-to-day life,

> *"A distinction may be made between lay and professional ethnographies, where a recognizable difference exists as to the ways in which ethnographic materials are analyzed … It would be very strange, indeed fractious, if you were to start classifying a family member's descriptions of her day in terms of formal analytic schema in order to analyse it, for example, yet that is what a social science researcher might well do with such ethnographic materials." (Crabtree et al., 2006)*

The implications of the findings around semantics found across the three literature reviews is that there should be the expectation amongst AmIE design-engineers and researchers in both industry and academia that knowledge dissemination suffers when terminological standards do not exist or are not applied consistently. Practitioners and academics alike should be militant in their terminological precision, especially in writing, lest people think they are on the same page when they are not. Until that semantic agreement arrives, the reviewed literature indicated that terminological roadblocks might limit collaboration between disciplines and fields which would be a great disservice to the field as expertise across a wide array of disciplines will be needed.

7.2 Constituent Element Gradients

A total of 21 constituent elements were surfaced during the data analysis phase of the systematic literature review. Presented as gradients between two extremes of any given element (e.g., *no-conflict – conflict*, *passive – active*, or *singular – varied*) the elements contribute to the field of design-engineering research of AmIEs in two ways. First, the fact that these elements exist on gradients help to show that AmIEs are complex systems that can be precisely tuned. Second, and especially as this work does not propose that the 21 surfaced elements are the only possible conceptual elements, but rather, the elements surfaced in a close examination of 43 documents, the challenge of creating a working Cartesian design space of AmIE is underscored.

In the unlikely event that these 21 elements do indeed comprehensively address the whole AmIE design space, the design space would be a 21-dimensional design space. In other words, orders of magnitude above comprehension of an average human design-engineer or AmIE inhabitant. While at least one 23-dimensional design space has been published in the academic literature and was not altogether impossible to conceptualize (Zheng & McClarren, 2015), 21 dimensions does not make for a deeply accessible design-engineering tool.

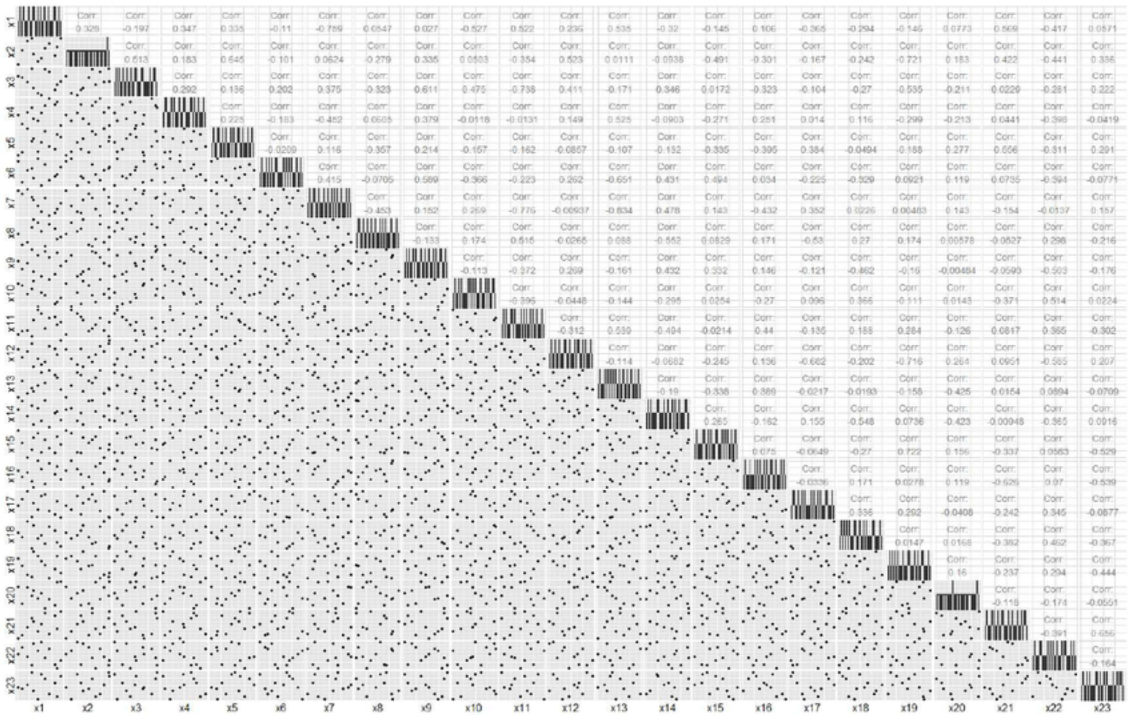

Figure 15 Latin Hyper Cube sampling design of a 23 dimensional space (Zheng & McClarren, 2015).

Depending on the hierarchical level at which categories are defined, in all likelihood, the entirety of constituent elements of an AmIE likely significantly greater than 21. Perhaps an AmIE processor can makes sense of this, but when returning to consider two notably accessible scientific codifications, the periodic table of elements and double helix, it becomes clear that that which a comprehensive taxonification valuable for a human is its relative accessibility and comprehensibility. The ongoing challenge, especially for academic researchers in this field, will be to taxonify the AmIE design space in such a way that it is both comprehensive *and* functional. The implication of failing to make any AmIE design space at all is clear: the AmIE, in so far as it is a computational object, simply cannot exist as the processor needs some amount of taxonification to processes gathered data and thereafter articulate changes to the built environment. The implication of failing to surface working theory of the AmIE design space that is comprehensible to humans is that design-engineers and, ultimately, end-users will be vastly limited in achieving a working comprehension of the domain.

The data reviewed in the systematic literature review indicated an awareness that perhaps instead of the early vision that the AmIE paradigm would be "seam-less" AmIEs should be explicitly "seam-full." In this way, the data suggested that researchers in the domain of AmIE understand the importance of comprehension of the AmIE design space,

> *"Consequently, it is with regard to the communication required for collaboration that the quest for invisible computing is questioned. Ambient technology has been focused on making technological agents invisible and autonomous [19]. However, the best collaborators, human agents, rely on reciprocal communication to achieve coordination, and, hence, in some ways, are not as invisible or autonomous as we would like technological agents to become. All agents in collaborative systems, such as the [problem solving systems] that characterize ambient technology environments, benefit from the continuous and accessible sensibility of other agents." (Eccles & Groth, 2004, p. 273)*

7.3 Minor Theory and Three Thematic Vectors

The goal of this work from its earliest beginnings was always to maintain a level of criticality in working towards producing design-engineering knowledge about AmIEs. At that point, the concept of socio-technological ethics in practice was the extent of my previous work on criticality in academic research. Thus, in the exploratory literature review there was an underlying ambition to surface a theoretical lens through which to work through the later grey and systematic literature reviews. Therein, the previously unfamiliar concept of minor theory surfaced and served thereafter as the theoretical lens through which the rest of the work was completed.

Challengingly, minor theory is not a specific methodological approach. Instead, it is a more global lens in so far as to produce minor theory is (simply) to center conventionally dismissed values, needs, concerns, and perspectives in domains that typically favor and focus on conventional values, needs, concerns, and perspectives. Minor theory scholars often refer to this centering as "political," and yet, minor theory, as a method, is deeply a-political in that it is neither dogmatic nor prescriptive. Thus, to have introduced and applied minor theory, as this work has done, is not to say that a particular series of minor theory prescribed steps were followed or that a specific array of ideas were prescriptively favored above others. Rather, and in this work specifically, employing minor theory was an emergent practice that found place across all three literature reviews in different ways. Or, as the proposer of minor theory, geographer Cindy Katz puts it, to work towards minor theory is to "provoke masculinist Marxist *and* poststructuralist theorists into deeper engagement with feminist thought and minor ways of theorizing" (Katz, 2017, p. 597).

In the exploratory literature review, minor theory helped to underscore the ambiguity of the concept of 'design-engineering.' In addition to the semantic ambiguity despite large institutions and publications using the term in their naming, including the department at the Technical University of Delft which is the receiving body of this work, The Faculty of Industrial Design Engineering, there was little discussion in the reviewed literature that indicated an awareness or curiosity about the unique opportunity that colliding the two terms presents. Namely, design-engineering (or 'design engineering' or 'engineering design') implies some kind of gradient between or across these two disciplines. This observation is minor in that it indicates a possibility space that is "always contextual…arising from the performed field rather than deriving from a universalising norm" (Lancione, 2017, p. 574). Which is to say, the fields of design and engineering are often perceived as wholly different, and, historically, they have been respectively gendered. Colliding the terms, regardless of whatever semantic inconsistencies of usage the exploratory literature review revealed, is (inadvertently) "attuned to a minor form of politics against the normalising forces that tend to control and reduce the potential of contextual becoming" (Lancione, 2017, p. 574). Which is to say, design-engineering as a compound concept implies an underdiscussed assertion that these two disciplines might be more than the normative ideas about them, instead affording more emergent conceptualization of the work and identity of professionals in and across these (two) fields.

The data from the grey literature review itself was inherently more minor than all other data reviewed in this work in that it comprised transcripts of people talking. In this way, the data was more casual, and in addition to being able to quantify findings, like how many times a given term was used, it also afforded more gestural observations. Notably, transcripts represented emergent thinking across nearly all participants. Except for the few specific occasions where participants specifically indicated they had already done a lot of thinking on a particular topic (and said as such, e.g., when Participant 4 said, "Yeah, so I may have thought about this too much so this may sound like a prepared answer."), participants were more likely to, seemingly, arrive at new thoughts in conversation. This is important, from a minor theory perspective, for two reasons. First, it supports data from the systematic literature review that inhabitants of AmIE need time to conceptualize their needs and that needs are not fixed. Said another way, perspectives not only formulate over time but also change over time. Second, these transcripts are early indications that even practicing professionals in this field are still developing their own mental models about AmIEs and their constituent parts. For example, in response to the question "are [spatial computing technologies] more or less vulnerable to ethical issues than other design artifacts?" Participant 1 had several sentences that indicated thinking before explicitly answering,

> *"Wow, that's a tough question. Um, so I think that. [PAUSE] Sorry. [PAUSE] The- Okay- So- I mean- yes. And I mean, it depends on the context and how you're using it, when you are and where you're using any of those artifacts. So it's[PAUSE] Wow, that's like a huge question. And so I'm trying to even think about, like, where to start…"*

Despite the non-procedural nature of minor theory, during the systematic literature review, documents included for final synthesis were labeled if they seemingly invoked minor theory concerns before data synthesis commenced. Labels included 'abuse,' 'age,' 'collaboration,' 'collective intelligence,' 'comprehension,' 'consent,' 'folk culture,' 'gender,' 'love,' 'multi-species,' 'ownership,' 'play,' 'pleasure,' 'socio technical system,' and 'tech literacy.' In this way, prior to more comprehensive coding, an array of themes primed the continued engagement with the documents. There is no perfect way of describing how these themes led to an emergent way of comprehesion and sense making of the documents. However, it is this imperfection of centering non-dominant ideas that minor theory intentionally attempts. In a reflection article twenty years after her initial article which proposed minor theory, Cindy Katz spoke to this challenge of adhering to the minor,

> *"I'm going to try to keep myself in this impossible minor space, and connect to the 'immanent politics' created in, through, and across these pieces. The task feels more difficult than 'staying in bed…'. To 'dig my burrow,' I will retrace my own meanderings toward and with minor theory, and try to 'bundle' it with these others to glimpse, feel, hear, and try to keep open new spaces of and for politics—politics of knowledge and creative action." (Katz, 2017, p. 597)*

However, in attempting to continuously maintain some level of a minor theory lens while producing this work, and especially during the systematic literature review, two main takeaways emerged. First, minor theory, and its cousin slow scholarship (Hartman & Darab, 2012), helped in (eventually) accepting that a cartesian design space was out of the scope of this work despite that being the initial goal of the work. Instead, both limited by time and resource to evaluate and validate any cartesian coordinates, this work proposes three thematic vectors and an array of 21 elements. Admittedly, accepting this scoping error was disappointing. However, more analytically, the fact that such a goal was not possible in the allotted time and resource for such a work (1 master's thesis researcher working for 5 months) speaks to the vastness and complexity of the AmIE design space. Importantly, considering that the first exploratory literature review also included a review of over 80 articles on critical theory, the fact that the ambitious goal was out of scope also indicates that producing design-engineering theory that employs a critical view is additionally challenging and time consuming. An awareness that producing work in the greater AmIE design-engineering field is time consuming and often does not go as planned is something which the gray literature review also indicated,

> *"A good manager [can] justify the money being spent … If you have a convincing [metric-based] argument, and you make your case, you can change directions. So I have example where I was restricted to certain way… [but could not reach] the accuracy that [they] want from me because it is not compatible with the way deep learning works, and [trying to make it work] took about a month of experiments. And a me demonstrating this point to say we need to redesign this because we're going the wrong direction [led to us going in another direction]."* – Participant 4

The second main minor theory takeaway of this work, is that instead of producing a full cartesian design space, taking a minor theory lens supported the synthesizing of the 21 elements into thematic clusters: 'attunement,' 'embodiment,' and 'anti-fragility.' These thematic clusters are dual purpose. First, in a grounded theory capacity, they help to propose theory about findings that emerged from the reviewed data in so far as they act as clustering-devices for the 21 elements. Second, the thematic cluster codes also forward three conditional principles necessary for design-engineering an alignment problem aware AmIE. Ultimately, what leveraging a minor theory lens in this work contributes to the field of design-engineering research is an applied awareness that the way items are conceptually organized transforms otherwise (possibly) neutral items into items that re-enforce certain power dynamics over others. By clustering and naming certain elements under the terms 'attunement,' 'embodiment,' and 'anti-fragility' minor values of being contextually adjusted to, understood and engageable, and widely accessible are underscored. In this way, this work presents one initial approach to applying minor theory in the domain of design-engineering.

8. DISCUSSION

The nature of AmIEs is to change based on data being gathered in-situ and processed in real time by ML. In effect, it is hubris to fathom all possible design space dimensions, AmIEs are simply too complex, and yet, we must still propose theory. Unfortunately, major theory does not give us good principles for dealing with the inevitability of spatiotemporal evolution in AmIEs. Minor theory, in contrast, helps by centering the reality that producing a design space requires both classifying and ordering concepts, a fraught task. Fraught, first, because classifying and ordering, especially as what is classified and ordered becomes increasingly complicated, is vulnerable to two dangerous traps: oversimplification and omission. Fraught, second, because ordering and classifying, including what is simplified and omitted, is an act of imposing values, and thus, an act of imposing certain power dynamics over others. Which is to say: striving for domain specific theory, like a design space, is not a-political (Katz, 1996). And yet, "research that concludes simply that 'everything is complex,'" is not a sufficient conclusion (Langley, 1999, p. 694), for it is the work of design-engineering researchers to address and make sense of complexity. Minor theory, thus, offers a theoretical lens through which to approach the complexity management this work must address in producing a design space. This work of codification is especially important when it comes to spatial alignment. Given that AmIEs rely on ML, minor theory helps us maintain sensitivity to the implications classification and ordering can have on the experience of end-users.

Thus, to propose a minor taxonomy, is to propose an intentionally imperfect taxonomy, a taxonomy predicated on the belief that the perfection can't be attained, instead, imperfect systems should "be envisioned and brought lovingly into being…[for they] can be designed and redesigned" (Meadows & Wright, 2009, p. 182). Based on the synthesized data from three literature reviews, this work proposes three thematic vectors which define a three-dimensional conceptual design space of AmIE. Rather than functioning as explicitly cartesian, instead these vectors identify the three core needs of an aligned AmIE: attunement, embodiment, and antifragility.

8.1 Attunement

8. DISCUSSION

Attunement (sometimes called 'affective attunement') is a concept first proposed by developmental psychologists in the 1980s (Gallese et al., 2007) which codifies the phenomena of responsive-interactional-adjustment. In other words, attunement occurs when responses are adjusted in such a way that another individual experiences a sense of being contextually reflected. Attunement is not mirroring, but rather the subtle but critical behavioral act that humans leverage to sync with one another empathically. In time, attunement also aids in learning from one another through imitation (Napolitano, 2021). Scholars believe there is a biological basis for attunement. That, despite the fact that attunement is not simple mirroring, it is the existence of the mirror neuronal system (Gallese et al., 2007) that allows for attunement to occur. But the presence of such a mirror neuronal system, researchers caution, in no way guarantees that attunement will occur, rather that the underlying capacity for attunement exists.

This work offers 'attunement' as a way of understanding making sense of a given built environments' capacity to reflectively adjust to contextual needs withing a space; in other words, 'spatial attunement.' If affective attunement is about adjusting to support the emotional experience of another, then spatial attunement is about adjusting to support the situational experience of the dwellers. Conventionally, spatial attunement is limited by the fixity of the built environment. Besides windows, doors, curtains, and objects that roll (like furniture on wheels), buildings, typically, do not move. And besides lighting and HVAC (heating, ventilation, and air conditioning) systems, buildings, typically, also do not adjust atmospherically either. And yet, the way buildings are used, much to the displeasure of Modernists, is rarely as static as the buildings themselves.

Time and time again we see how crafty people are with their spaces, bending spaces beyond their intended functions to meet dwellers needs, wants, desires. A conference room, for example, has, of course, all the fixings for a conference-situation, it is a conference room after all. And a kitchen, also, has all the fixings for a cooking-situation, it being a kitchen and all. But we know, from experience, that we use spaces beyond their intended functions every day. A conference room can become a gym when all the chairs and tables are pushed to the side; et voilà! a workout-situation is now, also, accommodated under the umbrella designation of "conference room."

This multi-purpose accommodation is what architects refer to as 'program.' In non-AmIE programming, whether imposed hierarchically or adjusted situationally, is limited by the immediate affordances of the building and any objects therein. Want a window, but there isn't one? Tough luck, the light or air or view you seek, simply, does not exist. Buildings are typically intolerant of on-the-fly alterations, instead, people engage their agency to change spaces through interior design, media design, and using space in ways that were not initially intended. In this way, non-AmIEs, themselves, do not attune. They do not have agency. They are not responsive. They have no awareness of context. They are not aware. Attunement happens within them, but not by them.

What distinguishes an AmIE from any other environment is its capacity to have agency, its ability to be responsive, the fact that it is (computationally) "aware," that that "awareness" affords it the capacity to decipher context, and, ultimately, to attune. But attune to what and for what reason? That is the question.

> *"The findings attest to various challenges that families may encounter in identifying needs for smart-home technologies" (Salovaara et al., 2021)*

Data revealed that users struggled to answer this question, it seems that the built environment seems to do a decent job. Rather than a fundamentally new use case, AmIE offer a possibility to improve the exiting affordances of the built environment, e.g., Ho et al argue that to improve is akin to maximizing "the quality of life" for those that dwell in the home (Ho et al., 2019). Jakobi et al noticed, however that surfacing these quality of life improvements is challenging, citing multiple rounds of interviews necessary to surface novel needs (Jakobi et al., 2018).

8.2 Embodiment

8. DISCUSSION

Many of our primary tools-for-living don't require nor afford use of the whole body. The compelling opportunity afforded by AmIE is the "embodied" interaction between our human biological-'hardware' and the systems' mechanical-/computational- hardware. For an AmIE to operate, an array of sensors and actuators work in tandem to track and enact adjustment, respectively, to the environment. In theory, there should be enough sensing and actuating capacity in an AmIE that the system's interface can be accessed from anywhere in the space, which presents a unique design opportunity: what is an input when sensing is pervasive?

At present, we rely on proximity to a specific piece of hardware to input specific information. To make a call, for example, we reach for our (mobile) phones. Thereafter we mostly, if not exclusively employ our digits to tap-tap-tap our instructions into the device. While we no longer "dial" a numeric number, we still leverage our fingers and a discreet advice when we tap "call" on a contact name. Of course, you might use WiFi calling if you have the Apple suite and are located in the US. Gotten tired of all the tapping, maybe you have a voice-assistant turned on, "hey Siri, call the nearest Italian restaurant, please."

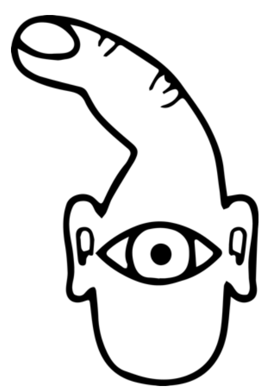

Figure 16 Igoe and O'Sullivan's illustration of dis-embodied human-computer interaction. {Citation}

Leveraging a novel body input (e.g., voice instead of finger) does not guarantee embodiment. Let me illustrate this with my own experience with voice-activated technology. When I awake to my Google Home Mini sounding my alarm, I must effectively shout a piece of code, a command line, "Hey Google, stop." {Object; Action}. What I can tell you from using my Mini each morning, is that I notice a stark confrontation with my own inability to externalize my thoughts into the desired input form the device has to receive in order to work. I think something vague, about wanting some ambient sound?, music?, white noise?, a podcast?, but the thought is barely formed in my mind by the time a parallel and competing realization begins to gel: I am going to have to choose, with only my words. No browsing through records, CDs, mp3 titles so that I might formalize it into an input that my device understands. And stat. Lest I hear in return, from my silence as I try to form words, a devastating, "I'm sorry, I didn't get that."

Klemmer et. al. suggests this phenomenon of struggling to articulate a desired interaction and outcome happens because "reflective reasoning is too slow"(Klemmer et al., 2006). In their seminal article, How Bodies Matter: Five Themes for Interaction Design, their second theme, performance, discusses how engaging physical artifacts is a way of making cognitive processes more fluid and tacit. Turning a light switch, thus, is a more reliable and embodied trust in what will happen with the lights than my current, "Hey Google, turn on the lights."

8.3 Antifragility

In search of the concept opposite of fragile, professors of architecture and urban planning Ivan Blečić and Arnaldo Cecchini from the University of Cagliari and University of Sassari, respectively, query, "Now, what is the opposite of fragile? Many words come to mind: hard, robust, resistant, resilient…But, to follow Taleb, none of these is exactly right: none is the strict opposite of fragile."(Blečić & Cecchini, 2017) Nassim N. Taleb, who they refer to, is the scholar who proposed the concept of this un-named opposite of fragile, 'antifragile,' in his 2012 book "Antifragile: Things That Gain from Disorder" (Taleb, 2014). Therein, Taleb that unpredictability prevails, and things are impervious to being effected by the diverse array of conditions that unpredictability guarantees. In time, of course, some event or another will test the "strength" of that thing, possibly damaging or destroying it. The more fragile the thing, the more likely to be harmed by a disturbance. Taleb, thus, reasons, why stive for "less fragile" when, instead, we might strive further for antifragile?

Antifragility is beyond resilience, resilience is the capacity to bounce-back, to return to as things were(Munoz et al., 2022). Antifragility is beyond robustness, which is both immune to harm, but also immune to benefit, in other words, unchanged (Blečić & Cecchini, 2017). Antifragility is the paradigm where in response to a disruptive event, the thing is changed, and changed into a new more beneficial state. Maybe the working out can be leveraged as an analog. You dare to take that reformer Pilates class, its brutal, you are dripping sweat, the next day your muscles are shaky with the weight of the workout, but you have built a tiny bit of strength. Things have changed, it's not a return, its movement towards a new future, at the hands of incurring the stress of a workout. An antifragile thing, in a similar way benefits from "perturbations, volatility, disorder—that is to say, from time." (Blečić & Cecchini, 2017)

This work leans on the concept of antifragility to encompass three themes that emerged from the systematic literature review: the need for AmIEs to be fault-tolerant, secure, and accessible. The link between fault-tolerance and antifragility is relatively well established in academic literature (De Florio, 2014)(Russo & Ciancarini, 2016)(Tseitlin, 2013)(Abid et al., 2014)(Verhulsta, 2014)(Monperrus, 2017), which is to say, the idea that computational artifacts are beyond resilient and robust, but instead can benefit from disruption, is a key promise of (theoretical) machine learning. Similarly, the link between antifragility and privacy and security in digital landscapes, has also been drawn (Hole, 2015)(Verhulst et al., 2015)(Buinevich et al., 2017). A lesser discussed element of antifragility, however, is the inherent exposure to adversity that antifragility is designed to grow from. It is this ethical dialogue between comfort and adversity that I speak to in leveraging antifragility to describe the elements of accessibility found in the literature.

9. CONCLUSION

As ambient intelligent environments (AmIE) grow in capacity and ubiquity, tangible interactions with the technologies that have dominated the last quarter century (like desktop computers, laptops, and mobile phones) will increasingly be replaced with ambient interactions with technology. Instead of a predominating reliance on graphical user interfaces, the human body, voice, and biometric data will all be possible vehicles for interacting with technology. This reliance on the human body, as well as the collection and processing of data thereon, poses a myriad of practical, social, and ethical challenges. This work contributed to the advancement of the growing design-engineering research on AmIE by proposing three thematic vectors that can be used for continued research into the productions of a value-aligned cartesian design space of AmIE: attunement, embodiment, and anti-fragility. However, whether defined by these three vectors or others, a design space alone will not be sufficient in achieving spatial alignment.

What this research demonstrated is that design-engineering AmIE is inherently complex and there are a lack of tools for creating AmIEs that strive to minimize (if not eliminate alignment problems). This is both concerning, in that as tools are being developed misalignments are likely, but it is also inspiring in that it requires us to produce new methods. In this way, we are invited to produce methods that are reflective of and supportive of our social values. Of course, values are not ubiquitous, they vary between people, contexts, cultures, times. So, in addition to working towards a minor AmIE design space that rigorously codifies all the constituent elements therein, we must also work to promote more global expectations about how AmIEs exist in our lives.

9. CONCLUSION

Therefore, in concluding this work, I borrow from the work of neuroethicist Marcello Ineca from the ETH Zurich in advocating for codified fundamental technological rights: liberty, privacy, integrity, and continuity (*We Must Expand Human Rights to Cover Neurotechnology*, n.d.). Originally conceived as foundational rights for the emerging technological paradigm where computing is implanted or otherwise integrated with your physical body, i.e., permanent and ubiquitous neurotechnologies, I end this work by offering how these four core rights might apply to AmIEs, which are set to also become (relatively) permanent and ubiquitous in the (not so distant) future.

(1) **SPATIAL LIBERTY:** the right to **spatial liberty** protects the right to make free and competent decisions regarding the use of ambient intelligent technologies including ambient intelligent environments. It guarantees individuals the freedom to monitor and modulate their environments through ambient intelligent computing technologies (or to do without). In other words, it is a right to spatial self-determination.

(2) **SPATIAL PRIVACY**: The right to **spatial privacy** protects individuals against the unconsented intrusion by third parties to their ambient intelligent technologies including ambient intelligent environments and collected data as well as against the unauthorized actuation on or collection of those data. This right allows people to determine for themselves when, how, and to what extent their ambient intelligent data (processed or raw) can be accessed by others.

(3) **SPATIAL INTEGRITY:** The right to **spatial integrity**, the right of people (independent of demographic factors like race, age, disability, income, etc.) to access and use safe and effective ambient intelligent technologies including ambient intelligent environments as well as to protect them against unconsented and harmful applications.

(4) **SPATIAL CONTINUITY:** The right to **spatial continuity** intends to preserve people's continuity of their spatial life from discontinuity at the hands of targeted withholding of ambient intelligent technologies including ambient intelligent environments or unconsented alteration of ambient intelligent environments by third parties.

There is so much more to say, I could write a book. Until then, more work on spatial alignment and the application of minor theory should be explored by design-engineers from both industry and academia so that we might have explicitly aligned experiences in the AmIEs of the future.

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APPENDICES

Appendix 1.A. Design-Engineering

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Appendix 1.B. Critical Theory & Taxonomy

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Appendix 4. Graduation Project Brief

(Attached on pages 126-131)