Sensor Illumination: Exploring Design Qualities and Ethical Implications of Smart Cameras and Image/Video Analytics

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ABSTRACT

Drawing analogies between smart cameras and electric lighting, we highlight and extrapolate design trends towards always-on sensing in intimate contexts, and the functional expansion of smart cameras as general-purpose and multi-functional devices. Employing a research through design (RtD) approach, we extrapolate these trends using speculative scenarios, materialize the scenarios by designing and constructing lighting-inspired smart camera fixtures, and self-experiment with these fixtures to introduce and exacerbate privacy and security issues, and inspire creative workarounds and design opportunities for sensor-level regulation. We synthesize our insights by presenting 8 *smart camera sensing design qualities* for addressing privacy, security, and related social and ethical issues.

Author Keywords

IoT, privacy, security, research through design, smart home

CSS Concepts

• Human-centered computing~Human computer interaction

INTRODUCTION

Digital devices and everyday objects are increasingly becoming “smart”—that is, embedded with network-enabled computing, sensing, actuating, and artificial intelligence (AI) capabilities. Colloquially referred to as the Internet of Things (IoT), these advances may create unprecedented opportunities to augment creativity, productivity, and well-being. At the same time, these technologies and their uses introduce and exacerbate privacy concerns [e.g., 138], security vulnerabilities [e.g., 48], and related ethical issues with trust, transparency, accountability, and bias [e.g., 85].

We focus on smart cameras as a particularly popular, powerful, and growing area of IoT sensing technologies [72,158,130] that poses significant and controversial privacy, security, and ethical challenges [e.g.,148]. For instance, Amazon’s smart security and doorbell cameras now employ facial recognition that can protect people’s homes, manage deliveries, and may even help locate missing children [1]. The same Amazon Rekognition video analytics technology also misidentified 28 US politicians as criminals [152], appears to disproportionally misidentify women and people of color [144], is sold to police and immigration departments [52,164], has been manually reviewed by Amazon employees allowing them to see users’ video feeds [12], and now claims to automatically detect emotions such as fear and happiness [5,111].

We use the term *smart camera* to signify a vision system with a built-in image-sensor and network capabilities. In addition to conventional image-capture, when combined with cloud-based or onboard image and video data analytics, smart cameras can perform advanced tasks such as motion detection, facial and object recognition, location estimation, dynamic masking, and even emotion tracking from facial analyses [25,38,128].

In this paper, we use speculative design to extrapolate current trends in the design, production, marketing, and use of smart home security cameras—focusing on consumer products such as the Nest Cam Indoor Security Camera and the Amazon Ring Video Doorbell. Unit sales for smart home surveillance cameras are expected to grow from 54 million in 2018 to 120 million in 2023 [149]. In 2016, smart home cameras generated more retail revenue than any other home automation category and were the most common entry point to the smart home market [158]. Soon over 80% of Internet traffic will be video and 3% of this will be video surveillance [31]. The global video analytics market is projected at 9.4 billion USD by 2025, with facial recognition the fastest growing application segment [72].

Because privacy protections and security vulnerabilities are typically framed and addressed in terms of *possible future harms* [e.g.,113,170], we argue that speculative design techniques are particularly well-suited for understanding, anticipating, and addressing these issues (c.f., [49,124,146,170]). Speculative approaches are useful for surfacing issues that are not obvious in current settings. Our research develops and demonstrates the application of speculative design research to the domain of privacy and security by framing and investigating two key research questions:

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Figure 1. Our ***Ambient-Arc***, ***Accent-Pivot***, and ***Task-Table Lamp Cams*** collage light fixtures with Nest Indoor Smart Home Cameras. Image ©James Pierce.

(1) What are the material, interactive, and experiential design qualities of smart camera sensing, including limitations and opportunities, and (2) What are the privacy concerns, security vulnerabilities, and related social and ethical implications of these qualities and the applications they enable?

We report on two primary contributions. First, we contribute a set of novel speculative design scenarios and products. We present scenarios that draw upon and extrapolate parallels between electric lights and smart cameras. We then materialize and enact aspects of our scenarios, designing, building, and self-experimenting with novel speculative products. Experimenting with a design and production technique we call ***product redirection***, we transparently collage consumer smart cameras with ambient, task, and accent light fixtures. Here we focus on three *Lamp Cam* product redirects that we experimentally used and lived with: the ***Ambient-Arc Cam*** provides a stationary overhead layer of camera illumination, the ***Accent-Pivot Cam*** provides adjustable accent layers of camera illumination, and the ***Task-Table Cam*** provides a portable task layer of illumination (Figure 1).

Second, we contribute the concept of smart camera ***sensor illumination****,* from which we articulate smart camera design qualities and privacy, security, and ethical implications. We characterize smart camera sensing as (1) materially shaped, (2) perceptually powerful, (3) invisible and ethereal, (4) spatial and social, (5) layered and textured, (6) diffuse and leaky, (7) regulable at the sensor-level, and (8) device- and sensor-specific. These qualities highlight the significance and uniqueness of smart camera sensing as a material and technology for HCI and design to study, shape, and improve with regards to privacy and security in particular. These ***smart camera sensing design qualities*** summarize and organize insights gained through our mix-method research through design (RtD) approach. We present these design qualities as tools: they mobilize our insights to help researchers and practitioners identify, anticipate, communicate, and formulate responses to privacy, security, and ethical issues connected to always-on/often-sensing devices in intimate everyday contexts.

RELATED WORK: ETHICS OF IoT AND AI

Recent HCI research has investigated a range of social and ethical concerns related to IoT and AI systems. Much of this work centers on privacy and security. Dourish and Anderson's (2006) work [44] reconceptualized security and privacy as social and cultural issues that transcend technical problems alone. From this work, a body of usable privacy and security research has emerged investigating IoT use in socially-situated context [164,173,174] including children's use of smart toys [95,110], and attitudes toward IoT cameras [159]. Other work has studied how to convey privacy information to end users through notices and labels [e.g., 46,90,136].

Despite successes, these so-called "notice and consent" approach have been criticized as insufficient to address privacy and security issues [e.g, 117]. We argue and aim to demonstrate that RtD and multidisciplinary design can address these limitations by framing issues, exploring responses, and synthesizing solutions that expand beyond notice-and-consent and screen-based software systems, and consider diverse users and non-users of smart sensing systems (c.f. [123,127,166,170]).

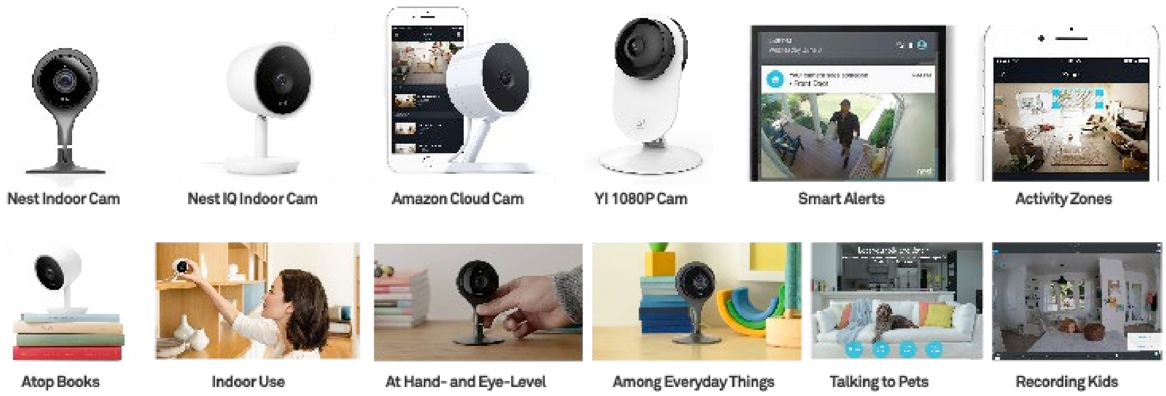

Figure 2. Examples of smart home cameras, features, and promotional materials analyzed. Promotional materials (bottom) are labeled with marketed uses cases we identified that exceed the ostensive functions of video recording, home security, and utilitarian applications.

Privacy, security, and surveillance concerns arise in a range of legal, social science, and humanities fields. Legal scholars [13,80,81] and governments [26,47,48] raise concerns about the proliferation of networked data collection and the legal challenges IoT devices create. Extending privacy and security per se, an interdisciplinary community of scholars concerned about values in design [53,55,94,100,134,139] has begun looking towards issues of fairness, accountability, trust, and transparency in IoT and AI [23,69,96]. This work draws attention to how IoT and smart systems (re)configure relationships and practices among humans, technologies, and institutions, and the implications for social values and power relations. For instance, Stark and Levy argue that tracking and IoT have led to surveillance as a "normalized mode of interpersonal relation that urges [a] consumer to manage others around her using surveillant products and services." [148 p. 1202]. HCI research has also studied concerns beyond privacy and security [57,160], such as labor in public IoT deployments [42,50], and diverse and alternate IoT values [28,82,120,150] and uses of IoT data [15,16,40,156].

These and related perspectives inform and inspire our work. Smart home cameras are a pertinent site at which to consider emerging paradigms such as Stark and Levy's surveillant consumer [148], and related concepts such as surveillance capitalism [176], dark patterns [73,74], contextual integrity [117], and the sovereignty of data [83].

Smart cameras have been a subject of much technically-oriented and theoretical HCI research (e.g., [76,129,140]) exploring new applications, usability, and interaction techniques. However we find a lack of HCI and design research focusing specifically on smart camera privacy and security. While prior work has designed smart home research sensors that mitigate concerns of privacy [27,122] we use RtD to design smart home cameras that amplify concerns of privacy and security. We build on prior design research and RtD to investigate intersections of IoT and social and ethical issues, such as design research investigating alternative values and visions of diverse communities [50,88,92,151]. Design research has also studied and innovated IoT design processes, including ideation, prototyping, and design metaphors [1,15,16,30,68,112,124,131,151,163].

APPROACH: DESIGN ANALYSIS AND SPECULATION

In order to understand smart camera design qualities and associated privacy and security challenges, we employed a research through design (RtD) approach (e.g., [62,91,154,175] drawing on interaction, graphic, and industrial design, as well as furniture, interior, and lighting design. For us, RtD means that the processes and outcomes of design are used as tools for, and products of, research and knowledge production. Our RtD process broadly entails designing *and* crafting artifacts, and iteratively reflecting upon that which we design and make. Our research involves 4 categories of methods and outcomes: (1) primary and secondary design analysis of smart home cameras, (2) speculative design scenarios, (3) operational interactive products and (4) self-use and self-experimentation studies.

SMART CAMERA DESIGN ANALYSIS

We conducted primary research through firsthand use and analysis of smart cameras. The first author has been living with a variety of smart home cameras (Amazon Cloud Cam, Yi 1080 Cam, Google Indoor Nest Cams, Google Clips; See Figure 2) and using them intermittently for 21 months. The entire research team used and lived with smart cameras (the Nest Indoor Cam) for shorter durations of 1-2 weeks. Additionally, we conducted secondary research surveying the broader field of smart cameras, IoT, and AI including reviewing literature from academia, news, popular press, and smart home product design and marketing materials.

In prior [121,122] and future work we report in detail on design trends and patterns resulting from our analysis. Here we offer a brief summary of several notable characteristics of the nascent smart home camera product landscape. Smart home cameras offer innovative features, such as smart alerts that detect motion and faces, automated time-lapses and cloud-based video histories, and the ability to select activity zones, such as doorways or windows to monitor for activity.

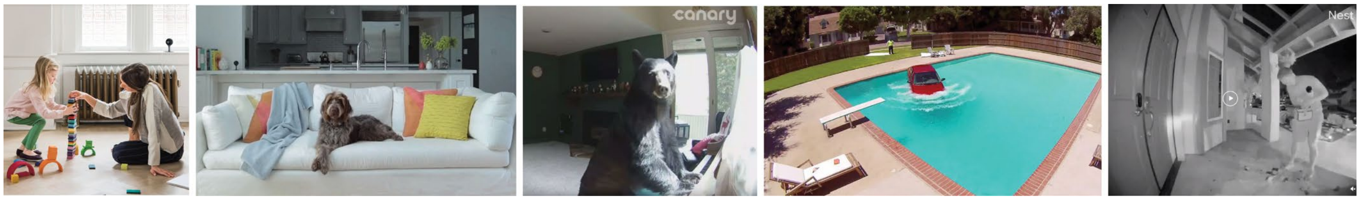

Figure 3. Entertainment, memory-making, and curiosity-driven aesthetic uses cases for smart home security cameras. Left to right: (a) Nest camera marketing image depicting a Nest Indoor Cam in a child's play area [71], (b) Nest camera marketing image depicting a use case talking to the dog [71], (c) Canary smart home camera footage catching a bear playing a piano [167], (c) a Nestie award winning video capturing a car crashing into a swimming pool [70], (d) A Reddit post sharing a Nest video of the contributor spilling a 6-pack of beer [135].

These technical innovations, enabled by cloud-based video analytics, greatly surpass the capabilities and usage scenarios of conventional video surveillance cameras.

Beyond utility, smart cameras are used for social, entertainment, curiosity-driven, and other aesthetic uses (Figure 3). Promotional materials for Nest cameras often depict scenarios involving pets and kids.

Nest users were invited to submit their videos captured on their Nest cameras under categories such as "Family Moments", "Nature" and "Pets" [115]. The best of this user submitted content is honored with "Nestie Awards" for categories such as "Best Dog in a Lead Role" and "Best Supporting Deer" [114]. Market research finds that while 83% of smart camera owners use it for home security, 53 percent also use it for tasks such as monitoring houseguests, pets, and kids [158]. Smart camera marketing may refer to the devices as "security cameras," but promotional materials and actual usage suggest smart home cameras are also lifestyle or entertainment devices with analogies to social media and to point and shoot digital cameras (Figure 2 bottom, Figure 3).

Design Analogies

Informed by the design trends we identified, and through our early design explorations, we further observed illuminating parallels between smart cameras and electric lights. At first these parallels were primarily used as inspirational design metaphors. Later, through reflection and repeated use, we formulated 3 analogies that helped us analytically compare, elucidate, and communicate similarities and differences between smart cameras and electric lighting. Here we summarize our insights and trends grounding each analogy.

Analogy 1: Electric Lamplight Illumination

Light is an essential material for both smart cameras and electric lamps. Both technologies involve a *directional illuminative field*: electric lights emit light waves from a lamp source, while cameras detect light at a sensor source. While more diffuse, ethereal, and invisible than lamplight, a smart camera's field of view is similar to artificial *illuminance*. From the perspectives of design, interactivity, and use it is instructive to conceptualize smart camera sensing as emitting or radiating an illuminative field.

Analogy 2: Light Fixtures and Lighting Layers

Smart camera support, positioning, and mounting fixtures are similar to light fixtures. Electric lights and smart cameras both require *fixtures* to position, support, and control their illumination sources. Current smart home camera fixtures offer greater variety, modularity, styling, and control than their predecessors—similar to light fixture design.

The expanding range of smart camera applications further exhibits parallels with the *layering* framework used in lighting design. Lighting designers use 3 layers to achieve desired lighting effects within a space. *Ambient lighting layers* provide overall lighting for a room. *Accent lighting layers* creates focal points and draws attention to features or objects. *Task lighting layers* are used when doing specific activities such as reading or cooking.

Analogy 3: Electrification

When electric lighting was introduced in the 1900s as the first large-scale application of electricity, many experts and members of the public expressed fears and anxieties [e.g., 154]. Today electricity is a normal, ubiquitous, and indispensible part of life. Similar to electricity, smart cameras and AI are becoming cheaper, image/video analytics applications are expanding rapidly, and smart cameras are becoming more normal and accepted—as evidenced by new *indoor* smart cameras (Figures 2 and 3).

SPECULATIVE DESIGN SCENARIOS

Informed by these design trends and analogies, we generated a range of speculative design proposals and scenarios. Formally, our designs employ visual and textual representations of possible future systems and scenarios [e.g.,1,17,20,20,67,126,170]. Functionally, our aim is to imaginatively extrapolate trends to envision possible futures that *extend and amplify* smart cameras and, consequently, *introduce and exacerbate* privacy violations, security vulnerabilities, and ethical concerns and debates.

Our work builds on prior use of metaphors to generate and communicate more usable [33], creative [30,85,102,103], and critical [124] designs, and analogies to inspire creative insights and innovative breakthroughs [59,60]. We use the analogies drawn between smart cameras and electric lighting to extrapolate and speculatively imagine how smart cameras might further parallel lamp illumination, light fixtures, and electrification. We frame a selection of our speculations using 3 anticipatory text-based scenarios, followed by a sample of our visual design explorations.

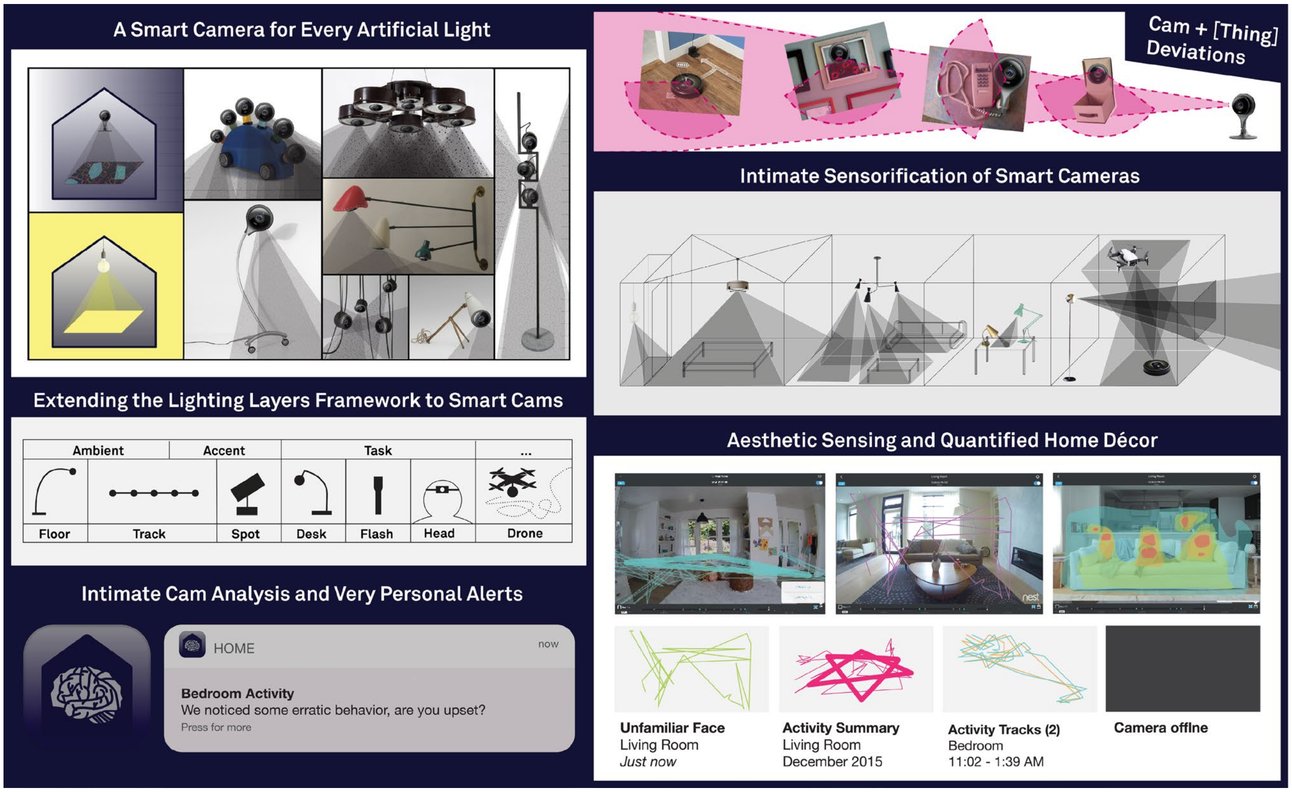

Figure 4. Selected design scenarios and proposals. Image ©James Pierce.

Scenario 1: Lamp-Like Smart Camera Configurations

What if smart cameras become as numerous and varied as light fixtures? This scenario imagines a future where smart cameras dramatically expand and multiply across homes, bodies, and neighborhoods, and evolve increasingly lamp-like positioning and support fixtures (e.g., overhead, adjustable, on-body, embedded within devices).

Scenario 2: Lighting-Like Image Analytics Applications

What if smart camera applications become as diverse and specialized as electric lighting and appliances? This scenario imagines a future where smart camera applications continue to exceed their ostensive functions as image-capturing sensors, security devices, and utilitarian products, and expand to offer a range of functions similar to artificial lighting for productivity, social, playful, decorative, reflective, symbolic, and mood-setting applications.

Scenario 3: Electrification-Like Sensing Development

What if smart cameras and vision-based sensor networks become as normal, ubiquitous, and indispensable as electricity? This scenario imagines a future where fears and anxieties over smart camera surveillance largely subside and the devices continue expanding into intimate contexts, and diffract into a dizzying array of applications using cameras more as a sensing devices to support machine vision and AI than as a traditional photography tools.

Selected Design Explorations

Below we exhibit and discuss selected design work exploring the scenarios of lamp-like configuration, lighting-like application, and electrification-like development.

A Camera for Every Artificial Light

An early, formative conceptual design proposal we devised involves literally replacing every lightbulb, LED, and other source of artificial light with a smart camera. This speculative exercise helped generate creative and unexpected designs (See Figure 4, top).

We conducted extensive research into lighting design and collected hundreds of examples of light fixtures, including contemporary, historical, experimental, mass-market, boutique, and artistic designs. By drawing upon the 100+ year history of light fixture design, our designs explored smart cameras occupying virtually every type of position and scenario in which artificial lights are used—a vast, intimate, and often absurd and creepy space of possibilities.

Figure 4 presents a sample of our speculative design explorations. We later brought aspects of these scenarios to life by creating and living with speculative products that collage consumer smart cameras with light fixtures.

MATERIALIZING THE SCENARIOS: PRODUCT REDIRECTS

Next we materialize our scenarios through a set of operational speculative products that extend our lighting analogies. These products continue to extrapolate current design trends: always-on sensing in intimate contexts with smart cameras exceed their ostensive functions as image-making, home security, and utilitarian products.

Figure 5. Stills from a short video we made exploring ***intimate sensorification*** in bedrooms, windows, closets, and more. Image ©James Pierce.

We refer to these operational speculative products as ***product redirects.*** As a speculative design and production technique, product redirection takes *existing* commercial products and everyday objects, *transparently collages* them together, and *redirects* them toward research goals—in our case, understanding current and anticipating future design qualities and ethical implications of smart cameras and always-on sensing devices. Practically and aesthetically, product redirection allowed us to make evocative bespoke off-the-shelf prototypes focusing on form and interaction without requiring custom electronics fabrication (c.f. [35]). They also allowed us to anchor our speculation in existing products (IKEA lamps, Nest Smart Cameras), thus supporting our anticipatory and extrapolative design aims.

Many prior design and art techniques informed our product redirect approach, such as readymades and collage [e.g.,162], detournement [93], and defamiliarization [10,142]. We were particularly inspired—topically and methodologically—by Wakkary et al's material speculation [161], Rogers et al's smart speaker speculations [131], Gaver's self-use of the video window [65], Gaver and Boucher et al's camera designs [18,19,61], Devendorf et al's improvisational and performative making [39], Odom et al's Photobox [118], and Romero et al's Tableau Machine [132,133]. Our work also aligns with other prior and subsequent camera and surveillance art/design works [e.g.,27,99,118,124,125,163].

In this paper we focus on a subset of our product redirects: The ***Lamp Cams***. Each Lamp Cam combines an inexpensive IKEA light fixture with a Nest Indoor Smart Security Camera. The Nest Indoor camera was selected because of its modular design, advanced features, enhanced usability, and design/marketing for intimate *indoor* home environments. ***The Ambient-Arc Cam*** provides a *stationary overhead layer*, inspired by ambient lighting. ***The Accent-Pivot Cam*** provides *adjustable accent layers* of sensor illumination, inspired by accent lighting. And the ***Task-Table Cam*** provides a *portable task layer* of sensor illumination, inspired by task lighting (See Figure 1).

We designed, built, and used these speculative products to achieve several goals: (1) to materially speculate [161] and enact [45,119] our scenarios, (2) to use speculative products as probes [66,83], triggers [97,137], and breaching experiment tools [34] to uncover design issues and opportunities, and (3) to gain firsthand experience with smart cameras in unusual, privacy-exacerbating scenarios, thus helping us anticipate future issues.

INTIMATE SENSORIFICATION: LAMP CAM VIDEO SCENARIOS

Alongside our firsthand use of the Lamp Cams, which we report on in the following section, we created a series of video scenarios to explore unexpected and intimate use cases. These videos explore in greater resolution our early scenarios of *intimate sensorification*—a scenario that parallels the history of electrification, which led to a staggering array of electrical appliances and devices in virtually every context imaginable. These scenarios involve additional product redirects including a Google Clips AI-powered hands-free camera affixed to a Roomba robotic vacuum cleaner, and an Amazon Cloud Cam modified with privacy curtains. Video stills from these intimate sensorification scenarios are presented in Figure 5.

These explorations led us to formulate a speculative framework for designing the future of pervasive smart cameras [e.g., 130] and IoT sensing. The framework involves expanding the reach of sensor illumination into *bedrooms*, *windows*, and *closets*. Inspired in part by PARC's famous tabs, pads, and boards framework for developing the future ubiquitous computing [168], we speculate that everyday sensing will expand to include cameras in bedrooms, windows, and closets. We mean this quite literally as well as metaphorically:

> **Bedrooms**, along with **bathrooms** and **bodies**, are considered among the most private of spaces. Within bedrooms people change clothes, sleep, groom, have sex, tell secrets, relax, and let their guard down. The bedroom as a metaphor is a space where sensors may register the most intimate human activities, thoughts, feelings, and desires.
>
> **Windows**, along with **doorways, walls, fences,** and other **architectural, political, and symbolic thresholds**, act as personal, social, and physical boundaries. Windows are a surface through which these boundaries are regulated, managed, and periodically or permanently opened up or closed off. Windows are also spaces where leaks and boundary violations occur. The window as a metaphor is a space and

surface where sensors may cross and perhaps violate personal, social and physical boundaries.

Closets, along with **basements, attics, and sheds**, are places where people store things, including mundane items, precious belongings, ill-gotten gains, dirty laundry, bodies and skeletons, and junk. Each of these is a potent metaphor. Figuratively, closets represent spaces where sensors register our darkest and most hidden secrets, our most prized and precious things, along with our most innocuous, boring, though potentially revealing material extensions of our selves.

Our speculative explorations of intimate sensorification led us to experiment firsthand with our Lamp Cams in our homes by living with smart cameras that illuminated our actual bedrooms, windows, closets, and more.

SELF-EXPERIMENTATION: OBSERVATIONS & INSIGHTS

Next, we present key insights emerging from our self-experiments living with the Lamp Cams. We do not present a formal ethnographic prototype deployment study (e.g., [63,118]). Instead, our self-experimentation constitutes a material and empirical extension of our prior design analysis and speculation (e.g., [43,116,161]).

The first author designed and built each product redirect. Author 1 lived with each redirect for approximately 1 year, using them intermittently. Authors 2 and 3 lived with all three redirects at once for approximately 1–2 weeks each. Authors 2 and 3 brought new perspectives to bear to the extent that they were not involved in the conceptualization, design, and construction of the products. Each author kept reflective field memos [13], and we debriefed as a team.

Our self-experimentation involved committing to configuring the Lamp Cams in a variety of spaces in our homes, especially configurations that felt uncomfortable or unnecessary. We configured our Lamp Cams to surveil our own living rooms, pets, offices, desktops, kitchens, windowsills (and consequently our neighbors' and public spaces), and even our bedrooms, bathrooms, and showers for limited periods of time. This self-experimentation led to experiences and insights that did not emerge with our earlier self-use studies using out-of-the-box smart cameras.

Our use of self-experimentation is predominantly a means to *complement* our other modes and forms of design analysis and speculation. Self-experimentation allowed to us to expand and refocus our analysis through firsthand experience exploring extreme scenarios that we, and most users might otherwise not encounter or tolerate. While self-use and autobiographical design have limitations (e.g., subject positions explored and generalizability), these methods also have unique strengths such as gaining deep insight into sensitive subjects [40,116].

Social, Spatial, Layered, and Leaky Sensing

Based on our usage—including social frictions and privacy violations—we gained insight into the qualities of smart cameras, and as compared to other sensing technologies.

Spatially diffuse camera sensing. Like lamplight illumination, smart cameras sensors "shine", so to speak, upon physical, embodied, and social space. This spatial sensing was quite different from other sensing and tracking technologies we used, such as Fitbit activity monitors, smart phone location services, or online click tracking. Whereas those technologies are highly personal and containable to the individual user, smart cameras sensing is not: as we found, *it is inherently difficult to contain to single user's space, face, body, activities, or possessions.*

Socially shared and negotiated camera sensing. Different residents and guests expressed different preferences regarding the cameras. Negotiating smart camera boundaries was a social process, and some residents were reluctant to participate in our experiment. This echoes findings that *multi-user settings* for smart speakers are the greatest source of privacy tensions [98, p. 20-21].

Leaky camera sensing. We experienced instances where we felt we crossed or violated social boundaries by inadvertently spying on friends, family, neighbors, and passersby. These experiences and prior work [121,141] led us to characterize smart camera sensing as diffuse and leaky: it tends to spread out spatially, crossing personal, social, and political boundaries. All cameras exhibit this quality. For example, film cameras capture subjects through windows, across property lines, and in the backgrounds.

However *smart* cameras create additional layers of diffusion and leakiness. As we noted earlier, smart cameras are becoming more than image-capturing devices. The Nest Cams can, for example, automatically detect a person, face, or motion and send automated notifications to users' smartphones (Figure 2). The Nest Cam automatically creates a scrollable timeline of captivating time-lapse videos. During our self-use, we scrolled through engagingly detailed time-lapse videos revealing the mundane activities of family and roommates. We were also notified of our neighbors' activities—without their knowledge. These *digital analytics layers* of camera illumination created opportunities to spy on family and strangers inadvertently and out of curiosity, activities that were seemingly encouraged through the automated notifications and online camera dashboard features—evidence of Stark and Levy's concept of the surveillant consumer subject [148].

Aesthetic Interaction and Self-Regulating Behavior

By configuring the cameras in unusual and uncomfortably intimate contexts, new uses emerged. Some of these were curiosity and/or aesthetically driven—such as casually spying on friends, family, and pets by scrolling through engaging time-lapses. Another emergent use/effect was self-regulation. We regulated our behavior because of the cameras, such as restraining emotions when an important computer file was corrupted—with the Ambient-Arc Cam looming overhead. At times we performed for the cameras and altered our behavior to act how we thought we ideally should, e.g., by making our beds, tidying our homes, covering our bodies, and correcting our postures.

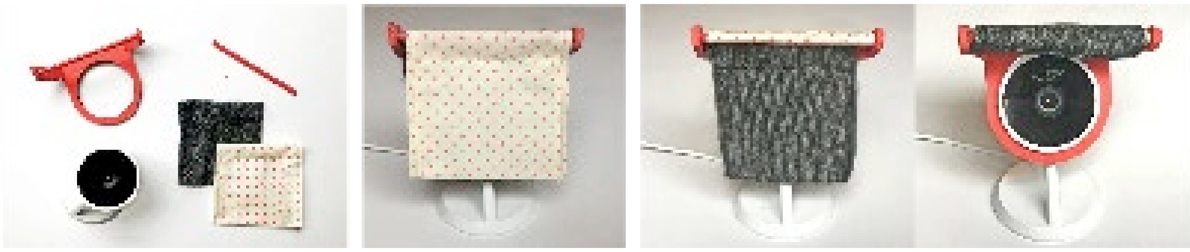

Figure 6. Product redirect exploring light-regulating curtains as interactive controls for sensor-level regulation that is trusted and secure because it is (1) perceptually intuitive, (2) physically layered, (3) after-market, and (4) adjustable. Image ©James Pierce.

Trust and Control Issues

A major issue we each experienced was progressive loss of and failure to gain the trust of the cameras. We identified 3 key issues, which reside primarily with the design of the Nest Indoor Smart Camera and similar cameras we used:

Not trusting it's OFF. We each experienced multiple instances and generalized feelings of distrust that the camera was actually OFF and not sensing. Two key aspects of the interface design contributed to this lack of trust. First, the Nest Indoor Cam (and all similar smart cameras we reviewed) can only be electrically switched ON/OFF via the cloud-based software app. The device contains no physical ON/OFF switch. Second, the indicator light can be disabled when the camera is actively sensing and recording video and audio.

The virtual ON/OFF switch, while convenient in certain regards, also creates privacy and security concerns. Most troubling for us, multiple users can easily switch ON the camera remotely at any time without any visible feedback. Additionally, we found the software interface prone to user and system errors and further lacking in clear, trustable feedback. In one particularly disconcerting instance, Author 1 turned the camera OFF using the digital interface but it failed to deactivate. This created an invasion of their partner's privacy, and caused the author to lose trust in the digital ON/OFF switch.

Forgetting it's ON. We each occasionally forgot the cameras were present and/or sensing, and were troubled by this. We also commonly wondered if the cameras were indeed OFF, given the issues discussed above.

Lack of control options. In addition to issues with the software based ON/OFF switch and unreliable indicator light, we found a lack of options for more granular control of the cameras. For example, there were no options to prevent manufacturers from accessing person, face, or motion data, or to lower the image resolution or dynamically mask faces, activities, or objects.

Regaining Control with Workarounds

Given our commitment to self-experimentation in intimate contexts within our own homes, we devised simple workarounds: control techniques that address the above issues to achieve tolerable levels of privacy and security.

The first workaround is ***unplugging the cameras,*** a workaround that prior work has shown in several instances that users similarly consider or have actually practiced with smart speakers [2, p. 22; 98, p. 15; 127, p. 9] in order to ensure that the device is powered off and the microphone is no longer sensing. We note that the design trend to *not* integrate physical power switches corresponds with the trend toward always-on and often-sensing devices we discussed earlier. While lower cost and simplicity of construction is one reason to forego a physical ON/OFF switch, another explanation is to promote the always-on paradigm and encourage often-sensing usage.

The second workaround is ***tilting or repositioning the camera***. In contrast to unplugging, this technique is fairly well supported by current manufacturer design of smart cameras that employ adjustable 360-degree fixtures. While the ostensive marketed purpose of the adjustable fixtures is to achieve the desired camera view, another usage of these fixtures is to "close" the camera by tilting the lens up at the ceiling, down at the floor, or away towards a wall.

Physically obfuscating the sensor, our third workaround, involves placing an object over or in front of camera lens. For example, Author 2's relative placed a sock over the camera.

It is important to note that all of the workarounds we employed were generally successful in that we trusted these techniques to deactivate or prevent the camera from capturing light and image data. This led us to consider these workarounds as design opportunities.

Formalizing Our Workaround Techniques

Our self-use and self-experimentation revealed trust and control design issues, which led us to devise workaround techniques. Previously, our design analysis using lighting analogies revealed that current smart home cameras lacked many of the common controls found on lights, such as physical switches, dimmers, and shades. Here we discuss one key design opportunity we identified.

Interactive Sensor-Level Regulation Controls

In response to these issues, we devised mechanisms for improving the privacy and security of smart camera illumination, and increasing their salience and usability. We drew upon lighting control metaphors to explore sensor-level regulation mechanisms using physical masking layers, including designs inspired by light-regulating curtains and light-controlling switches (Figure 6).

These additional product redirects explore *sensor-level* *regulation* that is more trustworthy and secure because it (1) is perceptually intuitive (not opaque like software or hardware), (2) is a physical add-on (not susceptible to software attacks), (3) is produced and/or added by the user or separate manufacturer (and thus potentially more trusted), and (4) allows selective and variable filtering (e.g., blocking face detection but still allowing motion detection).

Sensor Specificity: Microphone Versus Camera

Similar to the camera sensor, we experienced a lack of trust in the smart home camera's microphone sensor (forgetting it's ON, not trusting it's OFF, and a lack of controls). However, we also found that the microphone posed its own unique privacy and security challenges. Some of our camera workaround techniques did not work for microphones. For example, tilting or covering the microphone does not adequately regulate the omnidirectional sensor.

DESIGN QUALITIES OF SMART CAMERA SENSING

Our research has integrated a range of methods and studies: design analysis of current smart home cameras, speculative design scenarios, speculative products materializing our scenarios, and self-experimentation studies. Our exploratory, mixed-methods RtD approach allowed us to investigate unexpected parallels between lighting design and smart camera design. It also enabled us to identify and extrapolate current smart camera and sensing trends. Through our speculative self-experimentation, we amplified and extended the reach of smart cameras, forcing us to experience uncomfortable use cases and develop workarounds to address privacy issues.

We conclude by discussing a set of smart camera sensing *design qualities* and corresponding privacy, security, and ethical implications—key insights that emerged from our research. Within HCI design research there is interest in understanding the design and craft qualities of interactive materials [3,8,86,101]. Löwgren and Stolterman write that "the main purpose of product quality articulation is to develop the ability to make judgments, which constitute a thoughtful approach to understanding the qualities of digital artefacts" [104, p. 104]. In this spirit of inquiry, our research develops qualities that designers can use to understand and shape sensing technologies for users, with an eye toward improving privacy, security, and related ethical choices.

The following design qualities mobilize our insights as tools for identifying, anticipating, communicating, and addressing privacy, security, and ethical issues with smart camera sensing–and with IoT more broadly.

1. Sensor Illumination is a Designed & Crafted Material

From a scientific perspective, the light registered by image-sensors is modeled as a wave. Yet from a design and phenomenological perspective, light is crafted and used as a material [e.g., 157]. Sensor illumination is also a material—albeit invisible, ethereal, and diffuse—that is crafted and experienced. The *layering* principle is a fundamental tool lighting design for designing and crafting light as a material. Interactive and IoT designers would benefit from similar principles, such as the qualities we outline here.

2. Smart Camera Illumination is Perceptually Powerful

Smart cameras, similar to electric lights, visually illuminate space to increase human perception. However, the perceptual powers of smart cameras vastly exceed those of lighting illumination and conventional (non-smart) camera image-capture (e.g., via object and facial recognition, automated person alerts). Our speculative designs anticipate increasingly perceptive powers of smart cameras, including those extending beyond productivity into aesthetic uses. Today, the perceptual powers of smart cameras are already being used to engage and record pets and kids (Figure 2-3), nurture local community and law enforcement surveillance networks [77, 78], police with facial recognition [12, 52, 77, 172], track shoppers' activities and emotions [38, 128], influence and control citizens [23, 108, 105, 176], and manipulate intimate partners [11, 21 ,32, 54, 109].

3. Smart Camera Illumination is Spatial and Social

Like visible illuminance, camera sensor illumination is spatial in nature. Smart cameras and the control, coverage, and effects of their illumination fields are spatially distributed, and consequently socially negotiated. As our studies revealed, this can lead to social friction.

Private, secure, and trustable designs must address the shared, spatial nature of smart camera sensing. The spatial, socially shared nature of smart camera illumination highlights the need to consider people beyond primary device users and owners. Prior research finds significant privacy tensions emerge during shared-use situations [37; 98, p. 20-21; 174]. *Non-primary users*, *indirect users*, and *usees* [9] must also be considered in the design and use of smart cameras. This includes children [95,110]; elderly [56], survivors and subjects of abuse [11,21,32,54,109]; non-normative home dwellers [41]; disabled persons [127,129]; domestic workers and neighbors [121]; and diverse, differentially vulnerable users in general [123,166].

4. Smart Camera Illumination is Invisible and Ethereal

Unlike artificial light, camera sensor illumination fields are imperceptible to the naked human eye and body. Because of this, ethereal smart camera illumination can be very difficult to control, contain, and avoid. This creates significant privacy and security challenges, such as the ability to conceal an actively sensing smart camera, and the difficulty of perceiving camera sensing—and of avoiding it. Future work might continue to explore ways of increasing awareness and visibility of sensor illumination, potentially building on prior work exploring sensor legibility [64, p. 2216-17] and electricity visualization [58].

5. Smart Camera Illumination is Layered and Textured

Like artificial lighting, smart camera illumination can be modeled, crafted, and controlled using the concept of *layers*. Our research developed parallels between the *ambient, task,* *and accent lighting layers* used in lighting design and the design and use of smart camera sensing.

One major difference between lighting and camera sensing is that smart cameras involve *digital and analytic illumination layers* that can, for instance, detect and isolate faces, locations, activities, objects, and even human gazes and emotions [38]. Because this analytic layer of sensor is so varied and broad in its capabilities—as compared to say, a GPS or heart-rate sensor—the sensor illumination from a smart camera is potentially *heterogeneously textured* with various sensing capacities, applications, and insights.

6. Smart Camera Illumination is Diffuse and Leaky

Like artificial lamplight, smart camera illumination is a diffuse, and leaky material. Spatial, socially shared illumination leaks through windows; invisible illumination is difficult to detect and contain; and layered, and textured illumination contains revealing information.

Much prior work has observed that digital *data* is prone to *leak* [84,121,141]. However, the smart camera as a *source of raw sensor data* within the environment—prior to data conversion, storage, transmission, and analysis—is a primary source of data leakiness and a security vulnerability that must be addressed with the proliferation of IoT devices.

7. Illumination is Regulable at the Camera Sensor-Level

Regulation at the sensor-level is a critical yet underutilized point of intervention for trustworthy and reliable privacy and security. A common, practical example of sensor-level regulation is the use of webcam covers that physically occlude camera lenses, effectively deactivating image-sensing [75,106]. However most smart cameras and other IoT devices are controlled primarily via software, which is inherently vulnerable to cyberattack [165] and lacks intuitive physical controls.

In our studies, we and those we shared space with desired additional protections and employed workarounds such as unplugging devices, tilting cameras, and a covering lenses to achieve adequate sensor-level control and trust. Informed by these insights, we began to explore sensor-level attenuation mechanisms, such as interactive overlays and overrides, inspired by light-controlling switches and light-regulating curtains (Figure 6).

Sensor-level regulation increases in import with the potential for *billions* of unsecured IoT devices [6,79,89] and the vulnerabilities of new 5G networks, which lack centralized hardware chokepoints and present inherent security vulnerabilities given their software reliance [165].

8. Camera Illumination is Device and Sensor Specific

Our research and insight is specific to smart cameras, image-sensors, and video/image analytics. Some qualities generalize to other sensors and devices, but many do not. Consequently, we argue in line with others [30,151,157] that just as designers conduct research into physical materials, we must undertake *smart device and sensor specificity studies* to understand the qualities, limitations, and opportunities of specific smart technologies, and their privacy, security, and ethical implications.

FUTURE WORK

In the future, the emergence of distributed and pervasive smart camera networks [130], and new video analytics applications such as a facial recognition [85,172] and deepfakes [36] will compound the issues we illuminated. While *sensor-level overrides and attenuation* represents a key design opportunity for HCI to address these issues, additional research is needed to understand the particular and evolving design qualities and privacy and security implications of various always-on/often-sensing smart devices including, but also beyond, smart cameras. Moreover, addressing these challenges will require interventions that go beyond the agency and purview of individual users [9,44], consider differentially vulnerable and non-normative subjects [41,123,150,166], and extend beyond devices and interfaces into policies, laws, norms, and values [153,169]. In addition to actionable insights and prototype solutions, we will need tools to identify and anticipate privacy concerns and security vulnerabilities. Our use of design analogies, scenarios, and product redirects demonstrate such *analytic* and *anticipatory* potentials of speculative design and RtD to address privacy, security, and ethical design and technology issues more broadly.

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