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Developing Architectural Lighting Representations

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Abstract

This paper reports on the development of a visualization system for architectural lighting designers. It starts by motivating the problem as both complex in its physics and social organization. Three iterations of prototypes for displaying time and space varying phenomena are discussed. Fieldwork is presented to identify where in practice they will be most effective. A set of user studies, one of which is analyzed in fine-grained detail, show how building designers incorporate visualization on hypothetical design problems. This has positive implications for both energy efficiency and lighting quality in buildings.

CR Categories: H.1.2 [Models and Principles]: User/Machine Systems—Human factors; D.2.2 [Software Engineering]: Design Tools and Techniques—User interfaces; K.4.3 [Computers and Society]: Organizational Impacts – Computer Supportive Collaborative Work

Keywords: information visualization, qualitative analysis, ethnographic fieldwork, architectural lighting design, energy efficiency

1 Introduction

Electric lighting systems consume 50% of the electrical energy in commercial buildings in California—at times correlating with daylight availability. One adoption barrier to designing buildings with daylight is due to its complex physics. Daylight varies by time of day, day in year, sky conditions, and a number of design variables (such as the building's apertures and interior reflective surfaces). In comparison, most electric lights produce more predictable results. The other issue relates to the collaborative nature of designing buildings—lighting design is a distributed problem [Hutchins 1995; Hollan et al. 2000; Halverson 2002]. In lighting design, cognition is not limited to a single individual, but through interactions among artifacts, people, and professions. Hence, the complexity for daylight design is both in the structure of the data and the professions who manage it.

Some have approached this problem by looking primarily at the building physics. Optimization approaches in the building sciences look to improve performance variables such as visual quality of light, acoustics, and energy (e.g. [Costa et al. 1999] [Monks et al. 2000] [Caldas and Norford 2002]). Since performance is usually dependent upon a multitude of variables, these strategies offer quick ways of generating improved solutions. This automation does not come without risk, though, since functional performance indices can be incomplete ([Moeck and Selkowitz 1995]), contentious ([Jay 2002]) and have other unwanted side effects [Rittel and Webber 1973]. For example, moving a window may make the electric lighting system less efficient, interfere with the design style of the architect, among other factors. Hence, a visualization approach lends itself to this problem since it keeps the agencies involved in the planning process. It should be noted, though, that the optimization systems referenced here make reference to "front-ends", but are not developed with fieldwork or user testing.

Although there are a number of visualization programs for lighting simulation, only a handful are trusted by researchers and professionals. Radiance [Ward 1994] is a physically based global illumination package that has had widespread acceptance in the architectural lighting community (e.g. [Ubbelohde and Humman 1998; Reinhart and Walkenhorst 2001]). In order to overcome the barriers of Radiance's command line interface, graphical plug-ins and stand alone applications have recently been developed (e.g. Rayfront [Schorsch 2003] and Desktop Radiance [Building Technologies Department 2002]). Although these programs make visualization significantly more accessible, they do not explicitly support multiple parameter examination aside from animations. For example, seeing a room performance across two dimensions of time (time in day and day in year), and sky conditions would require the user to generate potentially thousands of charts and/or images. From an HCI perspective, although these programs address community needs, unfortunately there have been no systematic studies of these programs in use. In this paper, the prototypes under development look to support simultaneous viewing of charts across multiple parameters. It also describes semi-structured feedback sessions and three user studies, one of which is highly detailed.

2 First Prototype

The first prototype, Space Series, was designed to meet the need of displaying copious simulation data. To date, there is no comparable program for visualizing the multidimensional aspects of lighting design. Space Series uses focus-plus-context techniques in a novel way, presenting both spatial and temporal dimensions of daylight in a single 2D plot. Space Series embeds spatial data within two major axes representing time of day and day of year. Similar to traditional methods of display, in its initial state, Space Series provides the user with a global view of the data. This context is represented by reducing spatial data into a single data point via a user specified function. The novelty arises from the users' ability to focus into spatial regions along one or both time axes. Focusing on one axis produces one-dimensional spatial details. Focusing along both axes simultaneously produces an intersection that shows the original data, revealing 2D spatial details. Thus, at a global level, the user can see a temporal distribution, while focusing reveals the spatial dimension of the

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data set. Figure 1 is a screen capture of Space Series. Details about how this and other charts are read are found at [Glaser and Hearst 1999].

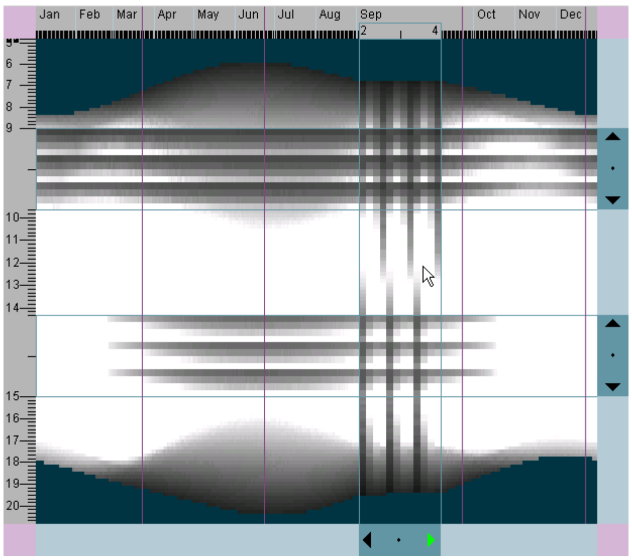

Figure 1. A screen capture of Space Series showing focus and context regions for a square room in Berkeley, CA with a southern window.

Five daylighting consultants (Barbara Irwine, George Loisos, Joel Loveland, Mirietta Millet, and Susan Ubbelohde) were shown still images of Space Series for a semi-structured evaluation. The slides showed how the new focus+context technique could bring insight into different design scenarios. They noted that Space Series could succinctly explain difficult daylighting concepts related to sun angles, intensities, and illuminance patterns. Nevertheless, two experts preferred the explanatory slides to the actual interface. The slides separated time from space and generally broke Space Series into sequences of simpler renderings. One consultant was only interested in traditional methods such as model building and photography and had no interest in computer representation.

Since the population of daylighting consultants was so small ("at most a dozen people in the U.S.!" they self reported), three lighting and two energy consultants were also asked to critique the interface. The lighting consultants did not like the focus+context technique and preferred form fill in and generally less descriptive interfaces. The energy consultants, Lisa Heschong and Jon McHugh, confirmed that much simpler representations could have a significant impact on lighting professionals who ordinarily do not use daylight. Hence, the semi-structured evaluations showed that there were other relevant, less experienced profesisonals that could use a simpler representation.

3 Fieldwork

Fieldwork [Hughes et al. 1994] was conducted among a broad range of professionals. This included interviews and observations with professionals and participation in workshops. Interviews were conducted at either design offices or neutral locations such as the Pacific Energy Center, San Francisco or the Lighting Design Laboratory, Seattle. Designers were asked about recent work and project samples. Their responses were recorded in a notebook, pictures taken of relevant design artifacts, and approximately 20% of them audiotaped. Later the handwritten and audio notes were transcribed onto a word processor. Attending over a dozen workshops and a professional lighting design conference facilitated learning the domain of lighting, offered a number of informal interactions with fellow lighting designers in attendance, and also provided a chance to get involved firsthand on lighting design problems. It should be noted that the fieldwork still extends to this day.

Table 1 illustrates the types and number of professionals interviewed and their relative expertise with respect to electric light and daylight. An ***architect*** designs the building fenestration system (along with many other aspects of a building). In a fraction of cases where there is a large budget ("2-3% of times") they will work with a ***daylighting consultant*** to improve daylight use. These experts at daylight simulation included those who reviewed the Space Series prototype plus two others (Hayden MacKay and Jeff Hattrop from Ove Arup). They hand off the design to a ***lighting consultant*** ("50% of commercial jobs") to design the electric lighting system. The lighting consultant sends their work to the ***electrical engineer*** for completion. If there is no lighting consultant involved, the electrical engineer does both lighting and implementation details. After a building is designed, occupants and ***facility managers*** can redesign a building. Other professionals are also involved in the supply chain of lighting systems [Tsao and Tommelein 2001].

professional	electric light	daylight
architect (4)	n/a	low
lighting designer/consultant (12)	high	low
electrical engineer (1)	high	low
daylighting consultant (7)	some	high
facility manager (1)	some	n/a

Table 1. Expertise level in daylight and electric lighting by profession.

Expertise was ranked as either high, some, or low. For electric light, high expertise was if professionals were current with the vast array of contemporary lighting technologies while some expertise was delegated to those who understood the basic principles of electric lighting systems. For daylight, high expertise was for professionals who understood basic physics of daylight. Low expertise meant that they would be unable to describe the difference between clear and overcast skies from a physics standpoint. As reported in [Glaser et al. 2002], for example, of four architects sampled only one actually discussed direct and indirect aspects of sky models.

One main finding was that integration of daylight was not common for lighting consultants and electrical engineer. This was observed in their design artifacts and also what they said during interviews. They cited two pragmatic reasons for not using daylight—its complexity and cost of doing so. They also cited an assumption in the lighting and energy community in general—that one must always design for worst case, or nighttime lighting. The logic is that since buildings may be occupied, say at midnight, than the electric lighting systems should be designed to illuminate the entire building themselves. Hence, electric lighting design focused on the electric lights, without noticeable consideration for daylight.

Figure 2 illustrates a sampling of images taken at lighting consultant offices. The image on the left shows a sample sketch of a lighting designer drawing on top of an architectural plan using trace paper. In this sketch, there are two indicators that daylight was not utilized as a light source during the design of the electric lighting system. First, the planned fluorescent lights do not integrate well with the large windows on the south side of the drawing (e.g. they are perpendicular to the windows, a noted design shortcoming [Benya et al. 2001]). Also there are no noticeable differences in the lighting system between interior and exterior zones.

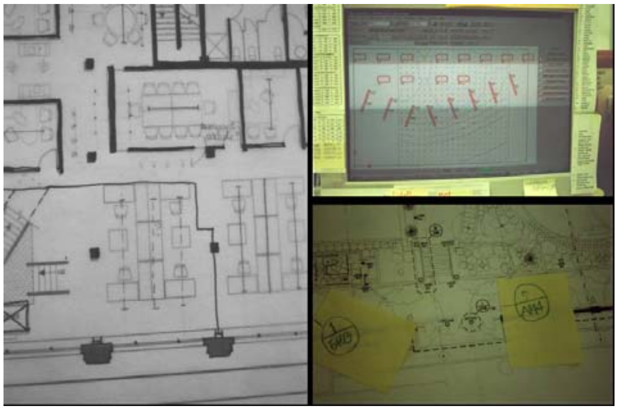

Figure 2. Daylight integration was not found at lighting consultant offices (left) on reverse ceiling drawings provided by the architect (top right) with computer simulation programs (bottom right) and with controls.

In the top right image of Figure 2, a lighting consultant has run an illuminance simulation for a design scenario (this simulation is not from Radiance, but software tailored towards electric lighting design). Although two sources of electric light are modeled, the windows were not. This was due to both the tedious interface and also since there was little industry incentive to capitalize on the available daylight. The bottom right image is of a near completed drawing connecting light sources together into banks. Controls were left to the engineer. This division of labor could potentially be problematic since the engineer may not connect banks and design controls that integrate the lighting system in ways the architect or lighting designer imagined..

The observations from the field on daylight integration are supported by a sparse literature on lighting design practice. Telephone surveys of 58 architects and 18 lighting professionals revealed that lighting designers did not consider daylight, "lighting consultants and electrical engineers then do the lighting design, which becomes, de facto, strictly an electric lighting design" [Turnbull and Loisos 2000]. [Tsao and Tommelein 2001] stipulated that electric lighting design relies heavily on illuminance plots using "point by point" illumination calculations. A survey showed lighting designers self-reported that their design work is the single most relevant variable to improving energy efficiency in buildings. [Heschong-Mahone-Group 1999]. In other words, previous studies of practice showed that lighting designers used a limited set of tools to analyze electric light, without using daylight, at a cost to energy efficiency. This led to focusing the daylight visualization prototypes to this area of need.

4 Second Prototype

A second, unnamed, prototype was designed and developed to accommodate the feedback from the first. The prototype was simpler since it did not employ focus and context techniques that users found difficult to learn. Instead, it used multiple, simpler plots for navigating the data. Figure 3 is a screen capture of two linked plots—temporal (left) and spatial (right). The temporal plot is ordered by day of year (x-axis) and time of day (y-axis). It plots the performance of a point selected, via rectangular brush, in the spatial plot (3, 5) across time. The spatial plot shows a floor-plan with a window on its southern side. It charts daylight at the time selected by the brush in the temporal plot (Oct 24th, 2pm). The interface could manage multiple, variable size brushes, tessellations, and algebraic functions for simplifying data [Glaser and Ubbelohde 2002].

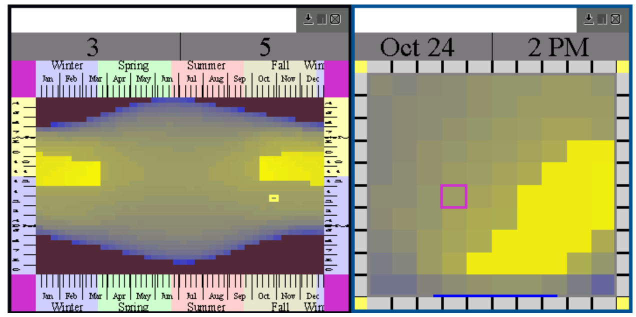

Figure 3. A calendar plot (left) showing the temporal distribution of light for sensor (3,5), and (right) spatial plot showing the lighting condition on October 24th at 2pm in a square room.

A video [Glaser and Ubbelohde 2001] contextualized prototype 2 in terms of historical representations (Figure 4). The movie starts with the simplest simulation method of using physical models (Figure 4, upper left); progresses with combining with a heliodon, a calibrated devices (Figure 4, upper right), shows how physical models interface with microcomputers (not shown in Figure 4) shows an advanced representation by the daylight consultant (Figure 4, lower right); and finally the second prototype (Figure 4, lower left). This progression was meant to show all designers that the new representations were not just "novel", but rather an extension of existing practices.

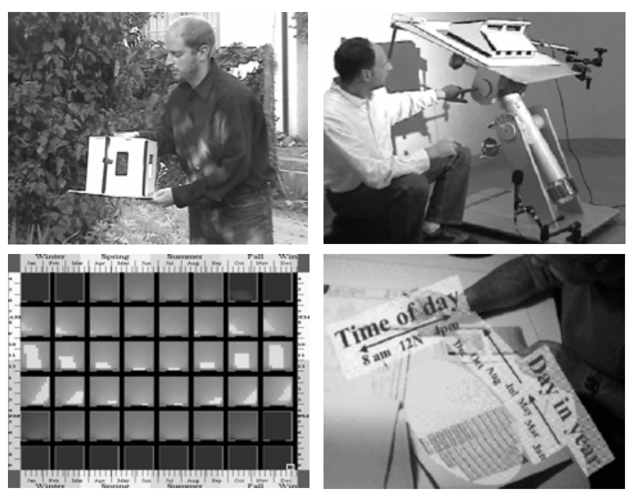

Figure 4. Four snapshots show, from top left (clockwise) increasingly sophisticated representations (images from [Glaser and Ubbelohde 2001]).

5 User Studies, Second Prototype

Three in depth studies were conducted to understand how designers incorporated the new interface into hypothetical design problems. The tests were with an advanced graduate student, lighting designer, and daylight consultant. Each was shown either a paper prototype (the graduate student) or a working system (the lighting designer and daylight consultant) and asked to use it on an open ended design problem. The studies were videotaped and transcribed.

Each tape was reviewed with methods from conversation analysis [Suchman 1983; Bodker 1996; Woodruff et al. 2002]. This technique was used to describe how the new interfaces changed the discourse between the practitioners and observer (Glaser). Considering there have been no published evaluations of lighting design software, we felt this method was suitable due to its data driven approach. This differs from protocol analyses of visualization systems (e.g. [Trafton et al. 2000]) since attention was on the distributed system surrounding the use of the interface rather than the user's cognitive states. In other words, understanding how a designer considers professional expectations, analogizes historical representations, or marks disciplinary boundaries was the focus, rather than classifying mental states.

5.1 "Tan" user study

"Tan" studied lighting for five years in graduate architectural schools and had expertise in daylighting and some knowledge of electric lighting systems. He was tested with large-format printouts in a low-fidelity [Rettig 1994] test. One significant finding was that Tan had difficulties reading pixilated graphs of lighting performance. Specifically, he could not find "hotspots", circular shaped regions of sunlight, which he needed to see to assess spatial aspects of daylight distributions (Figure 5). This information is *historically* present due to previous experience with software that interpolated data with curves. Tensions between historical stability and innovation are expected between discussions between professions (see, for example, [Hall et al. 2002] for an extensive ethnographic illustration of this).

Figure 5. (left) Tan highlighting his inability to find a "hotspot" in the chart. (right) gesturing the preferred shape of a hotspot.

5.2 "Greg" user study

"Greg" has expertise both in architectural design (he was a registered, practicing architect for 15 years) and daylighting consulting (which he has had a practice for 3 years). He helps designing the fenestration system of large commercial buildings. He was able to identify limitations in the sky models employed (as reported in detail at [Glaser et al. 2002]), describe chart preferences, and preferred color maps.

5.3 "Brina" user study

The lighting designer study was conducted at the Pacific Energy Center in San Francisco, California. The participant "Brina" had 13 years of years of industry experience. She was shown some of the features of the software and asked how she could incorporate them into a hypothetical design scenario. Specifically, Brina was asked how she would the tools for designing a lighting system for a pentagonal office with three windows (Figure 6).

Figure 6 shows the plot titled "AVERAGE" that Brina is engaged with during this portion of the user study. This spatial plot shows the average daylight distribution across the pentagonal room across most of the year (Jan 1 to Dec 26, 4am to 9pm) under clear sky conditions. This plot was constructed in two steps. The first by selecting a range of times of interest (Jan 1 to Dec 26, 4am to 9pm) in the temporal plot (not shown). This would show a series of pentagonal rooms and lighting performance graphs (similar to Figure 5, but with the pentagonal model). The second step was to conflate *all* the plots into a single chart (shown in Figure 6 right) which describes an *average* during daylit times. This resulting plot shows, on average, some parts of the room will receive very high amounts of illumination (about 1000 Lux), while others are relatively dim (in particular the east side of the room). This plot, while not representing a specific time, provides an overview of lighting performance.

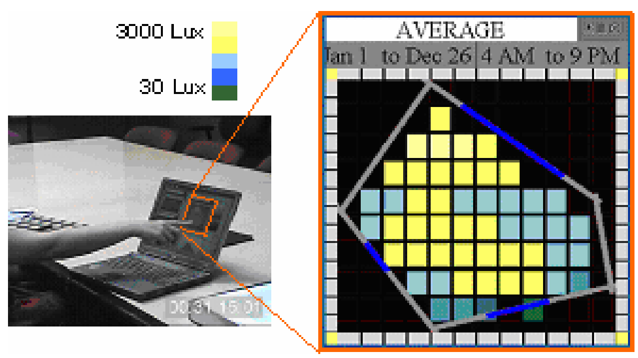

Figure 6. (left) A screen capture of the user study "Brina" and (right) close-up view of the panel she is pointing at.

5.3.1 Study Overview

The analysis identified two repeated phenomena during Brina's user study, a ***design intervention*** and ***conversation segment***. Design interventions occurred when the user created a lighting system verbally or thorough gesture. Each design intervention consisted of a number of distinct ***steps***. For example, one step was discussing a general lighting system while another wall sconces for balancing. Each is a distinct component of a lighting system, but together they form a complete design intervention. Design interventions are proceeded by and concluded with a conversation segment. These verbal segments serve as generators for and reflections about design interventions. Together design interventions and conversation segments form a ***stage***.

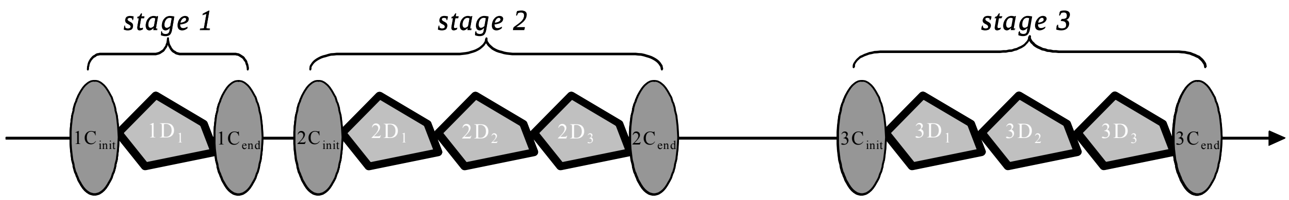

Figure 7. Timeline overview of the conversation (oval) and design (pentagonal) events during the Brina user study. Stages 1 and 2 were sequential, whereas there is a 12 minute gap between stages 2 and 3.

Figure 7 is a timeline of the design interventions and conversation segments coded in the Brina user study. Each stage is coded according to the symbols illustrated in Figure 8. The timeline shows that there were three stages of activity. At stage 1 there was only 1 design intervention, while stages 2 and 3 had 2. The gap between stages 2 and 3 shows a twelve minute omission in the transcript. This portion of the user study was unrelated to the design problem.

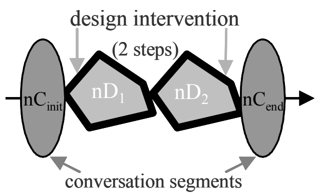

Figure 8. Timeline legend.

5.3.2 Stage 1- Initial Problem Framing

This stage marks Brina's introduction to and first attempt at solving the problem (Table 2). During the first introductory conversation segment ($1C_{init}$), Brina agrees to design an electric lighting system for the hypothetical room. She first described a design method for achieving a "good balance" (lines 6-7) in the space. Designing for uniform work surfaces is congruent with industry standard methods for electric lighting. Nevertheless in lines 8-10, she begins to read the graph ("we are looking kind of dim over there", referring to daylight availability), and starts a design consisting of a single sconce (Figure 9, 1D, lines 8-10). Sconces are light fixtures that adjoin walls and wash light above them. At this point, she short-circuits the single step she took to reflect upon it.

30:53

1	$1C_{init}$	[D]	would you use that in, actually, your design for, for, uh=
2	$1C_{init}$	[B]	=I [will]
3	$1C_{init}$	[D]	[the] electric lighting system and things like that
4	$1C_{init}$	[B]	=now that I have seen it, I will=
5	$1C_{init}$	[D]	=aha
6	$1C_{init}$	[B]	=uhm, there we are always trying to get a balance with
7	$1C_{init}$		that type of lighting, so even though you get a lot of
8	$1D_1$		daylight, in this pattern, and we are looking kind of
9	$1D_1$		dim over here so we want to get a wall sconce or
10	$1D_1$		something happening,

31:16

Table 2. Transcript of the first conversation segment and design intervention. Here the design question is framed and responded to.

In conversation segment $1C_{end}$ (Table 3), Brina, through invoking professional norms, questions the relevance of designing for daylight. She says that it is unrealistic to design for the sun since it has a high degree of variability (lines 12-18) and is still concerned with the "balance" (line 12) of electric light. This result was not surprising since it was consistent with the fieldwork in lighting design offices. She uses the utterances, "we are assuming" (line 13) and "there is this sort of *general* assumption" (lines 18-19) to reflect that it is not she, alone, who is making this assumption. Nevertheless, she reflects upon "lighting for when it is dark" as being "not a very good idea" (lines 19-21) and understands that this may not be realistic. Hence, Brina is able to critically reflect about her profession's beliefs.

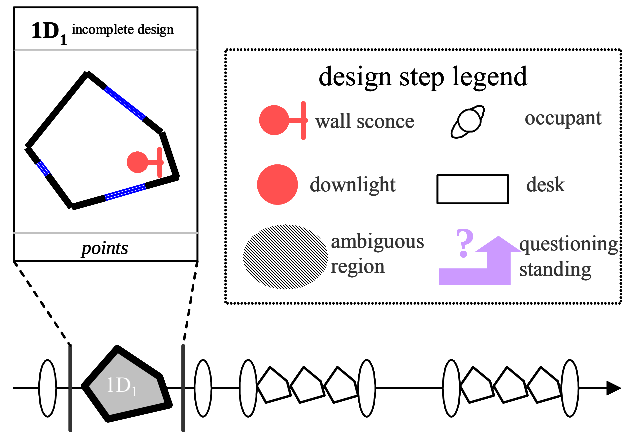

Figure 9. The first design intervention was interrupted after only a single wall sconce was specified.

31:16

11	$1C_{end}$	[B]	uh- there, we are always trying to design for a good
12	$1C_{end}$		balance, uhm and and good work light, <u>no matter what's</u>
13	$1C_{end}$		<u>happening with daylight</u>, because we are assuming a
14	$1C_{end}$		cloudy day or
15	$1C_{end}$	[D]	ok, [aha]
16	$1C_{end}$	[B]	[or bad] circumstances ((short laughter))
17	$1C_{end}$	[D]	=ok [great]
18	$1C_{end}$	[B]	[or ev] evening circumstances- so ther there is this
19	$1C_{end}$		sort of general assumption that <u>which is probably not a</u>
20	$1C_{end}$		<u>very good idea,</u> that, you know, lighting is for when it is
21	$1C_{end}$		dark and=
22	$1C_{end}$	[D]	=aha
23	$1C_{end}$	[B]	°when you don't have a lot of daylight°,

31:44

Table 3. Transcript of a conversation segment justifying why she interrupted her previous design solution**.**

5.3.3 Stage 2- Revised Design

Immediately after completing the first stage, Brina develops a new solution (Table 4, Figure 10). She starts to gain confidence in the interface's representation of daylight ($2C_{init}$, lines 24-25). She uses it to describe a general lighting system that can be turned off ($2D_1$, lines 26-27). The invention of a general lighting system is important since its function is contingent upon daylight—differing from standard practice. She proceeds to add wall sconces again ($2D_2$, lines 27-28) to brighten areas of the room that do receive low amounts of sunlight, on average. Lines 29-30 also show an expansion of her definition of lighting quality to include the building occupant as part of the solution. Hence she develops a notion of occupant which can lead to both improved lighting quality and a more energy efficient solution. Nevertheless she has concerns about occupant comfort and believes sensors will remedy the situation (32-34). Brina is able to utilize the interface since her expertise in lighting design allows her to engage this "new" light source.

			31:45
24	$2C_{init}$	[B]	so, uhm but I think, I think it would be a useful tool to
25	$2C_{init}$		know where the daylight is coming in,
26	$2D_1$		so that maybe, maybe there is a general lighting
27	$2D_{1-2}$		system that can be turned off and we add wall sconce
28	$2D_2$		over here and wall sconce over here
29	$2D_3$		then we have the person at the desk, be willing to get
30	$2D_3$		up, which is [the whole problem]
31	$2C_{end}$	[D]	[Right]
32	$2C_{end}$	[B]	=with those sensors, so that people don't have to get up
33	$2C_{end}$		from their desks to change the light,
34	$2C_{end}$	[D]	aha
			32:13

Table 4. Transcript of the second design intervention (2D) between two conversation segments ($2C_{init}$ and $2C_{end}$).

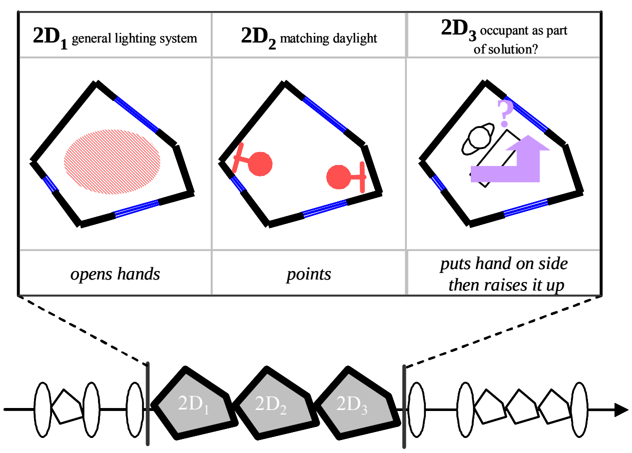

Figure 10. The second design intervention starts to reconcile daylight with the electric lighting system. Brina questions its feasibility, though, due to perceived occupant difficulties.

5.3.4 Stage 3- Revisiting Design Problem

About 12 minutes later in the user study, Brina suddenly revisits the design problem (Table 5, Figure 11). In $3C_{init}$, Brina discusses the necessity of adopting information that is pertinent to her job. She is able to quickly revise her solution (3D) to accommodate the concerns she had about the occupant in the second design intervention. Specifically she recommends daylight sensors to switch the lights (so that the occupant does not have to be bothered). Although this particular control strategy may not be favorable to all occupants (as noted in [Illuminating Engineering Society et al. 2000]), Brina is now satisfied with her solution ($3C_{end}$). It should be noted that the in depth consideration of sensors and lighting controls by Brina was not typical to her profession, but instead delegated to the electrical engineer.

			44:03
101	$3C_{init}$	[B]	you have to figure out, you have to get enough
102	$3C_{init}$		information to do the job properly. You have to get sort of
103	$3C_{init}$		the least amount of information to do that job=
104	$3C_{init}$	[D]	ok
105	$3C_{init}$	[B]	to the best of your ability. So as soon as you understand
106	$3C_{init}$		where you're going, =
107	$3C_{init}$	[D]	[uh huh]
108	$3D_1$	[B]	[like] I now understand that this side of this room
109	$3D_1$		could be the wall sconce and this side of the room,=
110	$3D_1$	[D]	=ok.
111	$3D_1$		[uh huh.]
112	$3D_2$	[B]	[ok] and that, you know, if I put a fixture in
113	$3D_{2-3}$		the middle, and I give the daylight
114	$3D_3$		sensor here and there, near the, you know,
115	$3C_{end}$		ok, I've [got it]
116	$3C_{end}$	[D]	[uh huh]
117	$3C_{end}$	[B]	sort of solved in my mind, and
118	$3C_{end}$	[D]	[aha]
119	$3C_{end}$	[B]	[so I] can move onto the next [thing].
120	$3C_{end}$	[D]	[aha]
			44:42

Table 5. Transcript of the third stage, $3C_{init}$. to $3C_{end}$.

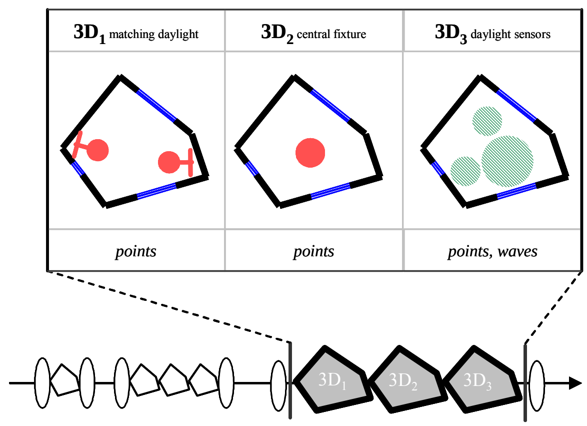

Figure 11. Excerpt of the third, and final, design intervention. Brina is content with her solution.

5.3.5 Summary

There were three stages in Brina's user test each showing an increased mastery using the visualization tool. In the first stage she started to propose a solution that integrated both daylight and electric light, but interrupted herself due to beliefs held by practice. Nevertheless, she was able to critically reflect on these assumptions and starts a second stage of design work. In this stage, she proposes a solution that she has some reservations with. Over ten minutes later, in the third stage, Brina revisits the problem and resolves it to her content.

From the perspective of building performance, Brina improved both the lighting quality and energy consumption in her proposed design. The lighting quality was improved due to her balancing daylight with electric light. Specifically, by designing two electric lighting systems (a general system, with wall sconces for highlighting) the occupant (or sensor) can chose to turn on or off one or both to make the lighting more even during daylight hours. This flexibility also has significant energy benefits since it allows for reducing lamp loads during daylight hours by the design she created.

6 Third Prototype

A modular third generation prototype is currently under development. It consists of three programs: LightSketch, Scythe and Sew, and LiQuID. LightSketch [Glaser et al. 2003] is a sketch-based interface for creating architectural lighting models. It provides a vocabulary for rapid, freeform drawing of both daylight and electric lighting systems. This informal mode of interaction allows lighting designers the flexibility of pen and paper as interface to a robust lighting simulation environment. It also develops sky models referenced in Greg's user study.

Scythe and Sew is an environment for manipulating simulation results that are generated with LightSketch. It provides a spreadsheet like framework for managing simple plots of data. This allows for ease of use (since the components are simple) as well as power (by algebraic linking of data). The later is important since for the Brina user study, she was not provided sufficient resources to navigate from the "AVERAGE" plot back into individual points of data (such as looking at clear versus overcast sky performance).

The last program under development is LiQuID. It is a module that classifies performance results by similarity and also with normative measures. It was motivated both by Brina's need to understand lighting quality in stages 2 and 3 of her user study and also to produce representative patterns in the data like the "AVERAGE" plot. One challenge that Brina had was imagining how people felt in the space. LiQuID looks to address this issue by providing representative views and times to examine as well as performance indices.

7 Conclusions

This paper has illustrated an iterative design approach towards designing a visualization system. The first stage showed a proof of concept for how information visualization could be used to manage such a complex multivariate problem as architectural lighting design. The field work described how lighting design was divided among professions. It showed that lighting designers could significantly benefit from improved daylight analysis tools. The second prototype was refined and one in-depth user study detailed how the interface could be incorporated into her work practice and lead to significant energy and visual quality improvements. Third generation prototypes are currently under development.

The "Brina" user study showed how a person was able to learn, in stages, how to utilize a visualization plot. This process allowed her to engage the drawings with both an increased architectural (by considering apertures) and engineering (by specifying controls) awareness. The new visualization of the boundary object [Star 1989; Ackerman and Halverson 1999] (the shared drawing) can enhance the communication and quality of work among professionals. There still are challenges, though, for integrating lighting information with other aspects of design like thermal performance.

Aside work on improving the software and conducting user studies, further work is needed to describe the distributed activity of architectural lighting practices. The last issue is important, for example, since in the Brina user study, the profession of lighting designer significantly impacted the individual's conversation. It remains to be seen how this type of discourse can be brought back into design offices. Other considerations such as the influence of training programs, building codes, and divisions of labor are important areas to study for stabilizing new visualization methods in practice.

Appendix

Transcript notation for "Brina" user study

Conventions were adapted from conversation analysis for coding Brina's user study (Table 6). First, time codes appear at the top and bottom (SS:SS and EE:EE) of each transcript. Utterances are numbered consecutively from the start of the analysis. A break in numbering occurs once (between lines 34 and 101) to signify about twelve minutes of the user study that were omitted from this paper. Each line is categorized into a segment code for cross referencing in the analysis and paper figures. The speaker is denoted as [D] for Dan, the person who is asking questions, and [B] for Brina, the lighting designer.

		SS:SS	
Line #	segment code	[speaker]	utterances
		EE:EE	

Table 6. Transcript notation.

Segment codes for "Brina" user study

Segment codes are labeled as follows. Design interventions are denoted by nD_X, where n is the stage and x the step. The symbol nD is used to describe all steps in an intervention (e.g. $2D$ refers to $2D_1$, $2D_2$ and $2D_3$ if there are 3 steps). Conversation segments are coded by the symbols nC_{init} and $nC_{end.}$ where n is the stage and *init* and *end* are their respective order sandwiching the design intervention.

Utterance qualifiers for "Brina" user study

Table 7 lists all the qualifiers that were used in coding the utterances of Brina's user study.

?	Rising intonation
‘	pause within a grammatical sentence
.	pause between grammatical sentences
<u>louder</u>	Emphasis: pitch and/or volume
°softer°	De-emphasize: pitch and/or volume
=	Latching: grammatical sentences connected with a pause
[]	overlapping talk

Table 7. Symbols used in the utterance section.

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