# Evaluation of User Interaction with Daylighting Simulation in a Tangible User Interface

*Joshua Nasman* and *Barbara Cutler*
Department of Computer Science
Rensselaer Polytechnic Institute
nasmaj@cs.rpi.edu cutler@cs.rpi.edu
To appear in: *Automation In Construction*

**Abstract**

We present a study of a tangible user interface for design and simulation applied to architectural daylighting analysis. This tool provides an intuitive way for architects and future occupants of a building to quickly construct physical models and interactively view in them a projected simulation of resulting daylighting. A user study was conducted of both architecture students and non-architects in a set of analysis and design exercises. The study investigates the effectiveness of this interface as an educational tool, the precision and accuracy of the constructed physical models, and the overall effectiveness of the tangible interface for creative design exploration. The four part study investigates users' intuitions about daylighting and their interaction with the tangible user interface for analysis of an existing space, for proposing renovations to that space, and for designing a new environment. These exercises revealed and corrected misconceptions in many of the participants' intuitions about daylighting, and overall the participants praised the ease-of-use of the tool and expressed interest in this simulation tool for daylighting analysis in architectural design.

## 1. INTRODUCTION

Effective architectural design for daylighting places windows and reflective surfaces to use natural light from the sun and sky for functional and beautiful interior space illumination. Increased use of daylighting reduces the need for supplemental electric lighting during the day; however, the distribution of daylighting within a building for a particular moment can be difficult for non-experts to accurately and quantitatively predict (Figure 1). Detailed simulations require quality 3D models and are computationally expensive. When designing an office space, the typical daylighting goal is to maximize the *daylight autonomy*, the number of hours per day that the work surfaces receive adequate lighting for reading[1]. Too much sunlight is also problematic creating the possibility of *glare*, reduced visibility for occupants of the space due to high contrast in light intensity within the visual field. The tight integration of daylighting and architectural form split late in the twentieth century [2]. Up to that point, maximizing total window area was a major goal in design. To ensure all areas in the building

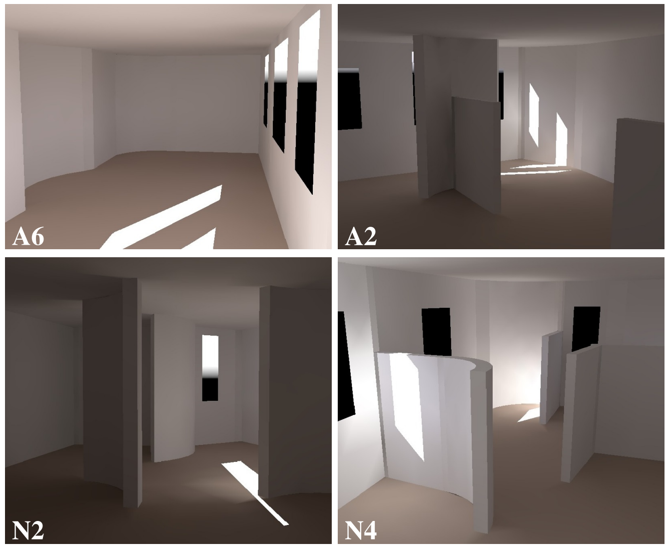



Figure 1: A sampling of the designs created by participants using a tangible interface. Each model is shown lit by the sun and skylight on March 21st at 8:30am.

had sufficient access to daylighting, most buildings were less than 60' (18 meters) wide. With the increased availability of cheap artificial lighting, daylighting became more of an afterthought in architecture. Recent concerns about energy consumption and a new emphasis on aesthetic choices have re-invigorated interest in daylighting analysis.

This paper evaluates the accuracy and creativity of tangible interfaces with application to architectural design and daylighting simulation. This interface uses Spatially Augmented Reality (SAR). SAR was first introduced by *Shader Lamps* and is leveraged as a way to project information onto existing surfaces in the real world [3, 4, 5, 6] (Figure 2). The tangible daylighting interface is intended for use in the earliest stages of architectural design: when the orientation of the building on the site, the relative positions of rooms within the building, the proportions of the rooms, and the placement and shape of windows is not yet determined. Existing commercial software for daylighting simulation focuses on more polished and complete designs. It can take significant time (from minutes to hours) for the designer to construct a digital model that both captures the current design and is suitable for accurate and efficient simulation. The tangible interface takes just seconds to build or edit a model and thus is appropriate for rough sketching and brainstorming with quick, projected visualization for evaluation of building performance. Our tool is useful for a wide audience; not only will it be useful for architecture students and professional architects, but also for interior designers and future occupants working on tasks such as furniture placement.

The common themes of education, accuracy, design, and creativity motivated our study of this architectural daylighting system. Our goal was to explore the effectiveness of the tool to model specific spaces and quantitatively assess users' ability to evaluate the dynamic variations in illumination. Educational tools must take into account the target audience, their background knowledge, and common misconceptions of typical

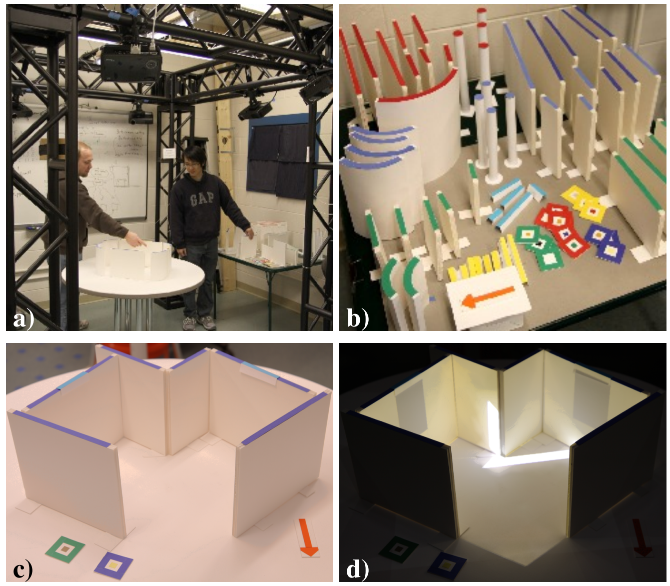



Figure 2: Our new TUI for architectural daylighting design allows multiple users to a) gather around a physical sketching environment and select from b) a set of wall primitives and window and material markers to c) build a rough sketch of an architectural design. A d) visualization of a daylighting simulation is projected onto these surfaces.

users for a tool to be most effective.

The accuracy of a simulation using a tangible design tool is dependent upon three factors: the precision of the tangible construction, the attention to detail of the user (recognition and inclusion of geometric details that affect light in the space such as interior partition walls), and the users interpretation of the displayed results (both the accuracy of the visualization and the users' ability to understand this display). Finally, it is imperative for an effective daylighting design tool to encourage architects to creatively solve problems. This tool should both allow users to quickly construct and edit unique designs. The contributions of our tool attempt to address each of these needs.

The contributions of our paper include:

- Exploration of participants' fundamental understanding of daylighting design, overillumination, underillumination, and glare.
- Quantitative analysis of the users' accuracy in using our physical sketching system to model a room they had just visited.
- Evaluation of the participants' use of our tool and their perception of quantitative and qualitative daylighting from the simulation visualizations.
- Demonstration of our tangible interface as a creativity-enhancing tool for architectural daylighting design.

## 2. RELATED WORK IN TANGIBLE USER INTERFACES

The unique interactions of Tangible User Interfaces (TUIs) make them exciting candidates for innovative educational practice. Furthermore, since TUIs feature lists include point and click interactions, layout design, and simulation, the accuracy of both the user's input and the user's perception of the output must be evaluated. We will explore TUIs in the areas of education, accuracy, design and creativity.

### *2.1. TUIs for Education and Information Exploration*

TUIs inspire innovation in teaching and learning through physical interaction with data. Ishii and Ullmer presented an interface of *phicons* (physical icons) to navigate campus information on multiple display surfaces They combined a back-projected display and an LCD screen to create the *activeLENS*, which allows users to view an overview map and 3D information [7]. Yee created a hybrid interface for a workspace with a large passive display and a smaller handheld display with stylus input [8] to effectively utilize both hands for data manipulation: one to hold and guide the lens and one for stylus input. Maekawa extended ActiveLENS to re-configurable physical blocks and mapped the current 3D configuration to a database of known shapes and virtual objects [9]. Jacob et al. developed the first system to directly project onto movable, tangible controls called *pucks* for data manipulation [10]. Spindler developed PaperLens [11], a TUI using a tangible 2D display to show a viewport into a 3D model. Similarly, Song presents a tangible interface with a touch screen for displaying select planes of 3D data based on its orientation relative to a large 2D display [12]. As illustrated by these TUIs and others, displays allowing physical manipulation provide unique opportunities to visualize, organize, and understand data.

### *2.2. Accuracy and Usability of TUIs*

The usefulness of TUIs is directly correlated to the correct and complete recognition of user input and, likewise, the user's ease and accuracy in interpreting the displayed output. The *Digital Desk* [13] used a projector and camera to create a hybrid desk surface-computer desktop interface. Data was manipulated and collected by writing on and interacting with information on the table surface and the desk enabled remote users to work on the same virtual surface by projecting the collaborator's input onto the surface. The "Bricks" system [14] is an example of a *graspable interface*, which utilizes multiple graspable controls in tandem to select or expand information. To ensure the usefulness and precision of the application, TUIs must accurately and precisely detect the user's actions. In addition to accurately responding to interactions, usability is a prime concern. A user study on the map viewing tool, "Like Bees around the Hive" [15], found that users enjoyed the interface, but were less adept at performing a specific task when compared to a traditional digital map interface. Even though the data displayed was accurate, the interface was not effective because of usability concerns.

### 2.3. *TUIs for Creativity and Design*

As the field of TUIs evolves, the variety of its applications for design has grown. Lucchi et al. compared tangible interaction and touch interaction for design [16] and found that the TUI allowed users to perform tasks more quickly. This comparison assumed fully functional interfaces for both systems and not simply the least common denominator. Mechanix is a tool that teaches children about simple machines and the interaction of objects [17]. The *URban Planning* system (URP) [18] provided a tangible "luminous workbench" interface for urban planning with visualizations of the buildings casting shadows and reflecting sunlight. Sheng et al. present a related SAR system for dynamic visualization of sunlight within interior spaces [4]. TUIs are designed to be both informative and encourage creativity. The JUMP tool [19] uses a variety of tokens to rectify multiple architectural documents (e.g., electrical and mechanical) for a construction project within a single interface. A study of this tool revealed that some users found the new design environment to be foreign and preferred a more traditional method of interaction (mouse and keyboard). While TUIs as design tools are an exciting prospect, it is important to ensure that users feel comfortable using the new tangible interface and similar or better efficiencies can be achieve when compared to traditional interfaces.

### 2.4. *A Tangible User Interface for Architectural Design*

This study evaluates the the architectural daylighting TUI first presented by Sheng et al. [4]. This daylighting analysis system simulates complex inter-reflection of natural light within a scene and uses a series of projectors surrounding the table to "paint" the physical primitives with the simulation results. Designing in the tangible SAR system is done by sketching with physical *wall primitives* that are detected by an overhead camera and interpreted to create a closed space. These wall primitives are provided in three different heights each with a different color on the top as seen in Figure 2. The overall orientation of the sketch is specified with a *north arrow primitive* and windows in the model are positioned by slipping folded cardboard *window primitives* over the top edge of the walls. Examples of these designs are shown in Figures 5, 7, and 11 and the supplementary video. This system was also extended to use movable full size wall configurations [6]. A calibrated overhead camera captures the current arrangement of the physical elements. Because the color of the wall indicates its height, the complete geometry can be inferred by a single overhead photo. This model is converted into a closed triangle mesh using an algorithm [20]. A radiosity shadow volume hybrid rendering method [21] is used to simulate light propagation within the space and the rendering system displays the simulated natural lighting on the physical model using multiple projectors positioned in a circle above the table. The system provides two different daylighting visualization modes: a static time and a dynamic time-lapse animation for a whole day. The lighting simulation can be done for any day of the year.

## 3. USER STUDY DESIGN AND METHODOLOGY

### *3.1. Goals*

This study was designed to gain a stronger understanding of the target audience for our TUI for architectural design, the effectiveness of our tool, and needed improvements and ideas for new features.

Our first goal was to investigate the potential of the system for use as an educational tool. We hypothesized that using our tool in combination with existing intuition about daylighting to provide a quick and seamless experience that enabled users to quickly evaluate, renovate and design architectural spaces. We expected users to have the basic intuition that there are more hours of sunlight in the summer and the sun follows a general east to west trajectory. Furthermore, we expected that some participants would understand that the sun was higher in the sky at noon in the summer than the winter and to recognize this affects the depth of sunlight penetration into the building. Thus, we hypothesized our tool would be most useful for identifying and correcting misconceptions on the specific areas of overillumination, underillumination, and glare. We defined overillumination and underillumination as too bright and too dark to comfortably work in an office environment (20 to 50 foot candles according to OSHA [22]).

Our second goal was to study the accuracy of users and their perceptions. The accuracy of users in recreating a space they have visited and studied is paramount to using our system. We expected that given the opportunity to sketch a room and make notes of it, users would reproduce a room with sufficient accuracy to successfully identify issues in the room even if the sunspots on the floor were slightly mis-positioned. We also needed to know how thorough users were at noticing details in the room. This includes interior walls and the location of windows. We believed the users would be more likely to make these close observations because they were instructed to draw a detailed sketch. Finally, we wanted to study how effectively users could perceive over- and under-illumination in the space using our system. We hypothesized that users would be able to identify these fairly well because they could use relative brightness for different simulation days and times to form a basis for their comparison.

Our last goal was to see if users' creativity was encouraged using the tool. In order to be useful, the range of designs allowed must be broad and the tool much allow users to express their creativity. While there are a limited number of primitives available (Figure 2), we believed that users would find creative ways to use these primitives and find interesting daylighting solutions.

### *3.2. Study Design*

The TUI for daylighting analysis and design is targeted to professional architects, architecture students, and may be beneficial for clients and other design fields as well. Because our tool does not require much training to use, it is a valuable general educational tool for daylighting. To test this hypothesis, a pool of thirteen university students were recruited. Six of the users were architecture students (labeled A1-A6), all with at least two years of formal architecture education and seven students from other departments (labeled N1-N7), but many with a background in electronic media, arts, and communication (5 students) or games studies (1 student).

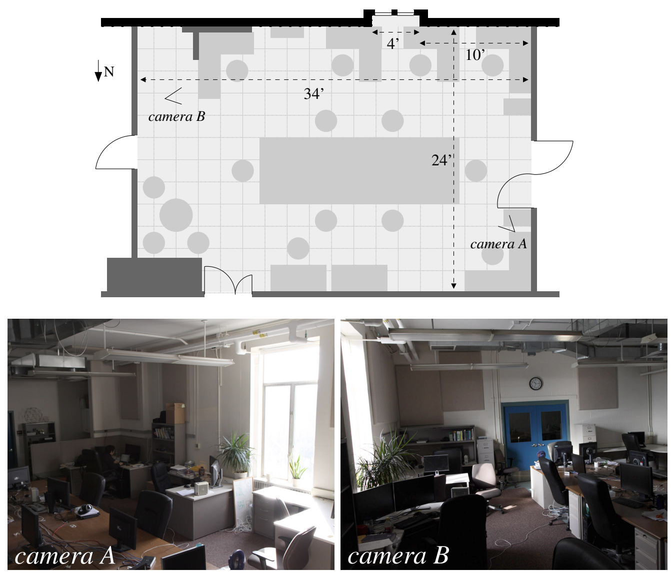



Figure 3: User study participants visited this simple open office environment as a case study for daylighting analysis. The room contains a single, tall and narrow, south-facing window that provides direct overly-intense illumination to portions of the room while leaving other areas relatively dark. Thus, occupants of the space typically turn on the overhead lights, and on sunny afternoons a diffusing shade is needed to prevent glare.

Our study was divided into four consecutive tasks. The first task was designed to prime the user for thinking about daylighting and gauge the user’s pre-existing intuitions. The other three tasks had the participant work with the TUI daylighting simulation system. Thus, prior to the second task, a brief, 5-minute introduction to the system was provided. The second, third, and fourth tasks of the study were designed in the spirit of a *cognitive walkthrough*, but with guidance on tool use available during the study and a self-reflective pen-and-paper questionnaire completed by the user after each task. Users were allowed to experiment with the system as they saw fit in completing each task. Each section began with brief explanation (1-2 minutes), open exploration time with the tool in which participants create 1 or more models and view multiple daylighting simulations (5-20 minutes), and culminated with a questionnaire (10 minutes). Users were encouraged to ask questions or provide feedback about the tool at any time. The tasks were designed such that the study took approximately 1 to 2 hours in total. This user study was each participant’s first use of the tangible user interface for daylighting simulation.

A short handout for users, the questionnaire, and the user study script (read aloud to each participant) is provided in a supplementary document.

### *3.3. Part 1: Daylighting Intuition for Existing Space*

The study begins with a tour of an open office space seating twelve graduate students with desktop computers and monitors (Figure 3). This room was selected for its simple geometry yet non-uniform daylighting from a single south-facing window. Portions of the room are gloomily dark while other areas receive direct illumination on the desk surfaces and computer monitors. Thus, this space is a good illustration of the need for careful analysis during design to maximize use of illumination from the sun and sky and minimize glare. The user is provided a handout with basic measurements of the space at the start of the tour.

The user is asked to identify areas in the room with too much or too little daylighting as well as the locations with glare, and to also specify daily and seasonal variations. Once the user has explored the room, he is asked to draw an annotated sketch of the room showing poor or problematic natural lighting (Figure 4). The sketch allows us to understand the complexity and accuracy of their daylighting intuitions. Similarly, the questionnaire for Part 1 focuses on the user's pre-existing understanding of daylighting. The user is asked to estimate the space's daylight autonomy and note the weather conditions and use of electric lighting in the room at the time they did the study. This provides information about their prior knowledge as well as any bias from the specific lighting conditions during their visit.

Each user spends 10-15 minutes in the space during this part of the study. They are free to walk around the space and explore different viewpoints and then sit at a desk in the room to complete their annotated sketch of the room and fill out the first part of the questionnaire.

### *3.4. Part 2: Using the TUI to Analyze Existing Space*

For the second part of the study, users are introduced to the TUI system for daylighting simulation. The participant constructs a physical model of the computer lab they just visited and sketched (Figure 5). The user has access to the provided room measurements as well as their sketch and notes. Then, the participant is invited to use the TUI simulation visualizations to evaluate the natural illumination, requesting multiple static time or timelapse animations of particular days of the year (Figure 6). By examining their choice of times and days selected, the thoroughness of their exploration can be quantified, and their understanding of the summer and winter solstice and the fall and spring equinox, and sunrise and sunset.

In addition to comparing the simulations with their earlier predictions, the questionnaire for this section also asks them to re-estimate the daylight autonomy of the space and discuss their understanding and perception of the simulation display. The first two parts of the study provide insight into the value of our tool as an educational interface as it evaluates users' perceptions both before and after utilizing the tool to evaluate daylighting within a simple geometry that they had personally visited.

### *3.5. Part 3: Analysis of a Proposed Renovation*

In the third section the participant is asked to propose a "modest" renovation of the existing space to improve the use of natural lighting. This exercise tests if users can effectively and efficiently make incremental design changes in response to daylighting needs. The edits are constrained to modification of the existing window, addition of new windows (but only to the exterior wall), and redesign of interior walls. Once again the users are free to explore their new design through daylighting simulations

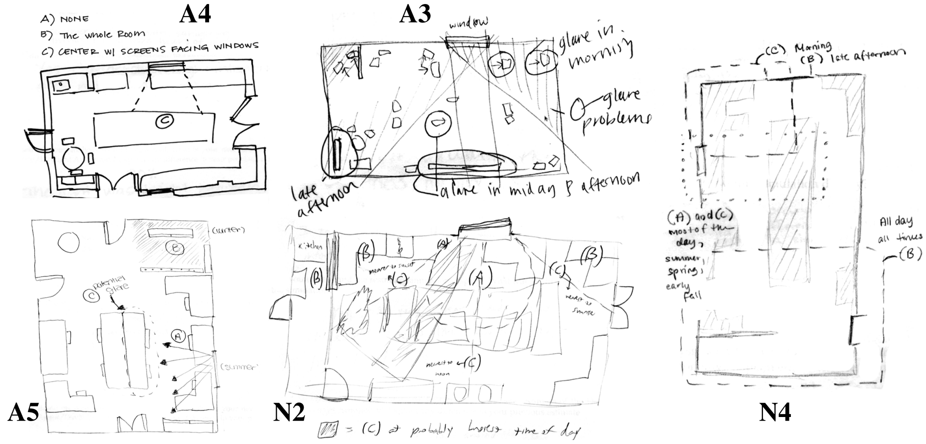



Figure 4: In Part 1 of the study, participants were asked to sketch the lab room and annotate this sketch with their intuition about areas with A) too much daylighting, B) too little daylighting, and C) potential for glare. The sketches demonstrate a variety of detail and accuracy in the analysis of the dynamic lighting conditions.

of their choosing. Users are permitted to further modify their design until satisfied with the daylighting in the revised model. The short questionnaire at the end of Part 3 asked users to provide the rational behind their renovation and to estimate the daylight autonomy of the new space.

### *3.6. Part 4: Analysis of a New Design*

The final stage of the study opened the tool to the participants' full creativity. In this stage, the user is simply instructed to create a brand new space with the same program to better serve the needs of occupants of the existing lab space. The new design can be situated anywhere on campus, in an existing or brand new building. The participant is encouraged to request daylighting visualization during the design process enabling them to creatively experiment with the tool for uncommonly-shaped spaces. The questionnaire for this section explores the user's motivation behind the new design, the expressiveness of the physical primitives for capturing the essential details of the intended design, and the user's estimate of the daylighting autonomy of the new design. The intent of Part 4 is both to test if users could freely express an intended design as well as to see if given complete freedom users are able to create a space that demonstrated good daylighting fundamentals.

## 4. USER STUDY RESULTS AND DISCUSSION

Users demonstrated different styles of design, both in modeling and in daylighting analysis strategy. Architects and non-architects alike entered the study with varying levels of daylighting intuition.

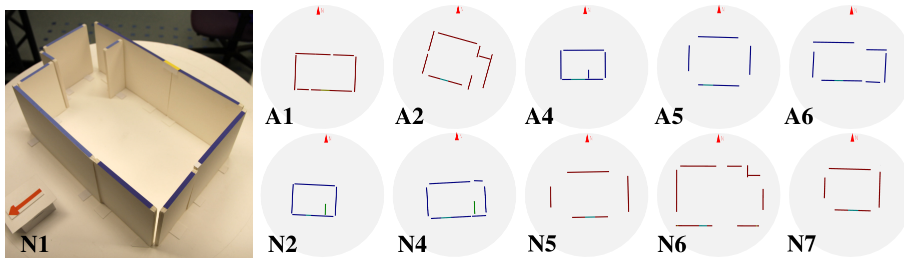



Figure 5: A photograph of the physical geometry of the original office space constructed by one of the participants for Part 2 of the study and 2D diagrams of the geometry constructed by the other participants.

### *4.1. Part 1: Intuition of Existing Design*

The first section of our study was focused primarily on the goals of evaluating our users' intuition. An important concept in understanding and evaluating daylighting is the sun's height and track across the sky for different seasons. The two extremes happen on the solstices. In the northern hemisphere, the sun reaches the highest point in the sky (angle to the horizon) during the summer solstice (June 21). The winter solstice (December 21) is the day the sun reaches the lowest point in the sky at midday. March 21 and September 21 are the equinoxes. The sun's track from east to west goes across the southern sky. This means that most direct light in buildings is obtained from south facing windows. Furthermore, direct sunlight will reach much further into a space from a southern facing window in the winter. From experience, it is known that the case study computer lab (Figure 3) has some very specific lighting issues. The desk closest to the window has significant over-illumination as well as glare issues for the morning hours, which are especially problematic in the winter. The northern and eastern areas of the room is consistently under-illuminated because of their distance from the window. The desks in the center of the room suffer from substantial glare issues, those facing away from the window suffer from glare on the monitors, while the ones facing towards the window have glare because the window is so much brighter than the monitors. This knowledge is compared with the analysis done by the study participants concerning the lighting in the space.

The users' sketches varied in level of detail and style (Figure 4), but users consistently identified areas of too much and too little daylighting in the room. Users did the study at a variety of times in a variety of weather conditions (cloudy/sunny, morning/afternoon, etc.), but their results showed no noticeable relation to these conditions. Five out of six of the architects identified a cone shaped area of bright light near the window. All of the architects used a 2D *plan* view to convey their information. However, the architects were not consistent in where they identified problematic areas for glare. Three of the architects discerned the desks in the center of the room would have problem with glare. Most users recognized that the desks near the window would be very bright, but only three of the architects recognized glare being a problem in this area. The majority of architects demonstrated a clear understanding of the approximate area lit by a window, but had difficulties discerning how bad glare would be and when it would be a problem. One architect claimed the worst over-illumination would occur in the summer. This intuition was exactly opposite of the true lighting condition at

|  | short wall (s) | long wall (l) | window width (w) | window placement (p) | wall height (h) | measurement ratios s:l | w:l | p:l | s:h |
|---|---|---|---|---|---|---|---|---|---|
| ground-truth | 24’ | 34’ | 4’ | 10’ | 12’ | 0.71 | 0.12 | 0.29 | 2.00 |
| A1 | 12.0” | 21.2” | 3.2” | 8.8” | 10” | 0.57 | 0.15 | 0.41 | 1.20 |
| A2 | 14.8” | 21.2” | 2.8” | 6.5” | 10” | 0.70 | 0.13 | 0.30 | 1.48 |
| A4 | 10.2” | 15.2” | 5.1” | 3.2” | 8” | 0.67 | 0.33 | 0.21 | 1.27 |
| A5 | 16.2” | 21.2” | 3.7” | 5.5” | 8” | 0.76 | 0.17 | 0.26 | 2.02 |
| A6 | 12.9” | 24.5” | 2.8” | 7.8” | 8” | 0.53 | 0.11 | 0.32 | 1.62 |
| N1 | 16.6” | 23.5” | 1.8” | 7.4” | 8” | 0.71 | 0.08 | 0.31 | 2.08 |
| N2 | 10.2” | 14.8” | 1.8” | 5.1” | 8” | 0.69 | 0.13 | 0.34 | 1.27 |
| N3 | 12.0” | 15.7” | 3.2” | 5.5” | 8” | 0.76 | 0.21 | 0.35 | 1.50 |
| N4 | 12.0” | 19.8” | 3.2” | 3.7” | 8” | 0.60 | 0.16 | 0.19 | 1.50 |
| N5 | 15.7” | 26.3” | 3.2” | 11.5” | 10” | 0.60 | 0.12 | 0.44 | 1.57 |
| N6 | 20.3” | 29.5” | 3.2” | 7.8” | 10” | 0.69 | 0.11 | 0.27 | 2.03 |
| N7 | 13.8” | 18.5” | 3.2” | 8.3” | 10” | 0.75 | 0.18 | 0.45 | 1.38 |
| averages |  |  |  |  |  |  |  |  |  |
| architects | 13.2” | 20.6” | 3.5” | 6.4” | 8.8” | 0.64 | 0.18 | 0.30 | 1.52 |
| error | -45% | -39% | -12% | -36% | -27% | -9% | 54% | 3% | -24% |
| non-arch. | 14.3” | 21.2” | 2.8” | 7.1” | 8.9” | 0.69 | 0.14 | 0.34 | 1.62 |
| error | -40% | -38% | -29% | -29% | -26% | -3% | 19% | 14% | -19% |

Table 1: The absolute and relative measurements of the models constructed for Part 2 of the study.

midday.

The style of the non-architects’ drawings were more varied. Two of the seven used 3D perspective to sketch the room. The non-architects did not specifically identify a cone-shaped area of over-illumination near the window but did provide appropriate detail of problematic lighting areas. Their intuition about lighting concepts also seemed to be of a similar depth and accuracy. In fact, one user from each category (architect and non-architect) demonstrated correct intuition in which areas would be problems at various points throughout a given day.

### *4.2. Part 2: Analysis of Existing Design*

Part 2 of the study focused on the users modeling the office space with the TUI. Table 1 presents a detailed comparison of the absolute and relative dimensions of the models built by the participants (Figure 5). Users were provided with the rough measurements of the lab: 24’ x 34’ and 10’ tall (7.3 x 10 and 3.0 meters tall ) at the beginning of the study. The suggested scale for the physical sketching environment is 1/12 scale (so 1’ in the real world would be 1” in the model) and the participants are told that the blue edged walls are 8” (20 cm) tall, the red edges walls are 10” (25 cm), and the small green walls are 5” (13 cm) tall. While eight out of thirteen users made an 8” (20 cm) tall model, this fact is not significant because the propagation of light is the same at different scales. Furthermore, several users specifically selected the smaller scale because there were more total 8” (20 cm) primitives than 10” (25 cm) primitives.

Overall, users were relatively accurate (within 15%) with the dimensions of the outer walls and with the placement of the window on the wall. Users were less accurate in the ratio of the height to wall, which does have significant impact on daylighting. This error was skewed to creating models that were taller than the ground

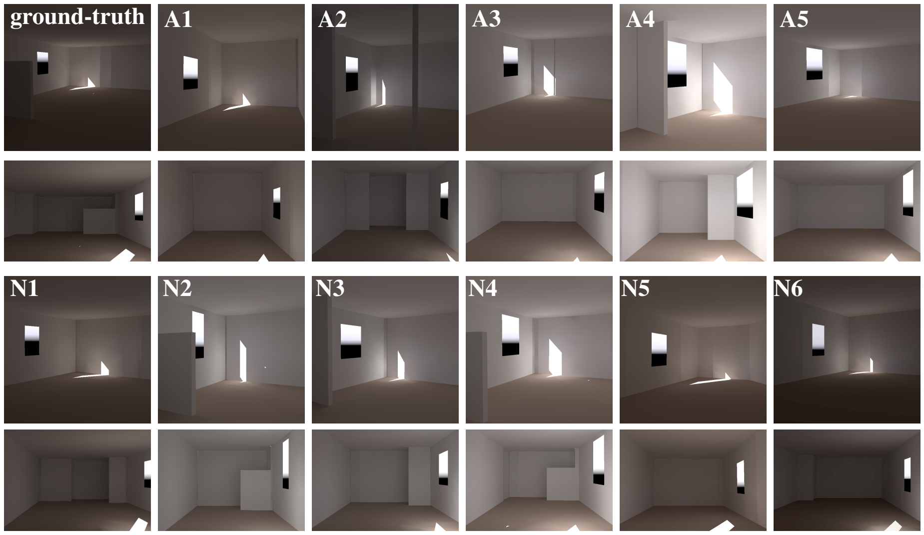



Figure 6: Simulation results for the original room geometry constructed by the study participants shown in Figure 5. The ground-truth model was constructed with the same tangible interface using the true room dimensions. All models are constructed using the same floor, wall, and ceiling materials. All renderings in this figure are March 21st at 8:30am. The desks in the southwest corner of the room (1st and 3rd rows) experiences glare at this time. The east side of the room (2nd and 4th rows) is quite dark all year, especially in the mornings.

truth, allowing more light to reach into the far corners of the room. Users were surprisingly inaccurate with the length of the window in relation to the size of the wall. The window width error was skewed to create models with windows that were too big, resulting in simulations that are noticeably brighter than the ground truth. It is notable that many users did not more carefully observe and reproduce the dimensions of the window. Global illumination renderings of the geometry created in Part 2 of the study are presented in Figure 6. All models correctly capture the problem with glare in the southwest corner of the room in the morning. However, the variation in brightness and distribution of light within the space, compared to the ground truth, does indicate the relative importance and negative impact of geometric errors in the modeling process.

As this was the users' first experience with the TUI daylighting tool, most users requested 5-10 different daylighting simulations. Most users chose to view a winter date, a summer date, and one or both of the fall and spring equinoxes. Two architects and two non-architects chose the solstices within a couple days. Others mostly chose dates across the seasons. All users recognized the importance of requesting multiple dates throughout the year. Some users were familiar with the seasonal patterns while others demonstrated incorrect initial intuition: e.g., two architects expressed confusion between the equinoxes and the solstices. After daylighting exploration with the tool, most users solidified a correct understanding of seasonal daylight patterns, although at least one user, A6, failed to grasp this concept. In Part 2, many users appreciated the complex visualization the tool provided, allowing them to better evaluate parts of the room that had significant glare. Although users still had a large range (30% to 90%) in their opinions of the daylight autonomy users only changed their original estimations

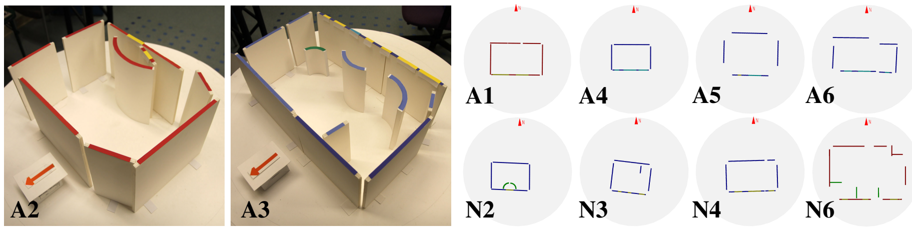



Figure 7: In Part 3 of the study participants were asked to propose a modest renovation to the geometry to improve the use of daylighting. Renderings of several of these geometries are shown in Figures 8 and 9.

by an average 20% from their original estimate.

On the questionnaire participants were asked: "What new insights did you gain about daylighting within the space? Were any of the simulation results unexpected?" 5 out of 6 architects and 6 out of 7 non-architects claimed they gained additional daylighting insight from this first task. A1 said "I learned there was much more light shed on the west wall than I expected, and was less light on the north and east walls, especially on the north." User A2 was surprised by the sun's penetration into the room: "New insights would be that the room's depth is rather shallow in the winter months when the sun is low, allowing the light to cause a significant amount of glare all the way across the room." Not only did users find areas of problematic lighting but users who requested the most simulations also were able to identify problematic times. Participant A5 said "I learned how the sun's direction relative to the date and time is a huge factor . . ." Some users credited the tool with reminding them of key daylighting properties: "I forgot to take into account that during the summer the sun is higher up, so actually less light penetrates throughout the room." Non-architects remarked on what they learned as well, but most of them offered more generic remarks. N6 commented: "I gained additional insight into how the lighting changes throughout the day, and at different times in the year. I was then able to compare them with each other to see the tendencies of the lighting in the room." Despite some inaccuracies in model dimension and scale, participants gained quite a bit of insight about the daylighting in the case study space with the TUI.

### *4.3. Part 3: Analysis of a Proposed Renovation*

In the renovations proposed for the third part of the study (Figure 7), all but two participants attempted to bring more light into the space by adding windows or by using multiple smaller windows (Figure 8). As a result, users indicated that they were able to achieve a much larger daylight autonomy averaging 76% in comparison to an average of 46% in Part 2. Some users chose to replace most of the entire south-facing wall with windows. While an effective way to make the room brighter, only a few users (4 out of 13) made modifications in an attempt to minimize glare (Figure 9), which is a significant problem in the current space, even with just one window. Both A2 and A3 used curved walls to diffuse the light into the room. While this will effectively balance daylight to reduce glare, it is at the expense of usable space in the room. Many of the other participants seemed to disregard glare. This may be partially because sufficient glare visualization has not been provided. Future work on the system will address this.

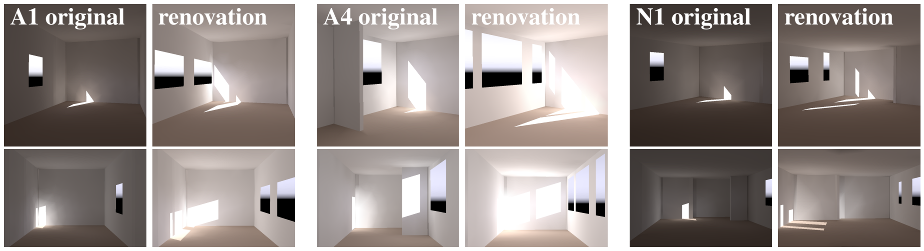


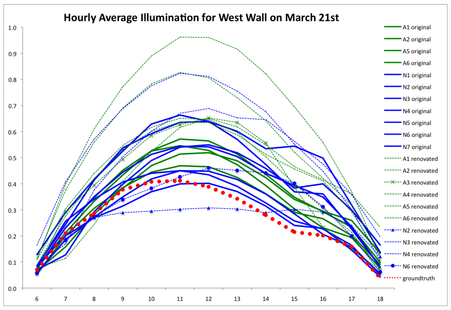

Figure 8: To address the general gloominess of the room, participants suggest adding more, taller, and/or wider windows on the southern wall (Figure 7). Some participants also removed the existing interior wall/partition that was deemed to be an obstruction to daylighting. While these modifications did brighten the room considerably, it will also increase the glare problems for those working at desks in the path of the light. Renderings in the top row are March 21st at 8:30am and the bottom row shows December 21st at 3pm.

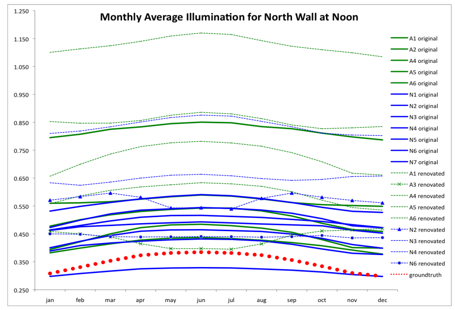

Figure 9: Only a few of the participants suggested renovations that attempt to mitigate the glare problems in the space through new geometry in the model. These proposals involve the addition of partitions that diffusely redirect the harsh direct southern light for more usable daylighting. Renderings in the top row are March 21st at 8:30am and the bottom row shows December 21st at 3pm.

Figure 10 presents a quantitative comparison and analysis of the models from Parts 2 and 3 of the study compared to the ground truth model of the existing room (dotted red curve). The modeling errors in window width and the errors in ratio of room height to room depth that lead to overly bright simulation results are clearly visible in all of these plots. There is little overall difference in the accuracy of the simulation results between architects (green curves) and non architects (blue curves). The participants who focused on glare reduction are clearly visible in the plot at mid-day for the northern wall (upper right plot). The complex pattern of seasonally varying illumination on the west wall in the mornings (lower right plot) emphasizes the importance of accurate modeling for predicting glare. While most models did capture the peak brightness at the equinoxes, the shape of the curve is not as pronounced in most users designs.

### *4.4. Part 4: Analysis of a New Design*

For the open-ended design exercise, many users experimented with curved walls (Figures 1 and 11). One user stated how they were trying to use a curved wall to redistribute light within the space. We were encouraged (but not surprised) to see a wide range of design shapes even with the limited palette of modeling primitives. Many of these designs were an extension or elaboration of the style of the renovations they proposed in the previous section. This showed that users felt free to be creative with their designs while using the tool. All users were successful in proposing designs



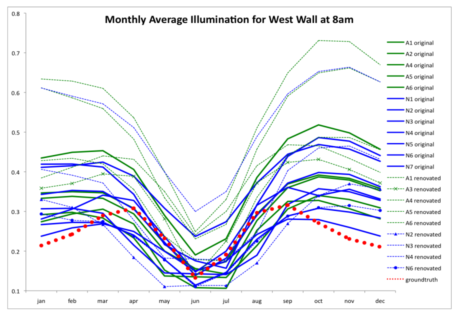




Figure 10: Plots analyzing the daily and seasonal variations in illumination for the users original and renovated models. We observe that on average the models built by participants resulted in a significant over-estimate of the available daylighting. In the top right plot, we can clearly identify the 3 users who focused on renovations to reduce glare (A3, N2, and N6).

to address what they viewed to be the most problematic daylighting issues. All users incorporated more windows into the design. Several participants (A4, N2, N4, and N5) specifically omitted windows on the southern wall, since direct sunlight yields the most problems with glare. Five participants (two architects and three non-architects) used interior walls to redirect and diffuse light and reduce glare. However, it was clear that other users still did not fully appreciate the problematic aspects of glare. Users reported daylight autonomy estimates that were similar to their estimates from their renovations in Part 3. Overall, participants spent much more time with Part 4 than the earlier sections. Although the participants did not request as wide a variety of simulation times for Part 4, they did use the simulation tool more frequently in revising their open-ended design. We conclude users spent more time on this exercise because we gave them the most freedom.

### *4.5. Lessons for Use of Daylighting in Tangible User Interfaces*

Many users were excited about the ability to track sunspots on the floor with this program and thought it was useful. Although users generally seemed impressed with the tool, the huge variance in the daylight autonomy estimates across participants confirmed that users did not receive an accurate quantitative perception from the system of what was too much or too little daylighting in the space. Eleven out of thirteen users said they were surprised or saw results they did not expect in the lighting simulation. Many of these comments involved seasonal variations in lighting between the summer and winter. Some users were surprised that a south facing window at midday is brighter in the winter than in the summer. Others were surprised by how deep into the room the sunspot reached in the winter months. Many users were pleased by the ease

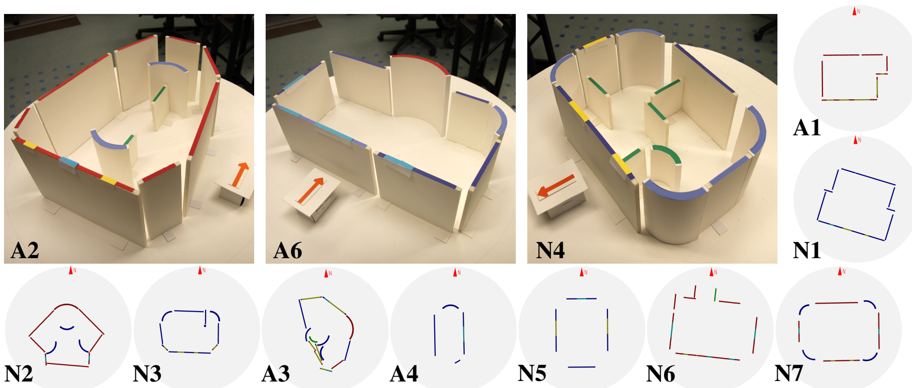



Figure 11: The final part of the user study consisted of an open-ended design exercise. Renderings of several of these models are shown in Figure 1.

of modifying designs using the TUI. Users consistently expressed that designing was simple and intuitive. Users complaints about the system focused on the limited number of primitives and not that designing was obscure or tedious. One user commented that the system was limited to single story models and requested a way to view lighting for the whole structure.

Though our study has focused on an application to daylighting simulation, we argue that these results can be generalized to other TUIs. A key advantage of these systems is the ease in building and iteratively editing a model for a custom building design. Using traditional tools to create geometric models suitable for daylighting simulation or other complex simulations can take special training and significant user time. In contrast, tangible interfaces accelerate both the learning curve and the model construction and editing time. However, as we show in our study, the accuracy of the constructed model can be problematic, even for users with domain knowledge and appreciation for the complexity and importance of model quality on the simulation. In retrospect, it is not surprising that people are not precise in re-creating physical dimensions, even of a space they just visited. It may be necessary to add subtle visualization cues to help. For example a grid could be projected on the floor with dimensions and area automatically calculated. Similarly, scale references of an average person height or furniture placement projected during modeling would allow the user to check their work.

Even a basic tangible interface with a limited palette of tools can spark and facilitate creative solutions to complex problems. Users with no prior experience with this tool created and iteratively revised interesting and effective designs. Furthermore, they used the simulation tool and overlaid visualization display to explore the complex interactions of daylighting with their new geometries. Challenges with SAR visualization and the relatively low dynamic range will need to be addressed to provide users with accurate perception of the intensity of illumination and issues with glare.

## 5. LIMITATIONS AND FUTURE WORK

While the TUI currently provides a valuable educational tool and can assist with early design, this study revealed several areas where improvements in the tool could provide more helpful feedback. Our current daylighting simulation tool does not output a measurement of the daylighting effectiveness (e.g., daylight autonomy). We plan to implement and visualize these metrics in future work. We would also like to perform a comparison study with our tool and a traditional computer-based daylighting interface. This comparison would investigate the accuracy as well as the speed in accomplishing daylighting simulations tasks. The main challenge in a direct comparison is the steep learning curve for existing modeling and daylighting software and the difference in purpose for our tool (early stage design exploration) vs. other tools (late stage design analysis). We hypothesize that comparison of the interfaces will highlight differences both in terms of creativity in design and iterative redesign and perception of light in the space. Currently we can only display information if it can be projected onto a physical element of the model; we do not visualize the interaction of daylighting with things such as furniture. To address this we would like to investigate additional augmented reality techniques, for example a handheld viewing device [7, 8, 9] to provide a more detailed window into the virtual space.

This study showed us that while users felt their daylighting intuition was enhanced by the tool, they still struggled to quantitatively estimate usable light in the space. This may be due to the high dynamic range of actual daylighting and the limited dynamic range of our tabletop SAR display. The tool could be modified to use false color and other visualizations to show problem areas, e.g., glare regions could be displayed with red arrows. Also, the system could present a summary of the daily and/or seasonal variations in a static visualization. The system is limited by the number of primitives available. Although the system can deduce that gaps between the walls should be filled, some users expressed concern that they did not have as many primitives as they would have liked to complete their designs, especially in the case of symmetric buildings. Our daylighting simulation and projection system is currently limited to diffuse material properties and clear glass. While this is sufficient to model most surfaces inside many typical office spaces, we hope to extend the material model, specifically with specialized diffusing, reflective, and refractive window materials, allowing users to explore the use new technologies in their design.

Complex daylighting metrics including glare could be calculated for users' geometries. Kleindienst and Anderson [23] proposed an alternate metric similar to DGP for glare calculation that is particularly well suited for lighting simulations. We plan on using this approximation for areas specified by a glare sensor token in future models.

## 6. CONCLUSION

Participants in this study were significantly and positively influenced by our tangible interface for daylighting simulation. Users consistently claimed that their lighting intuition was improved, their design was aided by the tool, and that the interface was accessible. Many participants used the tool to look at lighting in various seasons to understand how daylighting will vary throughout the year. Despite this, it was clear that users need additional quantitative feedback and visualization to more fully analyze glare in high contrast lighting conditions. Our results show that users felt that with a tangible user interface they were able to evaluate daylighting better than with their intuition alone. The interface provides an effective tool for designing the shape of an architectural space and with extensions could assist users in reducing glare and selecting window materials as well. These results generalize to other tangible interfaces emphasizing their advantages for ease-of-use, interactivity, and visualization. Our study results do caution users of these tools on the importance of accuracy and precision in modeling, specifically when complex simulations depend on quality input models.

## 7. Acknowledgments

This work was supported by NSF IIS 0845401.

## References

[1] R. P. Leslie, L. C. Radetsky, and A. M. Smith. Conceptual design metrics for daylighting. *Lighting Research and Technology*, November 2011.

[2] N. Lechner. *Heating, cooling, lighting: design methods for architects*. Wiley, 2001.

[3] Ramesh Raskar, Greg Welch, Kok-Lim Low, and Deepak Bandyopadhyay. Shader lamps: Animating real objects with image-based illumination. In *Rendering Techniques 2001: 12th Eurographics Workshop on Rendering*, pages 89–102, June 2001.

[4] Yu Sheng, Theodore C. Yapo, Christopher Young, and Barbara Cutler. A spatially augmented reality sketching interface for architectural daylighting design. *IEEE Transactions on Visualization and Computer Graphics*, pages 38–50, January 2011.

[5] Yu Sheng, Theodore C. Yapo, Christopher Young, and Barbara Cutler. Virtual heliodon: Spatially augmented reality for architectural daylighting design. In *VR*, pages 63–70. IEEE, 2009.

[6] Theodore C. Yapo, Yu Sheng, Joshua Nasman, Andrew Dolce, Eric Li, and Barbara Cutler. Dynamic projection environments for immersive visualization. In *2010 Computer Vision and Pattern Recognition Workshops (CVPRW)*, pages 1–8. IEEE Computer Society Conference, June 2010.

[7] Hiroshi Ishii and Brygg Ullmer. Tangible bits: towards seamless interfaces between people, bits and atoms. In *Proceedings of the SIGCHI conference on Human factors in computing systems*, CHI '97, pages 234–241, New York, NY, USA, 1997. ACM.

[8] Ka-Ping Yee. Peephole displays: pen interaction on spatially aware handheld computers. In *CHI '03: Proceedings of the SIGCHI conference on Human factors in computing systems*, pages 1–8, New York, NY, USA, 2003. ACM.

[9] Takuya Maekawa, Yuichi Itoh, Norifumi Kawai, Yoshifumi Kitamura, and Fumio Kishino. Mado interface: a window like a tangible user interface to look into the virtual world. In *TEI '09: Proceedings of the 3rd International Conference on Tangible and Embedded Interaction*, pages 175–180, New York, NY, USA, 2009. ACM.

[10] Robert J. K. Jacob, Hiroshi Ishii, Gian Pangaro, and James Patten. A tangible interface for organizing information using a grid. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, CHI '02, pages 339–346, New York, NY, USA, 2002. ACM.

[11] Martin Spindler, Sophie Stellmach, and Raimund Dachselt. Paperlens: advanced magic lens interaction above the tabletop. In *Proceedings of the ACM International Conference on Interactive Tabletops and Surfaces*, ITS '09, pages 69–76, New York, NY, USA, 2009. ACM.

[12] Peng Song, Wooi Boon Goh, Chi-Wing Fu, Qiang Meng, and Pheng-Ann Heng. Wysiwyf: exploring and annotating volume data with a tangible handheld device. In *Proceedings of the 2011 annual conference on Human factors in computing systems*, CHI '11, pages 1333–1342, New York, NY, USA, 2011. ACM.

[13] Pierre Wellner. Interacting with paper on the digitaldesk. *Commun. ACM*, 36(7):87–96, 1993.

[14] George W. Fitzmaurice, Hiroshi Ishii, and William A. S. Buxton. Bricks: laying the foundations for graspable user interfaces. In *CHI '95: Proceedings of the SIGCHI conference on Human factors in computing systems*, pages 442–449, New York, NY, USA, 1995. ACM Press/Addison-Wesley Publishing Co.

[15] Ann Morrison, Antti Oulasvirta, Peter Peltonen, Saija Lemmela, Giulio Jacucci, Gerhard Reitmayr, Jaana Näsänen, and Antti Juustila. Like bees around the hive: a comparative study of a mobile augmented reality map. In *CHI '09: Proceedings of the 27th international conference on Human factors in computing systems*, pages 1889–1898, New York, NY, USA, 2009. ACM.

[16] Aurélien Lucchi, Patrick Jermann, Guillaume Zufferey, and Pierre Dillenbourg. An empirical evaluation of touch and tangible interfaces for tabletop displays. In *TEI '10: Proceedings of the fourth international conference on Tangible, embedded, and embodied interaction*, pages 177–184, New York, NY, USA, 2010. ACM.

[17] Tiffany Tseng, Coram Bryant, and Paulo Blikstein. Mechanix: an interactive display for exploring engineering design through a tangible interface. In *Tangible and Embedded Interaction*, pages 265–266, 2011.

[18] John Underkoffler and Hiroshi Ishii. Urp: a luminous-tangible workbench for urban planning and design. In *Proceedings of the SIGCHI conference on Human factors in computing systems: the CHI is the limit*, CHI '99, pages 386–393, New York, NY, USA, 1999. ACM.

[19] Michael Terry, Janet Cheung, Justin Lee, Terry Park, and Nigel Williams. Jump: a system for interactive, tangible queries of paper. In *GI '07: Proceedings of Graphics Interface 2007*, pages 127–134, New York, NY, USA, 2007. ACM.

[20] Barbara Cutler and Joshua Nasman. Interpreting physical sketches as architectural models. In Cristiano Ceccato et al., editors, *Advances in Architectural Geometry 2010*, pages 15–35. Springer, 2010.

[21] Barbara Cutler, Yu Sheng, Steven Martin, Daniel Glaser, and Marilyne Andersen. Interactive selection of optimal fenestration materials for schematic architectural daylighting design. *Elsevier Automation in Construction*, 2008.

[22] OSHA. OSHA Ergonomic Solutions: Computer Workstations eTool - Workstation Environment, August 2010. http://www.osha.gov/SLTC/etools/computerworkstations/wkstation_enviro.html.

[23] S. Kleindienst and M. Andersen. The adaptation of daylight glare probability to dynamic metrics in a computational setting. In *Lux Europa 2009*, September 9-11 2009.