DESIGN AND EVALUATION OF LIGHT EVERYWHERE: A WALL-AND-CEILING CLIMBING ROBOT OFFERING LIGHTING FLEXIBILITY FOR DOMESTIC ACTIVITIES

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ABSTRACT

In response to spatial constraints of smaller living spaces, reconfigurable physical structures have been studied, while other spatial dimensions, such as lighting, remain underexplored. This paper introduces *Light Everywhere*, a robotic light fixture traversing walls and ceilings to deliver customizable lighting tailored to diverse domestic activities. Our research employs a four-stage design process: (1) a field study with home visits (N=15) to understand residents' conventional lighting experiences; (2) an online study (N=80) to assess initial design concepts; (3) prototype development informed by existing literature and design precedents; and (4) an in-person experiment (N=26) to evaluate the prototype's impact on human behavior in a small home setting. The interaction study suggests that *Light Everywhere* enhances user comfort and perceived control, improving spatial utilization for various activities. These results envision a future for robotic lighting and underscore its potential as a flexible element in space-constrained domestic spaces.

Keywords: Robotic Lighting, Design, Interaction Study, Housing Flexibility, Domestic Activity

BIOGRAPHICAL SKETCH

Hsin-Ming Chao is a Master of Science student in Design + Environmental Analysis (DEA) at Cornell University with a concentration in Emerging Technology for Design. She minors in Information Science and focuses on Human-Computer Interaction (HCI). Hsin-Ming holds a Bachelor of Business Administration in Technology Management from National Taiwan University with a minor in Philosophy. Her research interests lie in intelligent environments, interaction design, physical product development, and user-centered studies, particularly within residential contexts. With a vision for adaptive smart homes, Hsin-Ming's thesis research explores flexible, human-centered living spaces that respond dynamically to the diverse needs of their occupants.

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CHAPTER 1

INTRODUCTION

With the rapid growth of the global population [42], there is an increasing trend toward smaller living spaces, particularly in rapidly urbanizing environments [67, 78]. As the dwelling size decreases [78], residents face the challenge of managing various domestic tasks within these limited spaces, a demand that has intensified with the rise of remote work in recent years [4, 60]. This shift in home dynamics exacerbates the difficulty of balancing multiple functions in confined dwellings. Moreover, studies have studied discomfort and health concerns associated with such spatial constraints [6, 32, 43]. In response, the concept of "flexibility" in residential design is being explored as a potential solution [20, 32, 72].

Housing flexibility aimed at accommodating the constantly changing needs of residents has been considered by design researchers, architects, and interior designers [64, 65, 72]. Previous research has shown that affording flexibility may lead to better spatial utilization and functional efficiency [64, 65], potentially mitigating feelings of crowding. Furthermore, flexible housing offers inhabitants the opportunity to customize their living spaces, providing occupants more spatial control [64, 65, 72]. One's perceived sense of control over their domestic spaces has numerous benefits, including higher success in maintaining work-home boundaries [55] and greater home comfort and wellbeing overall [15, 65].

In previous efforts by researchers and design professionals, flexible housing design has focused on utilizing "flexible elements" that can physically reconfigure a room space to facilitate spatial transitions, such as portable furniture or moveable wall partitions [29, 64, 102]. However, the research literature and design precedents fall short in exploring other spatial dimensions that might enhance flexibility in relatively confined living environments. Given this shortcoming in design research and practice, our research team undertook the investigation of lighting as a "flexible element."

Of the various spatial components of the home, lighting provides an intangible spatial experience through a tangible device. For numerous reasons considered in the literature, lighting proved to be a compelling element to explore as a tangible/intangible response to the flexibility challenges. First, in a study of indoor office workers, Kaushik et al. [2023] measured the effects of various aspects of Indoor Environmental Quality [5] on working conditions. The results indicated that illumination, often equated with lighting and a primary element of visual comfort, is the highest driver of both comfort and productivity [34]. Second, lighting has been proven to facilitate certain functions outside the workspace, most importantly, relaxation [1, 14, 53]. Lastly, lighting is unique in that its adjustment, often just the flip of a switch, requires minimal physical effort to yield highly noticeable results. A change of overall lighting (i.e., from red to green or static to flickering) transforms a space dramatically [14] yet requires very little manual energy. This low-effort, high-impact quality of lighting makes lighting systems an ideal "flexible element" of the built environment to explore in support of the diverse needs of the confined living environment.

In undertaking the challenge of lighting small homes for a variety of tasks, we propose an innovative, flexible lighting system of our design that we call *Light Everywhere*. *Light Everywhere* is designed to introduce mobility to the traditional, fixed-position light source, allowing maximum lighting adjustability with little physical effort. With the *Light Everywhere* system, the occupant simply points the wand controller to a location on the wall or ceiling of the home where light is needed for a particular activity, and the lighting source quickly moves there. For instance, if an inhabitant of the space wants to read a book on the sofa, they point the wand close to them, and *Light Everywhere* moves there, providing lighting where they need it to accomplish the task.

Figure 1: *Light Everywhere*, a robotic light fixture that climbs across walls and ceilings.

This paper presents our design of the robotic light fixture, *Light Everywhere*, and reports on our between-subjects in-person experiment with 26 participants using our novel lighting system or a traditional lamp to support diverse tasks in a home environment constructed within our lab. For our in-person study, we employed a

Wizard of Oz (WoZ) approach [12] in which a research team member controlled the movement of the light fixture wirelessly to arrive at the location on the ceiling or walls where the participant focused the wand interface. We investigated whether our "flexible" lighting system empowered the user to utilize a home space more effectively and promoted a positive experience. In a few words elaborated in this paper, the results of our study suggest that *Light Everywhere* enhances users' awareness of optimizing the environment and choosing working areas according to their changing needs. Participants assigned to use *Light Everywhere* also presented an increased sense of comfort and control compared to participants assigned to the control group that used a traditional desk lamp.

CHAPTER 2

RELATED WORK

2.1 Interactive and Smart Lighting

Interactive and smart lighting has been a research focus for design researchers aiming to integrate and study human-computer and human-robot interaction in home environments [36, 62, 74, 98]. The maturation of such adaptive lighting technology has resulted in the development of a diverse array of products and mechanisms, underscoring its feasibility and practicality.

Designers have explored various elements of lighting that can be interacted with: lighting color [28, 51, 85, 94, 101], brightness [46, 79, 101], scheduling of on/off times [49, 90], and the creation of spatial atmospheres with acoustic interaction [37]. A particularly noteworthy element is the light's coverage area, referring to the total area it can illuminate [16, 57]. For instance, a study introduced a desk lamp with a flexible stem that allowed for adjustments in its angle and direction [57]. Another innovative lamp featured multiple small LEDs, enabling users to select specific coverage areas for illumination [16]. In addition to the interactable elements of lighting, various approaches to interact with lighting have also been developed. While traditional lights typically use a switch, other interactive methods include remote controls [13, 86, 95], mobile applications [46, 54, 86], motion sensing [21, 103], voice activation [18, 35], and gesture activation [57, 58].

To complement the interactive lighting systems enabled by various user inputs, "smart lighting" has been developed to automatically adapt to environmental changes without user commands, primarily aiming to optimize energy efficiency in buildings

[63, 75, 88] and urban areas [2, 3, 77, 80]. For instance, previous designs for intelligent street lighting utilized light-dependent resistors (LDR), ultrasonic sensors [3, 80], and edge cameras [2] to detect pedestrians and vehicles, controlling the streetlight's on/off and adjusting its brightness accordingly to reduce power wastage [2, 3, 80]. Other smart lighting applications include occupancy-based smart washrooms [75], adaptive automotive headlamps that minimize glare for safety reasons [48].

While previous research emphasized on/off control and lighting mode adjustments, smart lighting applications have also extended to the light's coverage areas for illumination, a focus of particular interest in this paper. Yoon et al. [2013] introduced a 3-degree-of-freedom (DOF) robotic lamp utilizing a spherical parallel mechanism that tracked human movement via a laser scanner to provide target lighting for each person. In more recent work by Schregle et al. [2023], an object-tracking lighting system identified various objects through an embedded camera and traced specific ones with the spotlight.

Compared to other interactable lighting elements, the light's coverage area remains relatively underexplored regarding interactive approaches beyond autonomous controls despite advancements in interactive methods and robotic lamp technologies. The wide range of feasible applications for adaptive lighting also informed this project's design exploration, which we examined through an online study and reported on here.

2.2 Movable Robots for Home Use

One way to support various tasks with adjustable coverage areas for illumination across a home environment is to make lighting "flexible," which may be manifested as a wall-and-ceiling-climbing, robotic light fixture. To inform our design, we explored the literature concerning where and by which interface robots have operated successfully in domestic spaces. With respect to interfacing, previous studies have suggested ways in which such a robot might be controlled: by motion sensor [47, 59, 83], voice activation [40, 59, 61], remote control [82], and via mobile applications [30, 99].

With regards to how the robot moves in such spaces, the most common surface for domestic robots to traverse is the floor, the most prominent design precedent being the iRobot's *Roomba* [31], the robotic vacuum cleaner capable of detecting dirtier areas of the house and autonomously navigating to clean them. With over 50 million units sold worldwide [31], the Roomba demonstrates not only the technological feasibility of movable robots for home uses but also their potential for widespread user acceptance. Beyond this well-known design precedent, another common function of floor-based robots is to move large-scale furniture across the room [81, 100].

To enable wall-climbing capabilities in robots, Zhang [2022] developed the Self-Organizing Robot Team (*SORT*), a multi-agent system of wall-climbing robots designed to assist users with organizing their domestic belongings on walls [96, 97]. Interaction study results with *SORT* suggested its promise, with approximately 80% of respondents favoring such wall-climbing robots to support independent living [96]. To remain adhered to vertical surfaces like walls, *SORT* utilized magnets within its wheels and operated exclusively on magnetic surfaces [96]. Conversely, *Climbot* [89], an on-the-wall tangible user interface (TUI), was capable of traversing surfaces of various materials, including glass and painted walls, using dry adhesive treads for climbing. However, these adhesive treads lacked stability when stationary [89], limiting *Climbot*'s applicability in residential environments with no need for continuously moving light.

Similar to the magnet-embedded design of *SORT* [96], researchers have equipped commercially available wheeled robots, *toio* [76], with magnets to enable prototype movement on magnetic walls [26] and ceilings [45]. Utilizing these embedded magnets for adherence to vertical and overhanging magnetic surfaces, Han et al. [2023] designed a swarm user interface that demonstrated the capability to climb walls and transition from tables to walls, and the *ThrowIO* system's wheeled robot developed by Lin et al. [2023] could navigate across ceilings.

Focusing on 3D spatial embodied interaction, *AeroRigUI* [93] has advanced the development of ceiling-based movable robots. *AeroRigUI* offers a robotic "armature" to suspend lightweight objects by threads ("rig"), such as room decorations or a small trash bin, relocatable on the ceiling within the room and controlled by hand gestures [93]. While the team suggested dynamic lighting as a possible application [93], the system's primary emphasis has been designing the spatial user interface without fully exploring the potential for interactive control over rigged systems, such as lights, beyond their positions and orientations, thus limiting adjustability in lighting applications.

In contrast, our *Light Everywhere* is a dedicated robotic light fixture, highly adjustable for color and intensity, controlled by a wand interface (envisioned as more accurate than hand gestures), that climbs across both walls and ceilings in response to the specific needs of people needing to accomplish an expanded range of tasks at home that needs illumination of different kinds for different locations.

2.3 Advancements and Gaps in Movable Lighting

Light Everywhere, a movable, interactive lighting system that adjusts color, brightness, on/off states, and coverage areas based on user input, addresses instability issues seen in *Climbot*'s dynamic lighting [89] and expands the limited interactive control of *AeroRigUI* [93]. *Light Everywhere*, moreover, addresses another gap in previous research: the limited or absent user studies for movable lighting systems (e.g., [96, 97]). Systems such as *Climbot* [89] and *AeroRigUI* [93] have not, to our knowledge, been evaluated with users, while the 3-DOF robotic lamp [91] and the object-tracking lighting system [73] have primarily involved human participants in assessing technological feasibility rather than validating user needs within their intended lighting applications. As the design research community is well aware, user studies are productive for developing and understanding novel design interventions' experience, usability, and efficacy [8, 39]. The lack of such studies leaves user acceptance and perspectives on current robotic lighting design largely unknown to the research community prior to the work we report here.

2.4 Research Questions

While previous research has demonstrated the technological feasibility of a robotic light capable of traversing the surfaces of a room, there is limited understanding of the interaction design of such lighting applications, their impacts in residential environments, and how users perceive the experience. As was referenced earlier, studies on housing flexibility have shown that increased flexibility can accommodate changing needs [64, 65, 72], leading to better spatial utilization [64, 65], more spatial control [64, 65, 72], and potentially greater home comfort [15, 65]. Building upon these findings, we hypothesize that a "flexible" lighting system can support the diverse requirements of a small home environment. To explore this, we developed the robotic light, *Light Everywhere*, and conducted an interaction study with it, seeking to address the following research questions:

- RQ 1: How does *Light Everywhere* support users in performing diverse tasks within a residential environment?
    - RQ 1.1: Does *Light Everywhere* increase users' perceived comfort in performing diverse tasks within a residential environment?
    - RQ 1.2: Does *Light Everywhere* increase users' perceived control in performing diverse tasks within a residential environment?
- RQ 2: How does *Light Everywhere* affect how users utilize a space?

CHAPTER 3

LIGHT EVERYWHERE

Light Everywhere (Figure 1) is a light fixture designed to climb walls and ceilings, controlled remotely via a mobile application. With the primary objective of our research being to assess the robotic lighting concept, our team developed a prototype that could afford the participant experience in a Wizard of Oz (WoZ) study rather than focusing our energies on technical refinement of a system fully operable in all envisioned respects. Our methodical design process involved four interrelated activities:

- A field study in which we visited the homes of 15 participants to learn more about people's attitudes and experiences with the conventional lighting they use every day.
- An online study in which we invited 80 participants to evaluate five of our design concepts for robotic lighting; these concepts were informed by our field study.
- Development of the prototype used in our in-person study to evaluate whether a movable light fixture as the "flexible element" can support versatile uses of space.
- A between-subjects, in-person experiment (N=26) to evaluate the impact of the flexibility provided by our robotic light fixture prototype, *Light Everywhere*, on human behavior in a small home setting.

3.1 Design Activities

3.1.1 A Field Study in People's Homes

We conducted a field study, directly observing users in their home environment to understand their behaviors, needs, and challenges with respect to the use of lighting to support their activities of daily living. These observations provided our team valuable insights that inform the subsequent design process, ensuring that our design meets people's real-world requirements.

In our field study, we visited 15 participants (10 female, 5 male) aged between 24 and 33 years (M=27.73, SD=3.06) in their homes (altogether, 13 different home environments). Participants were asked to demonstrate all the lighting devices in their homes to us and explain how they used them to perform domestic tasks. We then conducted contextual interviews with the 15 participants individually, asking each participant about their purchase decisions for each device and any issues they faced with them and their home lighting overall.

These interviews provided valuable insights into the design elements of light fixtures and the constraints posed by home environments. Key findings of the field study include the following: (1) the flexible adjustability of light fixtures is highly valuable due to the personalized nature of lighting needs; (2) despite the availability of numerous lighting modes, individuals typically utilize only up to three modes frequently; (3) some challenging and uncommon areas for lighting installation need more illumination, such as inside closets and above mirrors; and (4) visually wireless light fixtures are preferred due to the exposed wires' safety concerns for children and pets.

3.1.2 Initial Design Ideas

Informed by the insights gained from our field study, we developed a morphological chart [66] for a robotic light that facilitated the generation of five design concepts, each embodying different interactive approaches for repositioning the light and adjusting its modes. These designs are illustrated in Figure 2. While each idea was tailored to address particular user needs identified during the contextual interviews, all designs share common characteristics: a visually wireless, interactive lighting system offering three adjustable lighting modes and the capability to illuminate areas beyond the reach of conventional lamps, aligning with the four key findings presented in the previous section.

Design A, *Smart Light*, autonomously follows the user and adapts its lighting modes to their likely preferences. This design responds to the user's desire for lighting to seamlessly follow them across rooms, especially between floors, to prevent transitions in darkness. Design B, *Remote-Control Light*, is a ceiling-mounted light fixture repositionable via remote control, addressing user challenges with accessing and adjusting the "unreachable" ceiling installations.

Another recurring issue identified in the interviews was the physical space occupied by lighting devices, such as floor and desk lamp bases. These fixtures often take up valuable space on desks, tables, and living areas, limiting users' placement and usage options. Inspired by observations of users fixing workstations beneath wall sconces to reduce reliance on space-consuming desk lamps, we created Design C, *Move-Your-Light*, a touch-adjustable lighting module that can be manually detached and reattached to different walls as needed. Similarly, Design D, *Throw-a-Light*, was built on the same goal of space efficiency but focused on ceiling interaction. This design features a sphere-shaped "light ball" that users can throw toward and attach to the ceiling.

Expanding the conceptual boundaries of lighting, Design E, *Wall-Light*, envisions walls themselves as a lighting system. Users can hand "draw" closed curves on walls to "create" light in the desired shapes and locations and use voice commands to adjust ceiling lighting. By eliminating the need for physical movement of tangible devices, Design E addresses wire-related safety concerns more thoroughly.

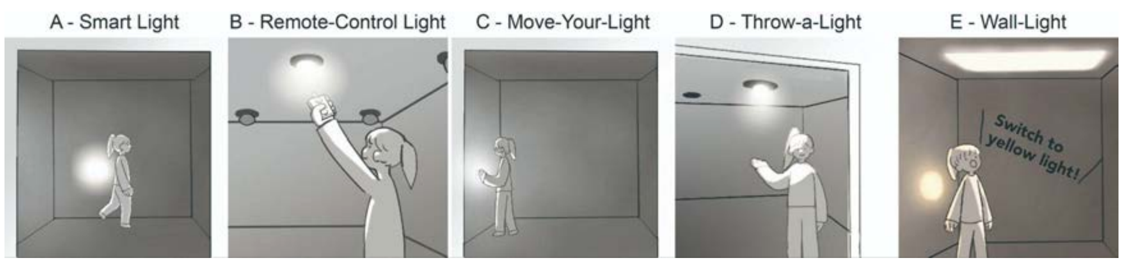


Figure 2: Five robotic light design concepts, each presented with one frame of the animated GIF we used in the online user study.

3.1.3 Online User Study

To select the most suitable concepts and gather insights for further design iteration, we conducted an online survey to evaluate our five design concepts. We recruited 80 respondents through the *Prolific* online research platform, ultimately analyzing data from 79 participants (39 female, 37 male, and 3 non-binary) after excluding one respondent who failed our online survey's attention-check questions.

Within the survey, respondents were asked to envision themselves performing various tasks at home and then introduced to the five design concepts presented in randomized order. Each concept was presented with a short text description, an animated GIF (Figure 2), and a low-fidelity prototype demo video (Figure 3). The text focused on user interactions with the light fixture (precisely how to move it across space and adjust its lighting modes), while the GIF and demo video provided a more vivid representation of these interactions. Following the introduction of each concept, respondents evaluated the concept's effectiveness and usability using eight statements rated on a 1 to 5 scale (1=Strongly disagree, 5=Strongly agree), as shown in Table 1. At the end of the survey, participants were asked to rank their preferences for different methods of moving a robotic light module (Table 2) and changing the light's brightness and color (Table 3).

Figure 3: The low-fidelity prototype of a “*Remote-Control Light*.”

3.1.4 Online Study Results

Among the five design concepts, the most preferred was "*Remote-Control Light*" (Design B, Figure 3), which allows movement and lighting mode adjustment via a remote control. "*Remote-Control Light*" received an average score of 3.49 out of 5 and achieved the highest scores on four out of eight evaluation statements (Table 1). The survey described it as follows: *"Remote-Control Light" is a moving light fixture* *connected to the ceiling. When light is needed, you use a remote to point at a light module and "drag" it (like a computer mouse moving a file) to a desired position. You can change the color and brightness of the light with the remote. When the light is not needed, you turn it off with the remote.*

Table 1: Evaluation of five design concepts (1=Strongly disagree; 5=Strongly agree)

Evaluation Statements for Each Design Concept	**A**	**B**	**C**	**D**	**E**
I understand how it works on a basic level.	4.14	4.41	4.30	4.38	3.99
It will help make routine tasks easier to perform.	3.05	3.27	3.15	2.68	3.32
I could envision it in my living space.	2.59	3.25	3.25	2.72	3.09
It will make daily chores fun.	2.73	3.05	2.84	3.05	3.30
It will be easy to have it move to where I want.	3.39	3.62	3.76	3.57	3.52
It will be easy to adjust its color and brightness.	3.20	4.06	3.99	3.84	3.90
I believe it will be more helpful than my living space's current lighting system.	2.46	2.89	2.59	2.43	2.87
I'll be worried about its safety issues if it is in my living space.**	3.28	3.25	3.67	2.80	3.51
Mean Score	3.04	3.49	3.28	3.18	3.31

* Gray cells indicate the idea with the highest score among the five on each statement.
** indicates an item to be reverse-coded. The recorded scores on the table are (6 - the actual scores).

Despite being the most preferred design idea overall, the "remote control" approach was only the second, not the top, choice in the two interactive method ranking questions. Tables 2 and 3 show that the most favored method for moving a light module was to "*physically move the module myself*," and the one for changing light brightness and color was to "*voice-command the module to change its mood*." Given the compatibility of these two approaches with the *Remote-Control Light* concept, we decided to integrate them into a single design for the next development phase.

Table 2: Method for moving a light module: rankings of seven options

Method for Moving a Light Module	**Ranking Mean**
Physically move the module myself.	2.58
Remote control the module to move.	3.25
Gesture to create a light where I want it.	3.75
Voice-command the module to move.	3.95
Move the module by using an iPad app.	4.43
Remove the module and throw it where I want it positioned.	4.61
Let the module move itself where it decides I want it.	5.43

Table 3: Method for changing lighting modes: rankings of six options

Method for Changing Lighting Modes	**Ranking Mean**
Voice-command the module to change its mood.	2.62
Remote control the module to change its mood.	2.86
Swipe on the module to change its mood.	3.11
Gesture the module to change its mood.	3.41
Change the module's mood by using an iPad app.	3.43
Let the module change its mood when it decides I want it.	5.57

3.1.5 Design Concepts

Based on the survey results, our design for the robotic light fixture incorporates the following functionalities: (1) the ability to climb both the wall and ceiling surfaces; (2) the ability to move across these surfaces either via remote control or manually; and (3) the option to switch between multiple lighting modes using voice commands.

3.2 Prototype Development

Recognizing that our primary objective was to evaluate the robotic light concept in an in-person experiment rather than innovate new robotic technology, we decided to build our prototype based on the available literature and design precedents and incorporate the WoZ method into the prototype's user experience from the outset. We aimed to create a lighting prototype capable of moving across wall and ceiling surfaces and changing its lighting modes using methods that our team could operate remotely.

Among the previous work on movable lighting, we identified *SORT*, designed by Zhang et al. [2022], as the closest to our design goal due to its potential to stably move on both ceilings and walls and to integrate interactive lighting control, as well as its use of a Bluetooth-connected mobile application for remote operation. Designed as a "wall-climbing robot," *SORT* attaches and moves on magnetic walls with two magnet-embedded wheels, each driven by a continuous servo motor [96]. Developed using the free online tool *MIT App Inventor*, *SORT*'s mobile application connects to the robot's Bluetooth module and remotely controls its movements in all directions [96].

Our team drew strongly from the *SORT* precedent, adapting it as a robotic light fixture that could also scale ceilings. Our *Light Everywhere* prototype consisted of four magnet-embedded wheels, four continuous servo motors, an Arduino Nano board, an HC-05 Bluetooth module, a 9V battery to power the Arduino and Bluetooth module, a Grove RGB LED ring consisting of 42 programmable mini LEDs, a 5V battery to power the LED ring, and a corrugated plastic lens to diffuse the light of the LED ring.

After the hardware modifications, we reprogrammed the mobile application using *MIT App Inventor* to include three lighting modes with their respective Arduino RGB codes: white (255, 255, 255), bright yellow (255, 100, 0), and warm yellow (100, 40, 0). These three modes were designed to respond to users' personalized lighting needs while minimizing redundancy in available options, aligning with the insight from the field study, our first design activity, that individuals typically rely on no more than three primary lighting modes for diverse domestic tasks. We then lab-tested the modified prototype and application across all lighting modes on both magnetic ceilings and walls. We also verified the robot's ability to climb right angles from floors to walls, ensuring its capability to move across all surfaces in a conventional living environment.

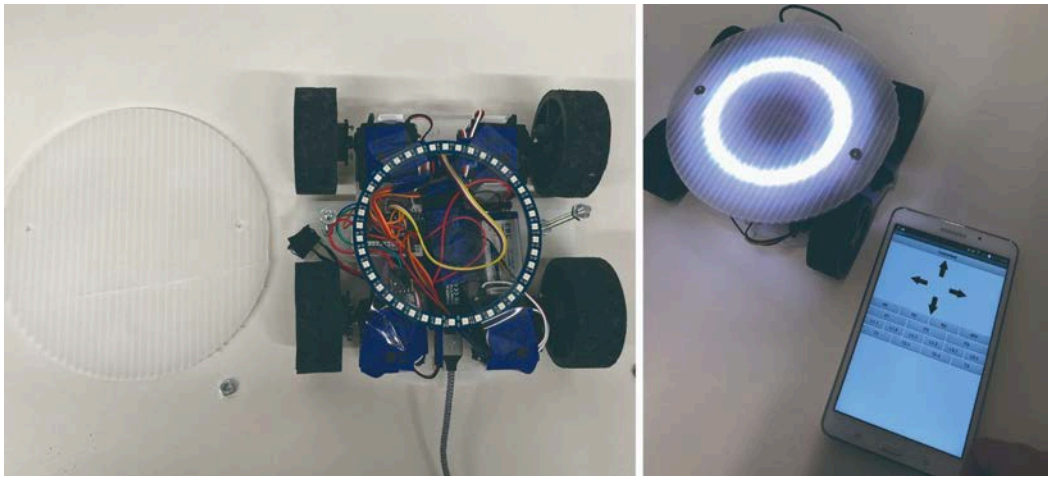


Figure 4: The prototype and mobile application of *Light Everywhere*, both modified from *SORT* [96].

3.3 Prototype Functions

3.3.1 Moving the Robot

The intended method for moving the *Light Everywhere* prototype involves using a remote control, as informed by our online study, manifested as a wand interface. Users point the wand at a location on the wall or ceiling, and the prototype will move to that location. Our lab has designed a wand that is fully operable with another robot, but we have yet to replicate the same for this project; for this study our wand remains a WoZ prototype which is simply a laser pointer. For the in-person study reported in the next section of this paper, a researcher controls the robot's movement by observing where the participant directs the laser point on surfaces and moves the prototype accordingly to that location via the mobile application. We designed the robot so that the prototype will stop when it arrives at the limits of the magnetic precinct on the walls or ceiling to prevent slipping or falling. Additionally, users can manually reposition the prototype by detaching it from one spot and attaching it to another, a feature informed by our online study, which revealed that users welcomed the flexibility to manually move the light module themselves.

3.3.2 Changing the Lighting Mode

The designed method for changing the lighting mode of *Light Everywhere* is through voice commands. Users can say *"white," "yellow," "dim," or "off"* to change the lighting mode to white, bright yellow, warm yellow, or turn it off, respectively (Figure 5). The default mode is white, which is activated when users say *"on."* Commands other than these five will not change the lighting mode. The lighting mode is switched by the observing researcher, who listens to the commands and adjusts the mode via the mobile application.

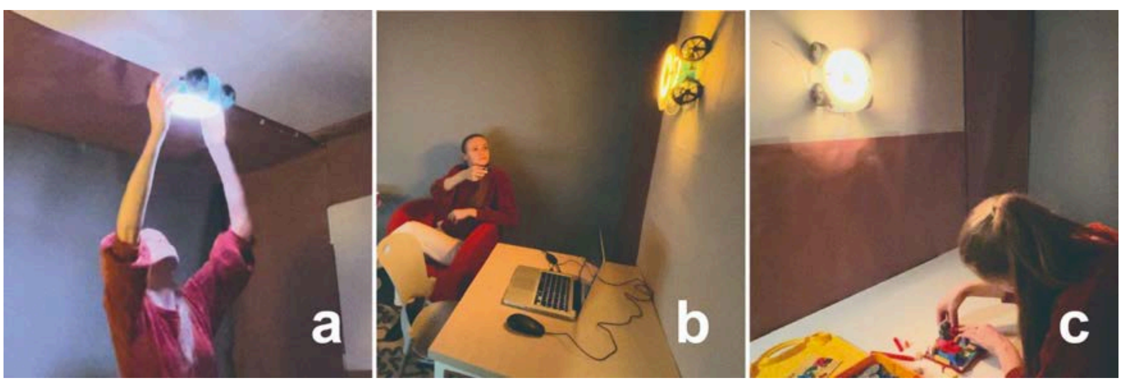


Figure 5: The prototype functions: a) being manually moved across surfaces; b) climbing wall and ceiling surfaces, controlled via a remote; and c) changing lighting modes between "*white*," "*yellow*," and "*dim*."

CHAPTER 4

METHOD

We conducted a between-subjects, in-person experiment to evaluate the impact of the flexibility provided by the robotic light fixture on human behavior in a home setting. Participants were randomly assigned to one of two groups: the intervention group, which used the *Light Everywhere* prototype, or the control group, which used an Arduino-programmed desk lamp. Each participant was invited to a small, furnished space resembling a living room and tasked with six activities using the assigned light fixture. Our objective was to compare the two groups' spatial utilization of the room and their perceived comfort and control, thereby addressing the research questions outlined in the preceding section. Recognizing the highly individualized nature of human behaviors at home and their dependence on the residential environment, we designed this laboratory study to minimize confounding factors by ensuring all participants were exposed to the same environment and performed identical tasks.

4.1 Participants

Twenty-six participants (16 female, 10 male), aged between 22 and 34 years (M=27.19, SD=3.32), were recruited from our institution's student population through posters, emails, and the snowball sampling method [56]. Participants were randomly assigned to either the intervention or the control group, with each group comprising 13 participants. All participants voluntarily participated in the study, provided written informed consent, and retained the right to withdraw from the study at commencing it.

4.2 Setup

The experiment was conducted in a room within our lab space measuring 8 feet in length, 10 feet in width, and 8 feet in height. To meet the operational requirements of the magnet-embedded *Light Everywhere* prototype, we constructed this custom study room using an aluminum frame and paper to incorporate the necessary magnetic surfaces. Within this room, near-paper-thin steel sheets covered a 4-foot by 9-foot area on the ceiling, a 4-foot by 3-foot area on one wall, and a 4-foot by 6-foot area on another. Due to budget constraints, we did not cover all surfaces with magnetic sheets but focused on essential surface areas to provide adequate flexibility for operation (Figure 6). Moreover, although the prototype demonstrated its ability to climb right angles from floors to walls, it could only stably traverse rounded corners from walls to the ceiling, which is uncommon in contemporary building designs. To simulate an actual residential environment and reduce safety risks, we did not install magnetic sheets at the wall-ceiling corners, preventing the prototype from moving mechanically across the corners.

Figure 6: The “living room” being constructed in our laboratory. The white areas are the embedded magnetic sheets.

The space was furnished to resemble a living room, excluding a bed or kitchen, as sleeping and cooking were not the focus of this study. As shown in Figure 7, the room included a dining table, a coffee table, a writing desk, two rolling chairs, a sofa chair, and a ladder for participants to use should they elect to manually move the prototype between the ceiling and walls. A floor lamp was placed in a corner near the dining table to provide ambient lighting, typical of a home setting. The floor lamp's position and lighting mode remained fixed throughout the study to minimize its impact on participants' interactions with the assigned light fixture.

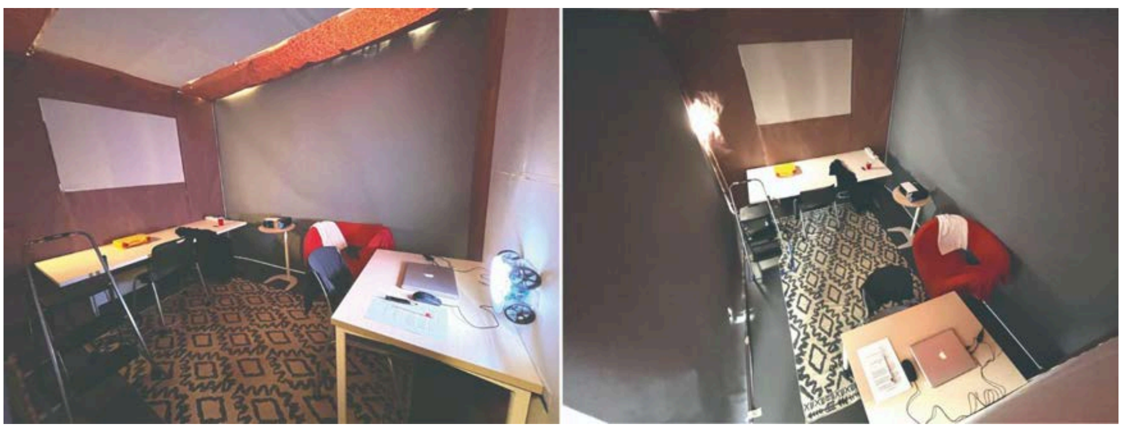


Figure 7: The furnished study room with all equipment and materials required for the experiment.

Sharing the same ambient lighting, the intervention and control groups differed in task lighting: the former utilized *Light Everywhere*, while the latter used a modified desk lamp with a flexible gooseneck, allowing users to reorient the light source (Figure 8). The modifications included replacing the light bulb with an Arduino Nano board, a Grove RGB LED ring, and a translucent plastic sheet as a light diffuser to replicate the light source embedded in the *Light Everywhere* prototype, ensuring a consistent lighting source for both groups. The lamp's commercial design, gooseneck function, and button-controlled operation provided an experience similar to commercially available products.

Figure 8: The modified desk lamp used in the control group, equipped with the identical RGB LED ring as embedded in the *Light Everywhere* prototype.

At the start of the study, the desk lamp was positioned on the writing desk for the control group, while *Light Everywhere* was attached to the wall adjacent to the same desk for the intervention group. Both light fixtures defaulted to white light, with bright and warm yellow options available through identical Arduino settings. All other environmental conditions were held constant throughout the study for both groups.

4.3 Procedure

To simulate a living scenario in a multi-purpose residential setting, we developed a one-hour experiment based on common home activities, drawing from the framework of Activities of Daily Living (ADLs) [33, 41, 84]. After excluding activities that involved personal privacy or required access to kitchen or bathroom facilities, we identified five primary task categories: "self-feeding" from Basic ADLs (BADLs) [33, 41], "housekeeping" and "using technology" from Instrumental ADLs (IADLs) [33, 41], and "mental exercise" and "hobbies requiring fine motor skills" from Domestic ADLs (DADLs) [84]. Representative tasks were designed for each category, as summarized in Table 4. Additionally, to reflect on the role of leisure in home life, we introduced a sixth category, "relaxation," bringing the total to six tasks for the study.

Table 4: Task description of the study

Source	Category	Task
Basic ADLs [33, 41]	Self-feeding	Eating a snack and sipping a drink
Instrumental ADLs [33, 41]	Housekeeping	Folding and packing four T-shirts into a carry-on
	Using technology	Selecting a flight on a laptop
Domestic ADLs [84]	Mental exercise	Reading a text and answering questions about it
	Hobbies requiring fine motor skills	Designing a small cabin with LEGO
n/a	Relaxation	Watching a short movie using a projector

The experimental setup was standardized across all participants, with all necessary equipment and materials provided and strategically positioned around the room (Figure 7). This arrangement was designed to reflect the typical need to navigate a home space while performing various activities, incorporating the "transferring" task from BADLs [33, 41].

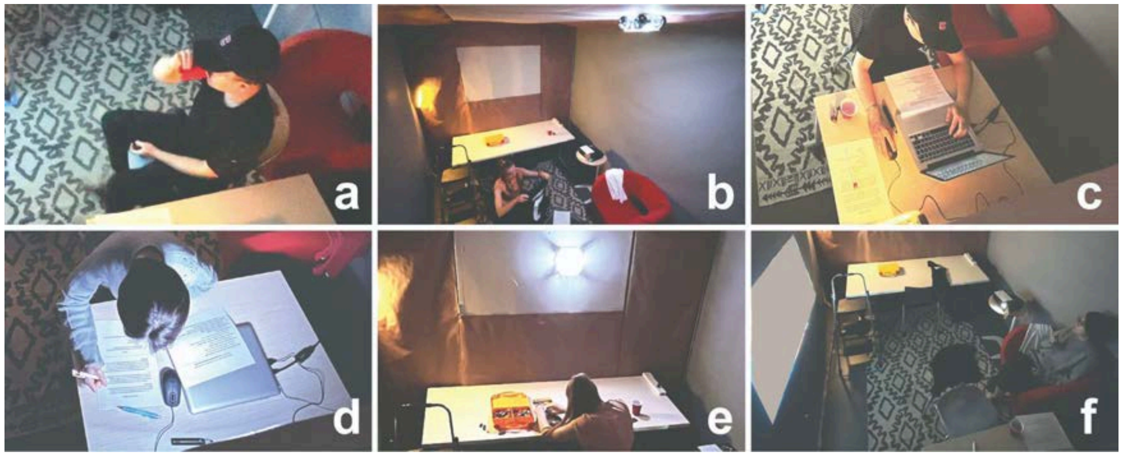


Figure 9: The six tasks in the study, representing (a) self-feeding, (b) housekeeping, (c) using technology, (d) mental exercise, (e) hobbies requiring fine motor skills, and (f) relaxation.

Before starting the experiment, participants were briefed on the study procedure, asked to sign an IRB-approved consent form, and received written task instructions. The instructions asked participants to perform the tasks "*in an order that follows your recollection of how you did these kinds of tasks recently at home*" and allowed them to use and move any equipment in the space. After obtaining written informed consent, one researcher led each participant to the study room and demonstrated the light fixtures – for the intervention group, *Light Everywhere*, and for the control group, our desk lamp fitted with the same LED ring as our prototype. Intervention group participants received a laser-pointer remote to move the prototype and were instructed to use voice commands to control the lighting modes, while the facilitator outside the room controlled the prototype via the mobile application using the WoZ method. The main researcher then left, closed the room, and started video recording with a camera placed inside the room.

The tasks had no time limit, with completion times ranging from 966 to 2651 seconds (M=1632.38, SD=463.01). Throughout the session, the facilitator observed the study through a gap in one wall and controlled the prototype based on the laser points and voice commands, while the main researcher observed through a hole in another wall to note participants' behaviors. Both researchers remained out of sight of participants to minimize the effect of being observed. We only approached participants when they indicated a need for assistance or study completion.

After completing the tasks, participants were led out of the room for a 10-minute interview. The interview covered their overall experience with the light fixtures, specific behaviors during the study, potential use cases for the prototypes, and any issues they encountered. Following the interview, participants completed a post-questionnaire covering demographics, perceived comfort, perceived control, and usability. The session concluded with participants receiving a $5 incentive.

4.4 Data Analysis

Our data consisted of post-questionnaire responses, interview audio recordings, and session video recordings. To facilitate comparative analysis, we labeled participants in the intervention group as P1 to P13 and in the control group as P14 to P26.

For the interview analysis, we used *otter.ai* to transcribe the audio recordings and had all 26 transcripts manually corrected by one researcher to ensure accuracy and consistency. We combined deductive and inductive coding methods, categorizing responses under three research focuses: *perceived comfort*, *perceived control*, and *spatial utilization*, while also noting emerging topics. Important sentences were then highlighted and grouped under iterative insight categories.

For the video analysis, our team defined from our study observation 19 behavioral codes: 12 events (6 specific to the intervention group, 3 to the control group, and 3 shared), such as "*moving the prototype using the remote*" and "*switching the lighting mode*," and seven states (2 specific to the intervention group and 5 shared) such as "*staying on the sofa*" and "*leaving the prototype on the ceiling*." After the team finalized the coding protocol together, one researcher solely conducted the video analysis of all 26 recordings to maintain coding consistency.

Marking the moment when the main researcher left the study room as 0:00, we recorded event times, start and end times of states and noted the relevant contexts. For example, for the event, "*switching the lighting mode*," we recorded both the initial and switched modes, and for the state, "*leaving the prototype on the ceiling*," we noted all tasks conducted during that period. We further counted event occurrences, calculated state durations, and summarized key findings for each participant. Finally, we organized all the behavioral data above and compared the two groups.

Combining these analyses, we developed a comprehensive understanding of *Light Everywhere*'s impact on human behavior in a home setting and the user experience of using it.

CHAPTER 5

RESULTS

5.1 Perceived Comfort

To address RQ1.1, *"Does Light Everywhere increase users' perceived comfort in performing diverse tasks within a residential environment?",* the post-questionnaire measured participants' perceived comfort by their satisfaction with "*light overall*," "*artificial light*," and "*reflection or glare*" on a 1 to 7 scale (1=Unsatisfactory, 7=Satisfactory). This measurement was based on the light section of the *Indoor Environmental Quality* questionnaire used in the *OFFICAIR* study [5, 70]. As shown in Table 5, the intervention group reported higher satisfaction with all three items than the control group, with an average score of 4.90 (SD=1.70) compared to 3.05 (SD=1.73). Notably, the difference in scores between the two groups was more significant for "*light overall*" and "*artificial light*" compared to "*reflection or glare*," with average gaps of 2.16, 2.85, and 0.54, respectively. This disparity suggests that the impact of using *Light Everywhere* on perceived comfort varied across different dimensions.

When asked about their feelings towards *Light Everywhere*, nine of the 13 intervention group participants described it as *"comfortable," "convenient,"* or *"effortless."* For example, P2 stated, *"It made me feel nicer and comfortable. At some point, it made me feel calmer."* P4 found it *"convenient"* as *"You don't need multiple lights around the room. You just need one."* Additionally, P12 appreciated its flexibility in moving on the ceiling rather than being restricted to the desk, calling it *"more human ergonomic."*

Table 5: Assessment of perceived comfort with lighting (1=Unsatisfactory; 7=Satisfactory)

Assessment Items	Intervention Group		Control Group	
	Mean	**SD**	**Mean**	**SD**
Light Overall	4.62	1.80	2.46	1.33
Artificial Light	5.23	1.64	2.38	1.33
Reflection or Glare	4.85	1.72	4.31	1.84
Mean Score	**4.90**	**1.70**	**3.05**	**1.73**

Conversely, four control group participants proactively reported discomfort using the desk lamp. Three participants mentioned eye strain from direct light exposure, with P22 stating, *"It felt like you're in the spotlight. There was one source of light just coming towards your face."* P24 noted a similar issue, claiming the desk lamp was *"an intense light but not distributed properly."* Additionally, P23 highlighted that the shadows created by their hands when using the desk lamp were *"distracting."* These responses suggest that, despite sharing the same lighting modes as *Light Everywhere*, the desk lamp exhibited, if not amplified, more discomforting factors.

Although most control group participants reported suffering discomfort from the desk lamp, only one control group participant attempted to improve their lighting condition by adjusting the lamp's gooseneck to reorient the light towards the wall to reduce direct light (P24). At the same time, nine intervention group participants moved the *Light Everywhere* prototype away from their tasks. This discrepancy suggests that more participants using the prototype demonstrated comfort-oriented behaviors compared to those using the modified desk lamp.

5.2 Perceived Control

To address RQ1.2, *"Does Light Everywhere increase users' perceived control in performing diverse tasks within a residential environment?"*, we adapted the *Perception of Control* survey from the *SORT* project [96], originally derived from the *NIOSH Generic Job Stress Questionnaire* [10], to measure participants' perceived control on a 1 to 5 scale (1=Not at all, 5=Extremely). Table 6 shows that the intervention group reported a higher sense of control than the control group across all three items, with an average score of 3.97 (SD=0.84) versus 2.51 (SD=1.19). This result suggests that the movable light fixture enhanced users' sense of control over their environment and tasks. Specifically, in response to *"How much does the light module make you feel you have control over the space?"* 92.31% of the intervention group rated it 4 or 5 (M=4.08, SD=1.04), compared to only 23.08% of the control group (M=2.46, SD=1.33).

Table 6: Assessment of perceived control (1=Not at all, 5=Extremely)

Assessment Questions	**Intervention Group**		**Control Group**	
	Mean	**SD**	**Mean**	**SD**
How much does the light module help you move through the tasks?	3.92	0.86	2.62	1.19
How much does the light module make you feel you have control over the space?	4.08	1.04	2.46	1.33
How much does the light module make you feel confident about performing the tasks?	3.92	0.64	2.46	1.13
Mean Score	**3.97**	**0.84**	**2.51**	**1.19**

When asked, *"Does this light give you more control over this space? Why?"* 10 of the 13 intervention group participants responded positively. P3 and P9 cited negative experiences with their current home lighting systems to highlight the improved sense of control with *Light Everywhere*. P3 mentioned being forced to work in a bright living room due to poor bedroom lighting, while P9 often had to move floor lamps around the home for different activities. They felt in control when using *Light Everywhere* because *"I can choose how to use the space because the light is movable."* (P3) and *"I didn't have to think about whether I could put it here or plug it in there. I could just move it."* (P9) Besides the enhanced flexibility, the prototype's ease of operation also contributed to the perceived control. P1 felt *"more empowered to change it (the lighting)"* and claimed they would feel comfortable adjusting the lighting even if *Light Everywhere* was not in their home but in their friend's.

However, the other three participants in the intervention group provided negative feedback. Two reported that the prototype did not respond immediately to commands or move as expected, which they found unsettling. P12 described it as *"creepy,"* while P11 felt vulnerable due to the unresponsive movements. P10 noted the light was not bright enough to light up the whole space, which reportedly attributed to their feeling of insecurity in the space.

In contrast, six participants in the control group felt a lack of control, and 12 desired a more adjustable lighting system. Although the lamp had a flexible gooseneck and was not fastened to the desk, seven participants chose to move task materials or furnishings to access more light rather than adjusting the desk lamp. When asked why not modify the lighting condition, some control group participants found it (in the words of P24) *"a hassle,"* while other control group participants did not consider it during the study. As P22 stated, *"I didn't even think about that as an option."*

Video analysis also showed the intervention group adjusted lighting more than the control group. All 13 intervention group participants moved *Light Everywhere* manually or via remote control, averaging 3.77 times (SD=2.17), while only three control group participants attempted to move the lamp or adjust its angle, averaging 1.67 times (SD=1.15). This disparity in adjusting behaviors was also observed in the event of switching lighting modes, in which two groups set identical Arduino settings. Eleven participants in the intervention group (M=4.18 times, SD=2.86) changed the modes, compared to only seven in the control group (M=2.14 times, SD=4.16).

These findings suggest that the movable light fixture enhanced users' perceived control and empowered them to adjust lighting more freely, consistent with the perceived control results from the post-questionnaire.

5.3 Spatial Utilization

Selecting lighting as the "flexible element" to enhance the space's capacity for supporting diverse activities, our team hypothesized that *Light Everywhere* could change how participants used their living space by providing them with more spatial options to perform tasks. To address RQ2: *"How does Light Everywhere affect how users utilize a space?"*, we analyzed spatial utilization based on the time participants spent in each area of the space. Given that most tasks were completed while sitting, we focused our analysis on three seating areas (i.e., two rolling chairs and one sofa) and the central open space as the fourth area. The four corners of the “room” were excluded from our analysis since no participant approached them during the study. We then measured each participant's time spent in these four areas and calculated the duration composition across the study, as shown in Figure 10.

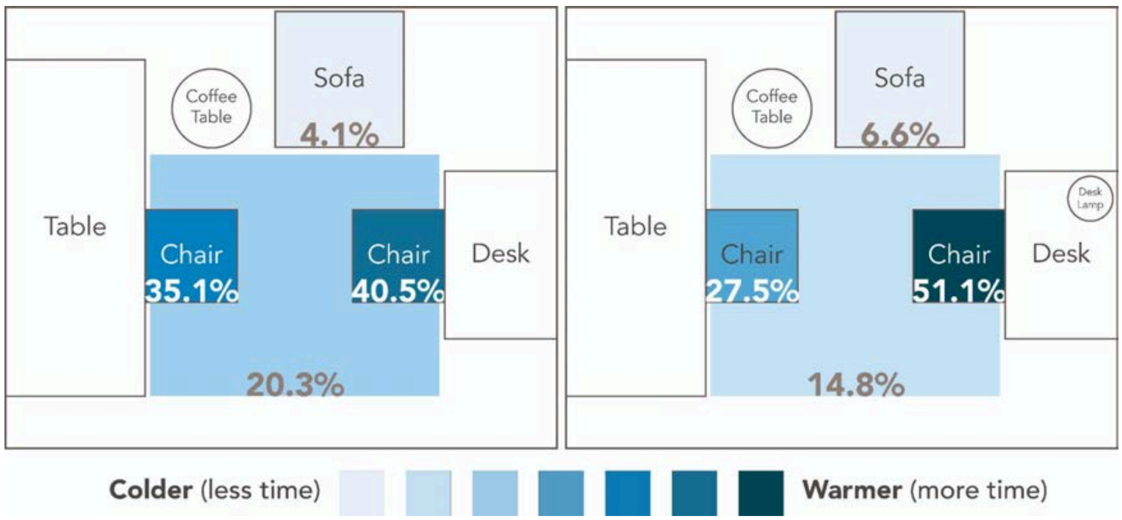


Figure 10: The heat maps showing the composition of time spent in each area: (left) the intervention group, and (right) the control group.

Although the total study completion times were similar between the two groups, averaging 1625.33 seconds (SD=377.83) for the intervention group and 1639.42 seconds (SD=551.23) for the control group, the compositions of time spent in different areas varied. In the control group, where the desk lamp was never moved from the desk, participants spent 51.07% of the study time (M=837.33 seconds, SD=667.56) in the chair next to the desk, and only 27.52% (M=451.17 seconds, SD=358.73) in the chair by the table. In contrast, the intervention group demonstrated a more balanced use of various areas: 40.45% in the desk chair (M=657.43 seconds, SD=153.79) and 35.10% in the table chair (M=570.57 seconds, SD=536.38). The intervention group also spent more time moving in the central open area, an increase from 14.77% to 20.32%, and less time sitting on the sofa, a decrease from 6.64% to 4.12%. These results suggest that, unlike the desk lamp, which created spatial constraints, the movable light fixture allowed participants to choose their preferred working areas more freely.

Additionally, during interviews, participants discussed new ways to utilize space with *Light Everywhere*, particularly in corners and on floors, areas that often lack sufficient light. P12 also stated that only in this study did they realize the possibility of interacting with the ceiling rather than just *"placing stuff on the ceiling for a very long time."* These insights suggest that the movable light fixture not only balanced the utilization of commonly used areas but also had the potential to unlock new areas for activities.

5.4 Usability

Considering that *Light Everywhere* used in this study was a WoZ-controlled prototype, we evaluated its usability using the post-questionnaire to determine if the prototype's immaturity and the WoZ method's human factors affected participants' user experience and their perspectives on the concept of a robotic light fixture (Table 7). As a result, the prototype scored 80.96 on the *System Usability Scale* (SUS) [44], receiving an A grade on the *Curved Grading Scale Interpretation of SUS Scores* [71]. This grade places it between the 90th and 95th percentile range among all studies testing SUS scores [71], suggesting that this early prototype's improvable functionality did not significantly impact the study experience.

Table 7: System Usability Scale of the *Light Everywhere* prototype (1=Strongly disagree, 5=Strongly agree)

System Usability Scale	**Mean**	**SD**
I think that I would like to use this system frequently.	3.92	0.95
I found the system unnecessarily complex.**	2.08	1.19
I thought the system was easy to use.	4.38	0.51
I think that I would need the support of a technical person to be able to use this system.**	1.62	0.96
I found the various functions in this system were well integrated.	4.08	0.86
I thought there was too much inconsistency in this system.**	1.62	0.65
I would imagine that most people would learn to use this system very quickly.	4.38	0.87
I found the system very cumbersome to use.**	1.62	0.51
I felt very confident using the system.	4.15	0.55
I needed to learn a lot of things before I could get going with this system.**	1.62	0.65
Mean SUS Score	80.96	

* SUS score = 2.5 x {[the sum of (score of each positively worded item - 1)] + [the sum of (5 - score of each negatively worded item)]} [44]
** indicates an item to be negatively worded.

CHAPTER 6

DISCUSSION AND CONTRIBUTION

As previously explored, “housing flexibility” (primarily defined from an architectural perspective) offers a solution responsive to various human needs within a confined space by enabling flexible spatial changes to accommodate different uses [64, 65, 72]. Spaces with high flexibility have been found to enhance occupants' sense of control [64, 65, 72] and reduce their negative feelings toward the environment [64, 65], thereby better supporting diverse tasks compared to spaces with low flexibility.

In this study, our robotic light fixture, selected as the "flexible element," played a crucial role in supporting participants as they completed various tasks. P3 from the intervention group noted that, with *Light Everywhere*, *"I could make use of the space the way I wanted to, not in a way I had to."* By lifting the spatial constraints imposed by the traditional desk lamp, the flexible lighting prototype allowed the intervention group to choose their preferred areas of the study room for different tasks.

Furthermore, despite similar study completion times on average, the intervention group reported higher levels of comfort and control than the control group, consistent with findings in previous research on housing flexibility [64, 65, 72]. Building upon these results, we further discuss the behavioral changes influenced by the robotic light fixture and explore the device's potential applications in what captures the key contributions of this work.

6.1 Reducing Unconscious Tolerance of Unsatisfactory Lighting Conditions

Among the control group, we observed an unconscious tendency to tolerate unsatisfactory lighting conditions. Unlike the intervention group, which utilized the robotic lighting prototype, the control group tended to accept lighting as an unchangeable environmental factor despite their frustration with it.

An example of this tendency was the control group's inaction with the desk lamp. Although the lamp was not fixed in place, no participant attempted to move it from the desk corner where it was initially placed. Of the 13 participants using the lamp, only three physically adjusted its position or angle, and all adjustments were minor and confined to that corner. Six participants never touched the lamp during the entire experiment. However, despite their inaction, the control group expressed significant dissatisfaction with the lighting conditions, rating "light overall" at 2.46 (SD=1.33) and "artificial light" at 2.38 (SD=1.33) out of 7. This discrepancy suggests that their inaction was not due to a lack of desire to change the lighting but rather a resignation to tolerate it.

When asked why they did not modify the lighting, P22 mentioned they were unaware of it as an option, saying, *"I felt I had to tolerate it. I was like, hey, I'm the user, so I need to go through it."* P26 attributed this unconsciousness to *"the manipulative aspects of the environment,"* stating, *"It (adjusting lighting) didn't even cross my mind."* These responses suggest that despite being informed they could move and use anything in the study room, the control group did not perceive this adjustability. They unconsciously considered lighting as a fixed factor they had to endure. In contrast, using *Light Everywhere*, the intervention group did not show this tolerance. All intervention group participants moved the prototype, and nine even manually repositioned it across different surfaces in the room.

We attributed this disparity to the distinct affordances the two light fixtures provided. Affordances refer to an object's properties that suggest how it can be interacted with [92], and for a space, they indicate the possibilities for actions that people perceive in the environment [24, 87]. With its four wheels and remote-control-car-like design, *Light Everywhere* clearly presented an affordance that it could be moved, which provided the study room with the perceivable affordance that its occupants could alter the lighting to their preferences. The traditional desk lamp, however, did not convey a similar affordance, leaving the control group unaware of their action possibility to modify the lighting conditions.

This finding suggests that we may have unconsciously tolerated some negative or hindering aspects of our residential environments, especially confined ones and/or ones with lower flexibility, without recognizing it. This outcome highlights the value of movable light fixtures and other "flexible elements" in supporting diverse tasks. By enhancing a space's affordances, such elements can reduce users' unconscious tendencies to tolerate suboptimal conditions, allowing them to better utilize their environment for changing needs.

6.2 Inviting Experience-Improving Behaviors

Beyond reducing the tendency to tolerate unsatisfactory conditions, *Light Everywhere* encouraged the intervention group to engage in behaviors that improved their task experience. As Withagen et al. [2012] proposed, affordances are not only action possibilities but also “invitations” for certain behaviors [87]. Our findings suggest that the movable light fixture “invited” participants to enhance their comfort and control during the study.

Consistent with previous studies on housing flexibility [64, 65, 72], the intervention group, which experienced a higher degree of spatial flexibility, reported significantly higher levels of perceived comfort and control. One contributing factor to this positive experience was the behaviors encouraged by the prototype. Regarding perceived comfort, both groups reported discomfort with direct light exposure. Given that keeping the bright lights out of sight is crucial for visual comfort [9], physically adjusting the light source is essential to address this issue. However, while nine participants in the intervention group performed this comfort-oriented behavior, only one in the control group did the same. Moreover, the intervention group exhibited more behaviors to control the lighting directly. For instance, all 13 participants in the intervention group moved the light prototype, 11 switched the lighting modes, while only three and seven participants in the control group engaged in these behaviors, respectively.

This behavioral difference provides a possible explanation for the higher levels of comfort and control perceived by the intervention group: they engaged in more behaviors that positively impacted their experience. By "inviting" users to perform experience-improving behaviors, the movable light fixture supported them in performing diverse tasks more effectively.

6.3 Future Applications

Based on our observations and participants' suggestions, we have come to understand some particular benefits of *Light Everywhere*.

6.3.1 Its Benefits to Detail-Oriented and Hands-Occupied Tasks

As a movable, single light source, *Light Everywhere* can intuitively support detail-oriented tasks and tasks requiring both hands-free. When asked about potential applications, eight of 13 participants suggested scenarios requiring close attention to details, such as reading (P5) and finding lost objects (P13). P6 proposed its application in surgical settings where the light needs frequent repositioning for specific small areas, stating, *"I think having a remote-controlled light that a surgery assistant could automatically reposition could be very helpful."* P9 mentioned its usefulness for tasks like mechanics or plumbing, for *"anybody doing hands-on tasks and trying to see through different pieces."* P9 also shared an experience holding a flashlight for their father during repairs under a car, highlighting the benefit of a flexible lighting system for detail-oriented tasks on the floor, an uncommonly illuminated area.

As seen in the car repair example, another application is for hands-free purposes. Seven participants noted the value of movable light fixtures in scenarios where they need to switch between tasks frequently with both hands occupied. P9 mentioned its utility in the kitchen: *"I could see myself using it in the kitchen, where I sometimes focus on the oven, sometimes want to do dishes... and sometimes I am chopping something on the other side of my kitchen. I could see that for moving from different tasks around the kitchen, it would be really useful."* Similarly, in an art studio setting, where people frequently move between stations, P1 envisioned the light *"automatically following you around from task to task... instead of you having to go around and turn off individual lights and return to old tasks."* These responses suggest that *Light Everywhere* can support wide-ranging task transitions without requiring users to put down their work.

6.3.2 Its Benefits as a Companion

An unexpected application that emerged for the movable light fixture is its potential to serve as a social tool that provides companionship [11, 23]. Users often attribute human or pet-like characteristics to robots [19, 22], and this anthropomorphizing may indicate the formation of a human-robot relationship [17, 19, 38]. This phenomenon was also observed in our study, where four participants referred to *Light Everywhere* using the personal pronoun *"him,"* and two started chatting with it during the study. Additionally, in 89.13% of the instances where participants switched the lighting modes via voice commands, they looked at the prototype, even though looking at the robot was not required for giving commands, as was demonstrated to participants at the start of the study. These behaviors suggest that participants may have perceived the movable light fixture as sentient and deserving of respect.

Despite being in an isolated laboratory environment, participants reported feeling comfort due to the presence of the prototype. P3 stated it made them feel accompanied, saying, *"It was nice to have someone."* They also admitted to *"personifying"* (P1) and *"humanizing"* (P3) the light fixture because it was *"cute," "lively,"* and *"listening to me"* (P3). Consistent with previous studies demonstrating that robots can boost mood and well-being [7, 68, 69], it is reasonable to assume that *Light Everywhere*, as a companion, provided solace and reduced participants' feelings of loneliness in this one-person study. While this was an unexpected outcome of our in-person study, future work might further explore the impact of using a robotic light fixture on users' feelings of isolation.

6.3.3 Its Benefits as an Energy-Saving Artificial Light Source

Five of the 13 intervention group participants discussed *Light Everywhere*'s potential to save energy. As P12 noted, *"If we are given autonomy to control the ceiling lighting, we don't need as much lighting as we need right now. We can save energy."* Additionally, P8 mentioned that they frequently forget to turn off lights when leaving a room and suggested that our design could reduce electricity waste *"if he (the movable light fixture) travels with me."* These insights suggest that *Light Everywhere*, as a single movable light fixture, has the potential to replace multiple static light devices, thereby reducing overall energy consumption for a more sustainable home.

6.4 Potential of Autonomous Lighting

In addition to the potential applications discussed above, another developmental direction for robotic lighting is enhancing its autonomy. While the concept of a fully autonomous robot is often illusive [25], developing a smarter, semi-autonomous light fixture that requires minimal human commands is feasible. Smarter robotic light fixtures might be capable of anticipating where users need light and, accordingly, moving to that location.

The prospect of a more autonomous light fixture was considered by participants with some measure of resistance, which concurs with the larger society's hesitancy to embrace fully autonomous robots [52]. On the positive side, a more autonomous light fixture could support the potential applications more effectively. Participants suggested that it could better support detail-oriented tasks and tasks requiring two hands-free if it is *"automatically following you around from task to task."* (P1). Additionally, an autonomous robot might better assist humans in social contexts [27], and an automatically controlled lighting system could save energy by optimizing electricity use [50]. On the other side, it also raises privacy and security concerns and could conflict with our design goal of enhancing the user's sense of control. P12 opposed a fully autonomous light, stating, *"I hate the feeling I don't have control over my tools."*

However, it is noteworthy that in the online survey we conducted, as reported earlier in this paper (Table 2 and 3), 81.01% of participants selected full autonomy as their least preferred interaction approach among six options, a strong negative perception not observed in the experiment participants. P7's feedback provided a possible explanation for this discrepancy: *"Before this experiment, I never experienced so much control of the light, so I never thought I needed it, but after I experienced that, I feel this feature is really nice to have. I would say the automatically moving light is the same thing."* It is reasonable to assume that part of the opposition to an autonomous light fixture stemmed from the concept's novelty and participants' lack of actual experience using it. Therefore, before making any conclusions about the prospects of the autonomous light concept, more experiential research is needed.

CHAPTER 7

LIMITATIONS AND FUTURE WORK

Our work had several limitations. The most significant limitation was the use of an early prototype controlled via the WoZ method. Since the prototype was designed to test the robotic light concept in an in-person experiment rather than being a fully functional product, we made several compromises for prototyping: (1) the light source was an LED ring that did not provide the same level of illumination as commercial products; (2) the prototype operated on magnetic sheets, which covered only part of the study room surfaces; and (3) interactions were controlled via the WoZ method, resulting in some delays between user commands and prototype responses due to human factors. To enhance the fidelity of the next movable light prototype, we propose to integrate a commercial-quality light source and an automated interaction system. Additionally, technologically feasible options to enable the light to stably move on non-magnetic surfaces need to be explored.

Due to the constraints of the current prototype, a laboratory study design was adopted rather than a longitudinal study in participants' own homes, leading to potential threats to ecological validity and novelty effects. Although participants were instructed to perform tasks as they would at home, the absence of their familiar residential environment may have affected their behaviors and, thus, the study outcomes. Moreover, the limited one-hour exposure to the prototype in the study room likely increased the possibility of novelty effects.

While the laboratory setting minimized confounding variables and enhanced the study's reliability by offering participants a standardized and controlled environment, its limitations are acknowledged. Future research should prioritize studies in real-world settings once the prototype has been refined. Addressing the prototype limitations mentioned above will enable field studies to be conducted in natural residential environments, thereby overcoming the constraints of the current laboratory study.

Lastly, we propose conducting more user studies in diverse scenarios, such as rooms with overhead lighting, multiple light fixtures, and multiple occupants. To reduce confounding factors and maintain consistency, we designed this study to involve a simple scenario with only one occupant and two light sources: one fixed floor lamp for ambient lighting and one desk lamp or the movable light prototype for task lighting. Future studies in more varied settings will provide deeper insights into the value of a robotic light fixture in real-world applications.

CHAPTER 8

CONCLUSION

In this paper, we introduced *Light Everywhere*, a robotic light fixture designed to climb walls and ceilings, offering "flexible" lighting solutions for a small home environment. The development process involved four interrelated design activities: (1) a field study (N=15) on conventional home lighting experiences; (2) an online study (N=80) evaluating five robotic light design concepts; (3) prototype development informed by existing literature and design precedents; and (4) a between-subjects, in-person experiment (N=26) assessing the prototype's impact on human behavior in a small home setting. Our findings suggest that *Light Everywhere* enhanced users' sense of comfort and control and improved their spatial utilization by reducing their unconscious tolerance of unsatisfactory lighting conditions and promoting their behaviors that optimize lighting. This research envisions a future for robotic lighting in home environments and underscores the potential of "flexible elements" – even flexible elements like *Light Everywhere* that are not physically reconfigurable – to support diverse domestic activities. Especially with the diminishing size of living spaces and the trend of working remotely, interaction designers have the capacity to address the challenges of housing, striving to help accommodate the dynamic needs of inhabitants. *Light Everywhere* represents a design exemplar of such an interactive system that offers a new dimension to housing flexibility.

APPENDICES

- **Project Video**: https://youtu.be/CfFNZ9iiR0E

Appendix A: Interview Questions of the Field Study

1. What lighting are you using here/for this task?
    a. Location: Where? With what? What's the surrounding?
    b. Area: How high? How far/close to what?
    c. Light Fixture: Size, Shape, Brightness, Color, Price
2. Please show me how you use them here/to finish this task.
    a. How do you use the light?
        i. How do you interact with it?
        ii. How do you turn on, turn off, and adjust the lighting mode?
        iii. How do you control it?
    b. How do you finish this task?
3. Why did you place the light here/use the light for this task?
4. Did you select this light by yourself? Why?
    a. If yes, what did you consider when purchasing it?
        i. Was it bought for this place/task?
        ii. What criteria did you take into account? (e.g., size, shape, brightness, color, price)
    b. If not, how did you get it?
5. Did you encounter any challenges using it?
    a. What concerns you? Why?
6. What do you think lighting for this place/task should do and support?
    a. Why?
    b. What kind of light would make you think “comfortable” and “convenient”?
7. What light would be if you could buy/design a new light for this place/task?
    a. Why? How does it differ from the current light?

Appendix B: Online Survey

Part 1. Background

1. What is your age range?
    a. 18-24
    b. 25-34
    c. 35-44
    d. 45-54
    e. 55-65
    f. 65+
2. How do you identify your gender?
    a. Female
    b. Male
    c. Non-binary / third gender
    d. Prefer not to say
3. How satisfied are you with the lighting conditions in your current living space?
    a. Very satisfied
    b. Somewhat satisfied
    c. Neither satisfied nor dissatisfied
    d. Somewhat dissatisfied
    e. Very dissatisfied

Part 2. User Scenario

Imagine your boss informs you that your work is being moved to a "hybrid" format, meaning **you will work from your studio apartment 4 days a week** on your dining room table. When not working, you spend much time cooking, reading, and watching TV in the studio.

Below, you are presented with **five interactive home-lighting systems that aim to support various domestic activities**. Please view these lighting systems' design concepts and movies, and answer questions about them.

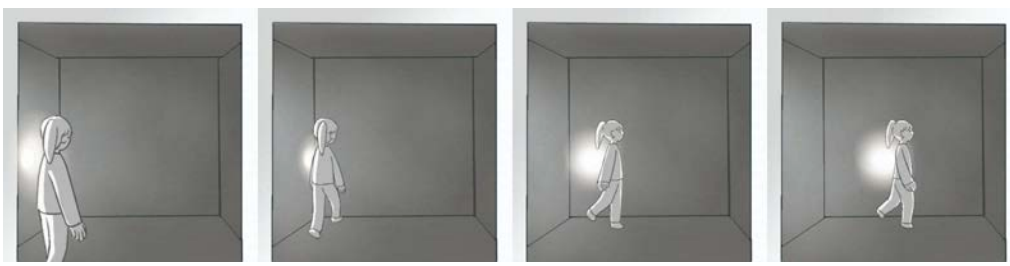
What is the sum of 6 and 25? Please enter your response below so we know you are paying attention: ________________

Part 3. Prototypes

1. **“Smart Light”**

   “Smart Light” modules move on the wall as you move around your living space, providing you lighting (color and brightness) where you most likely need it. You can tap a module to make it stay where it is. When a light module is no longer needed, you may triple-tap it to turn off and send it away.

- Selected images of the displayed GIF:

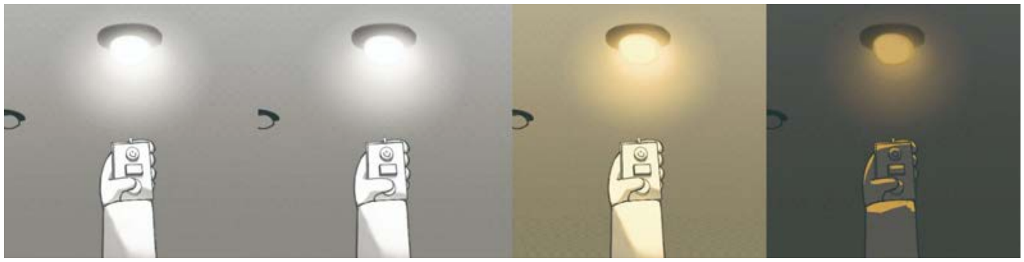


- Link to the embedded video: https://youtu.be/UXCjzFzTqrw

2. **“Remote-Control Light”**

   “Remote-Control Light” has multiple moving lighting fixtures connected to the ceiling. When light is needed, you use a remote to point at a light-module and "drag" it (like a computer mouse moving a file) to a desired position. You can change the color and brightness of the light with the remote. When the light is not needed, you turn it off with the remote.

- Selected images of the two displayed GIFs:

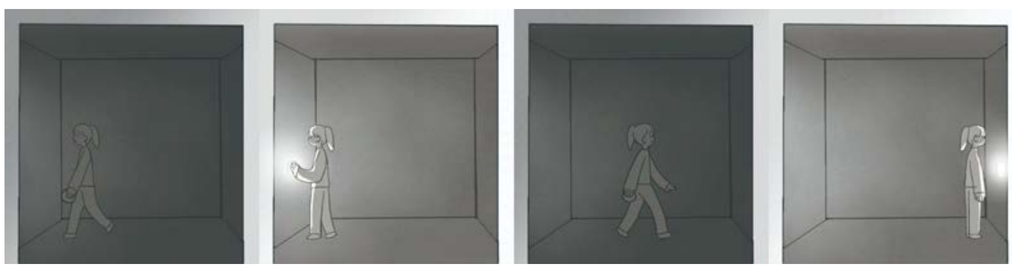


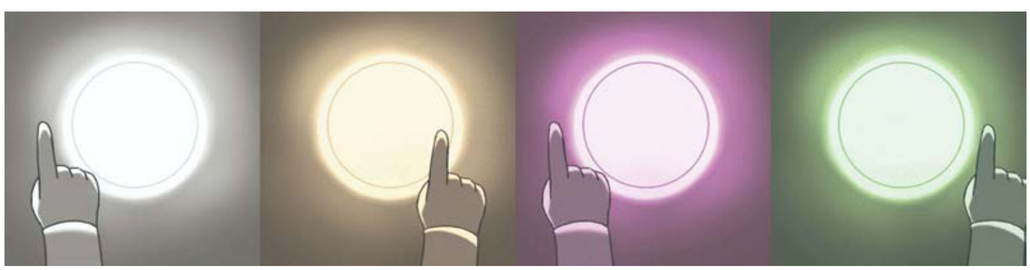
- Link to the embedded video: https://youtu.be/vAw6A9cS4N0

3. **“Move-Your-Light”**

   “Move-Your-Light” is a set of lighting modules of various shapes and sizes. You can pick up and attach a module to one of the ports on the wall where you need it. You can swipe the module's surface to adjust its settings (color and brightness). To turn off the light without moving its location, you rotate it 180 degrees.

- Selected images of the two displayed GIFs:



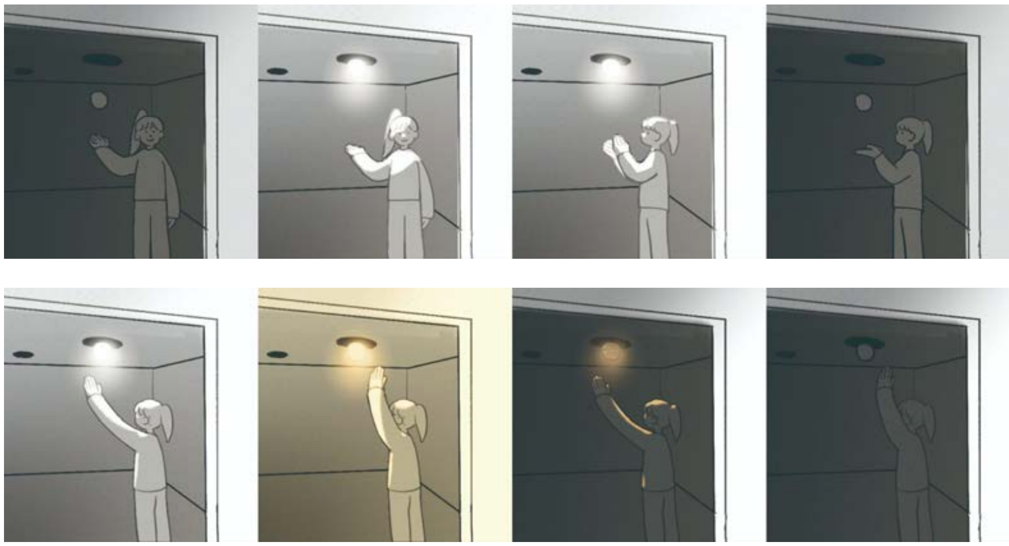


- Link to the embedded video: https://youtu.be/A6B-s4NQuvk

4. **“Throw-a-Light”**

   “Throw-a-light” is a lighting system that consists of sphere-shaped “light balls.” You throw a “light ball” towards one of the metal discs on the ceiling to provide lighting below that location. Each light ball offers a programmed color and brightness. If you want a different color or brightness, you can make a gesture with your arm towards the light to change the setting. If you clap, the light will turn off and drop from the ceiling for you to collect it.

- Selected images of the two displayed GIFs:

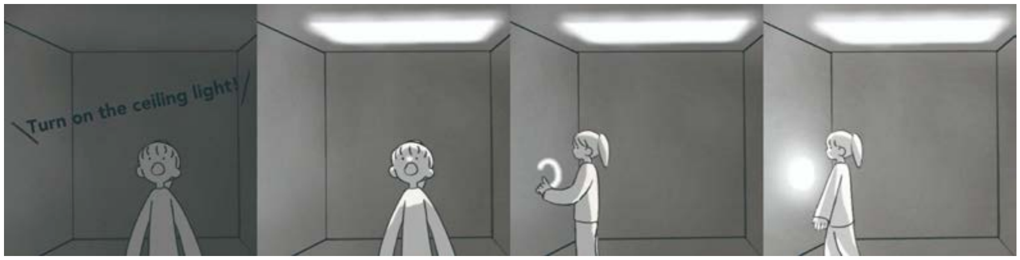


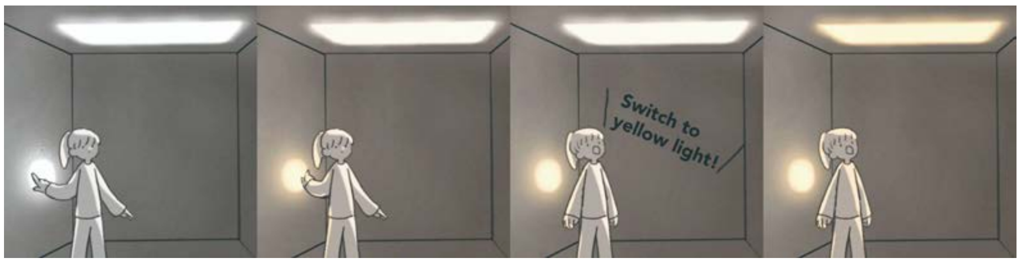
- Link to the embedded video: https://youtu.be/9j4Frol6OaY

5. "Wall-Light"

"Wall-Light" is a lighting system where the walls themselves are lights. Using your finger, you "draw" a circle on the wall to "create" a light in that position. If you want to change this light's settings (color and brightness), you can use your finger and swipe on the wall. If you want to create a light on the ceiling, you can say, "Create a light in the corner near the large window." You can adjust the light by telling it "More-bright" or "Turn light-blue," or create a mood by telling it to "Turn dreamy."

- Selected images of the two displayed GIFs:





- Link to the embedded video: https://youtu.be/HvaFXKD11FE

[Each design concept is followed by the same questions section, as below.]

For each of the following statements, please select the number that represents how you feel about "(name of the design concept)". (Strongly Disagree 1 – Strongly Agree 5)

1. I understand how it works on a basic level.
2. It will help make routine tasks easier to perform.
3. I could envision it in my living space.
4. It will make daily chores fun.
5. It will be easy to have it move to where I want.
6. It will be easy to adjust its color and brightness.
7. I believe it will be more helpful than my living space's current lighting system.
8. I'll be worried about its safety issues if it is in my living space.

Part 4. General Questions

Now, you understand the concept of our five designs, please answer the last two questions:

1. If you want to **move a light module**, how would you like to do this? Please drag to re-order your preferences. (1 for your "most favorite," and 7 for your "least favorite")
    a. __ Move it myself.
    b. __ Throw it where I want it positioned.
    c. __ Voice command it to move.
    d. __ Gesture to create a light where I want it.
    e. __ Move it by using an iPad app.
    f. __ Remote control it.
    g. __ Let it move by itself.
2. If you want to **change the light brightness and color** (i.e., "the mood"), how would you like to do this? Please drag to re-order your preferences. (1 for your "most favorite," and 7 for your "least favorite")
    a. __ Voice command it.
    b. __ Gesture it.
    c. __ Swipe on it.
    d. __ Change its mood by using an iPad app.
    e. __ Remote control it.
    f. __ Let it change its mood when it decides I want it.

Appendix C: Experimental Protocols

A. Preparation Before the Study (for Internal Check)

1. On our side
    a. Consent form
    b. Post-questionnaire
    c. Incentive sheet
    d. Incentive of $5
2. Consumables in the space
    a. Printed task instructions
    b. Printed article and questions (Task 1)
    c. Snack & drink (Task 3)
3. Equipment in the space
    a. **[For the Intervention Group]** Prototype & wand
    b. **[For the Control Group]** Desk lamp
    c. Floor lamp
    d. Laptop
    e. Projector
    f. LEGO Kit (Classic 10713)
    g. Pen
4. Laptop is ON
    a. Two tabs in the browser: movie & flight selection doc
    b. Movie: The Present by Filmakademie Baden-Württemberg (https://www.youtube.com/watch?v=3XA0bB79oGc)
    c. The doc should be empty.
5. Projector setting is correct
    a. Test it by following the projector instructions to turn it on
6. Light setting is correct
    a. OFF: ceiling light
    b. ON: floor lamp (dim), prototype/desk lamp (white)
7. Camera is ON

B. Before the Study

- Meet the participant at HEB 212.
- The ceiling light in HEB 212 is ON.

1. **Introduction**

   "Thank you for participating in our study! In this experiment, please complete five tasks on this task card (**show them the task instructions*) in this space (**lead them to the study room*). Please finish them in the order that follows your recollection of how you recently did these kinds of tasks at home. During the session, please feel free to move anything or do whatever you want in this space. We will be outside, so the space is all yours, but please do not hesitate to ask for help if needed.

   Also, for analysis purposes, we will video record the whole study here. We will make sure the data is only accessible to the research team. Would it be okay for you?

   Do you have any questions or concerns?

   If it sounds good (**lead them out of the study room*), please review this consent form and sign it at the end. Thank you!"

2. **Demonstration**

   - Tell the participant that they can leave their stuff outside.
   - Lead the participant to the study room.
   - The prototype should be attached to the wall and lit up white.

   "Before we start, I'd like to show you the light we'll use for this study."

   [For the Intervention Group] "This is a movable light (**point to prototype*) that can move across the white area (**point to the area*), both the walls and the ceiling. The way to move it is to use this wand (**raise the wand*). When you press the button and point it somewhere (**press the button and point it on the wall*), the light module will move to that position (**WoZ*). While it can move on the walls and ceiling, it cannot traverse the corners. So, if you'd like to move it across the surfaces, please feel free to take it and attach it to another side (*take it from one wall and attach it to another*). Also, the module has three lighting modes that you may switch to. You may change it by saying "Yellow," "Dim," or "White." (**WoZ*). Do you want to try it (*give the wand to them*)?"

[For the Control Group] "This desk lamp has three lighting modes. You may press the button to switch (*press the buttons*)."

"Do you have any questions or concerns?"

3. **Study Begins**

   "One last thing: since our study is about light, please do not use the flashlight on your smartphone during the session. Besides that, you may use or move anything you want in this space.
   I'm gonna leave this space and start video recording. You may begin the tasks whenever you feel comfortable. Please let us know if you need anything and when you complete all the tasks. Thank you!"

C. During the Study

1. **Research Team**
   - Main researcher: support the participants & take notes
   - Facilitator: WoZ
2. **Note-taking**
   - The order of tasks
   - Anything special (for interview)
3. **WoZ**
   - Control the prototype using the tablet by observing participants
   - Wand Control: move to the designated position
   - Voice Control: switch to the designated mode

D. After the Study

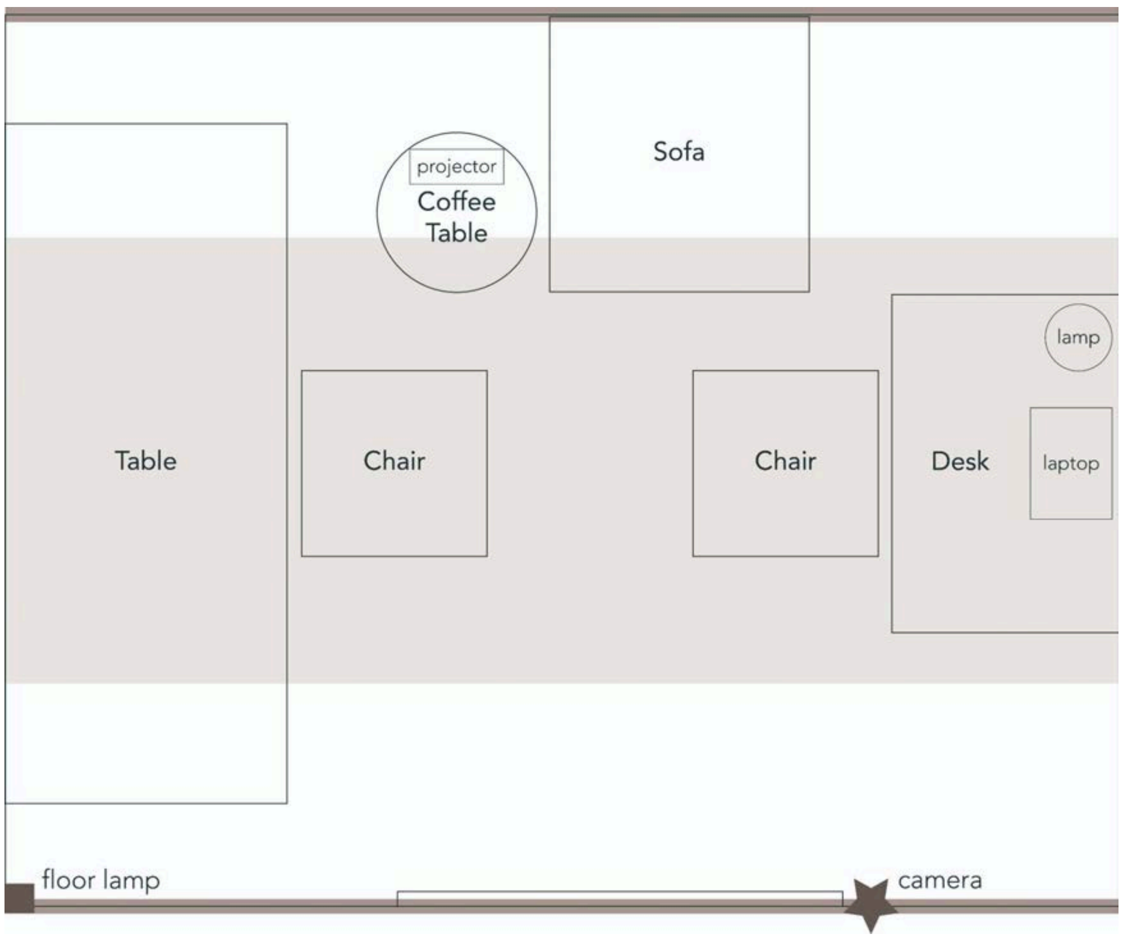
- After the participant claims they've finished all the tasks, lead them out of the study room.
    1. Conduct the interview
        a. Start audio recording with a smartphone
    2. Fill out the post-questionnaire
    3. Give them the $5 cash incentive
        a. Ask the participant to sign the incentive sheet

E. Check After the Study (for Internal Check)

1. Save video & audio recordings
2. Turn off camera
3. Take photos of the built LEGO cabin & the used study room
4. Label and put all the digital files in one folder
    a. Video recording of the study
    b. Audio recording of the interview
    c. The flight selection doc (downloaded as PDF)
    d. The photos of the LEGO cabin
    e. The photos of the study room
5. Label and put all the physical documents in one folder
    a. Incentive sheet
    b. Consent form
    c. Post-questionnaire
    d. Answer sheet of Task 1
6. Re-set up the whole space
7. Charge the prototype
    a. Power bank for LED ring
    b. 5V batteries for Arduino

Appendix D: Experimental Floor Plan

- The study room is 8 feet in length, 10 feet in width, and 8 feet in height.
- Gray areas indicate the parts covered by the magnetic sheets.
- Only the control group had the desk lamp. For the intervention group, the prototype was initially attached to the wall adjacent to the desk and positioned to closely replicate the placement of the desk lamp for the control group.



Appendix E: Consent Form

Study of Lighting in Small Space

We ask you to participate in our survey, "Study of Lighting in Small Space." This study is led by Hsin-Ming Chao, Department of Human-Centered Design at Cornell University. The Faculty Advisor for this study is Dr. Keith Evan Green of the same department.

What the study is about

The purpose of this research is to investigate the impact of lighting on domestic activities in a constrained space. This study aims to contribute to lighting solutions in residential settings and to enhance user experience with their living spaces.

What we will ask you to do

You will be asked to perform six designated tasks in an eight by ten space and then to fill out a questionnaire based on your experience doing them. We will observe and record the session and interview you with a short survey at the end. The whole session will be about 30 minutes in duration.

Risks and discomforts

We do not anticipate any risks or discomforts from participating in this research.

Benefits

We do not anticipate any direct benefits from participating in this research.

Incentives for participation

You will get $5 cash after finishing the study.

Audio/Video/Photographic Recording

With your consent, an audio/video/photographic device will be used in this experiment. Recording the activities may help us collect useful information from the participants. Photographs may also be taken to document the research process. We ask you to grant us the right to make use of and publish these recordings in whole or in part in academic conference presentations, academic conferences, or journal papers only for academic purposes. This includes the right to edit or duplicate any recordings. These recording files will not be used for any commercial purposes. Participants do not have the right to inspect or approve the finished product or published matter that uses the recordings. Participants will not receive financial compensation for non-commercial uses of the recordings.

Privacy/Confidentiality/Data Security

The data collected in the study, including the identifying information, if any, will be documented on the researcher's hard drive. Your confidentiality will be kept to the degree permitted by the technology being used.

Taking part is voluntary

Your involvement is voluntary, and you may refuse to participate before the study begins or discontinue at any time during the study. There's no penalty or effect on your current standing, record, or relationship with the university or other organization or service that may be involved with the research.

If you have questions

If you have questions, you may contact Ming at hc766@cornell.edu. If you have any questions or concerns regarding your rights as a subject in this study, you may contact the Institutional Review Board (IRB) for Human Participants at 607-255-6182 or access their website at http://www.irb.cornell.edu. You may also report your concerns or complaints anonymously through Ethicspoint online at www.hotline.cornell.edu or by calling toll-free at 1-866-293-3077. Ethicspoint is an independent organization that serves as a liaison between the university and the person bringing the complaint so that anonymity can be ensured.

Statement of Consent

Please check the box and sign below if you would like to participate in the survey.

▢ I have read the above information and have received answers to any questions I asked. I consent to participate in the survey.

Your Signature__________________________________ Date___________________

Appendix F: Task Instructions

Here are six tasks we'd like you to do. Please do them in the order that follows your recollection of **how you did these kinds of tasks recently at home**.

- ▢ **Place and pack all T-shirts into a carry-on in the designated order.**
  - *The carry-on is under the table. The code for its lock is 1021.*
  - *The order for the four T-shirts is: Black > Gray > Red > White*
- ▢ **Read a short text and answer two questions about it.**
  - *The printed text and questions are on the desk.*
- ▢ **Watch a short animated movie named "The Present" using a projector.**
  - *The video is opened in the browser on the laptop. You may also find it on YouTube.*
  - *Please follow the instructions on the projector to turn it on.*
- ▢ **Eat a snack and sip a drink**
  - *The snack and the drink are on the table.*
- ▢ **Select a flight based on the information on the laptop**
  - *Please follow the instructions and enter the flight information on the Google Doc opened on the laptop.*
  - *If the Google Doc is closed, you may find a Word document on the desktop.*
- ▢ **Design a small cabin for your weekend excursion with LEGO**
  - *The LEGO kit is on the table. You may also use anything you find to build the cabin.*

Appendix G: Interview Questions

A. For the Intervention Group

1. **Optional: Special Behavior (if applicable)**
    a. I noticed that you __(description of the user's behavior)__, could you tell me why you did that? What were you thinking at that time?
2. **Basic**
    a. How do you feel about this light module? Why?
        i. How about the way you interacted with it? What do you think about the interaction?
        ii. How comfortable were you using/moving the light module?
    b. Please describe your understanding of how this light module works.
        i. Do you have any confusion or concerns about it?
        ii. What improvements or changes would you make to this light? Why?
    c. How do you feel about being with a movable light in a room?
3. **Use Case**
    a. Will you consider using this light at home? Why/Why not?
        i. When? Under what circumstances? For what tasks?
        ii. Do you face any challenges with your current lighting system?
        iii. Compared to your current lighting system, do you think this light module is more or less helpful? Why?
    b. Are there any other purposes you can think of for this light?
        i. Like other scenarios or contexts?
4. **Closing**
    a. Does this light give you more control over this space? Why?
    b. Do you have any final comments/thoughts you would like to mention about this study?

B. For the Control Group

1. **Optional: Special Behavior (if applicable)**
    a. I noticed that you __(description of the user's behavior)__, could you tell me why you did that? What were you thinking at that time?
2. **Basic**
    a. How do you feel about the lighting condition in that space? Why?
3. **Current Lighting System**
    a. In your current living space, what type of lights do you use?
        i. What are they for?
    b. Do you face any challenges with your current lighting system?
4. **Closing**
    a. Do you have any final comments/thoughts you would like to mention about this study?

Appendix H: Post-Questionnaire

1. What is your age? _______________
2. How do you identify your gender?
    a. Female
    b. Non-binary
    c. Male
    d. Prefer not to say
3. How satisfied are you with the lighting conditions in your current living space?
    a. Very satisfied
    b. Somewhat satisfied
    c. Neither satisfied nor dissatisfied
    d. Somewhat dissatisfied
    e. Very dissatisfied
4. Which of the following devices do you own?
    a. An Amazon Alexa or similar AI device
    b. A robot vacuum cleaner (like a Roomba or similar)
    c. I own both of them
    d. None of the above

Part 1.

On a scale of 1 to 7, how would you describe **the indoor conditions in the experimental environment** during the study?

a. Light Overall	1 Unsatisfactory	2	3	4	5	6	7 Satisfactory
b. Artificial Light	1 Unsatisfactory	2	3	4	5	6	7 Satisfactory
c. Reflection or Glare	1 Glare	2	3	4	5	6	7 No Glare

Part 2.

On a scale of 1 to 5, please answer the following questions based on **how you have completed the six tasks** just now.

a. How much does the light module help you move through the tasks?	1 Not at all	2	3	4	5 Extremely
b. How much does the light module make you feel you have control over the space?	1 Not at all	2	3	4	5 Extremely
c. How much does the light module make you feel confident about performing the tasks?	1 Not at all	2	3	4	5 Extremely

Part 3.

For each of the following statements, on a scale of 1 to 5, please indicate the extent **you have felt this way with the light module** during the study.

a. I think that I would like to use this system frequently.	1 Strongly Disagree	2	3	4	5 Strongly Agree
b. I found the system unnecessarily complex.	1 Strongly Disagree	2	3	4	5 Strongly Agree
c. I thought the system was easy to use.	1 Strongly Disagree	2	3	4	5 Strongly Agree
d. I think that I would need the support of a technical person to be able to use this system.	1 Strongly Disagree	2	3	4	5 Strongly Agree
e. I found the various functions in this system were well integrated.	1 Strongly Disagree	2	3	4	5 Strongly Agree
f. I thought there was too much inconsistency in this system.	1 Strongly Disagree	2	3	4	5 Strongly Agree
g. I would imagine that most people would learn to use this system very quickly.	1 Strongly Disagree	2	3	4	5 Strongly Agree
h. I found the system very cumbersome to use.	1 Strongly Disagree	2	3	4	5 Strongly Agree
i. I felt very confident using the system.	1 Strongly Disagree	2	3	4	5 Strongly Agree
j. I needed to learn a lot of things before I could get going with this system.	1 Strongly Disagree	2	3	4	5 Strongly Agree

Appendix I: Video Coding Protocols

Part 1. Event

For the 12 events below, record 1) the time when the event occurs and 2) the relevant context.

1. Shared

Event	Definition
Switch lighting mode	● The participant switches the lighting mode of the light module (i.e., the prototype or the desk lamp) from A to B. ● If they switch the mode several times in a row (e.g., from A to C to D to B) in a short time, count it as once. ● It doesn't count if they switch between modes but end up back in the initial mode. ● Record both modes, A as the initial and B as the switched.
Test lighting mode	● The participant switches the lighting modes more than once in a row but returns to the initial mode at the end (e.g., from A to B to A.)
Move task	● The participant moves the materials and/or equipment required for one task (e.g., the printed text and pen for Task A, the LEGO kit for Task C) from the initial position at the start of the study to another side of the space. ● Minor movements on the same side of the space (e.g., moving the LEGO on the table) don't count. ● Record the moved task, the initial side, and the new side of the room.

2. For the Intervention Group

Event	Definition
Look at it with voice commands	● The participant looks at the prototype while giving voice commands to change its lighting mode. ● Both "switch mode" and "test mode" count as "change mode" in this event.

Talk to it	● The participant talks to the prototype. ● Record the context and what they say.
Move it closer	● The participant moves the prototype closer to them using the remote. ● Record the surface where the prototype moves on and the task the participant does when moving the prototype.
Move it away	● The participant moves the prototype away from them using the remote. ● Record the surface where the prototype moves on and the task the participant does when moving the prototype.
Manually move it on surface	● The participant manually moves the prototype on the same surface. ● Movements across surfaces don't count. ● Record the surface where the prototype moves on and the task the participant does when moving the prototype.
Manually move it across surfaces	● The participant manually moves the prototype from surface A to B. The surfaces are labeled as three: the wall by table, the wall by desk, and the ceiling. ● Manual movements on the same surface don't count. ● Record both surfaces, A as the initial and B as the new, and the task the participant does when moving the prototype.

3. For the Control Group

Event	Definition
Move it on desk	● The participant moves the desk lamp on the desk. ● Record the task the participant does when moving the lamp.
Move it to another side	● The participant moves the desk lamp anywhere other than the desk. ● Record the lamp's new position and the task the participant does when moving the prototype.
Adjust its angel	● The participant adjusts the direction of the light by rotating the desk lamp or changing its flexible gooseneck.

Part 2. State

For the seven states below, record 1) the start time of the state, 2) the end time of the state, and 3) the relevant context.

1. **Shared**

Event	Definition
By desk	● The participant stays by the desk, including sitting in the chair and standing/walking by the desk.
By table	● The participant stays by the table, including sitting in the chair and standing/walking by the table.
On sofa	● The participant stays on the sofa.
In center	● The participant stays in the central area, which is not included in "by desk" or "by table" or "on sofa."
Projector on	● The projector remains on after the participant watches the movie for Task D. ● It doesn't count if the projector is on when the participant is watching the movie. ● Record the tasks the participant does when the projector remains on.

2. **For the Intervention Group**

Event	Definition
Light on ceiling	● The prototype is attached to the ceiling. ● Record the tasks the participant does when the prototype remains on the ceiling.
Portable light	● The participant carries the prototype with them, not attaching it to any surfaces. ● Record the tasks the participant does when they carry the prototype.

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