Development of Two Heliodon Systems and Recommendations for their Use

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ABSTRACT

Heliodons aid the building design process by allowing the simulation of different solar angles with respect to physical scale models. At MIT, two different variations of this setup are being developed. The first one consists of a small, portable heliodon that is manually operated, and meant for use outdoors with the real sun and sky. The second is a larger indoor setup that consists of a computer-controlled moving table exposed to a stationary light source. A computer interface allows the designer to automatically take useful sets of model photos from a camera positioned next to or inside a model. Both approaches are presented in this paper and their limitations, causes of inaccuracy and potentialities are discussed based on experimental verification and through Radiance simulations. The results of a usability study with student volunteers and a case study on an existing research space on the MIT campus are also presented.

1. INTRODUCTION

Proper daylighting design optimizes the use of natural light in order to reduce lighting energy costs and maximize the visual comfort of the indoor environment. Ancient buildings relied strongly on daylight, but after the invention of electric lighting and modern HVAC systems, many modern buildings became sealed boxes with entirely artificial indoor environments increasing energy use and becoming less comfortable for occupants (1). Studies consistently show office workers' strong preference for daylight over artificial light as well as for views of the outside world through windows (2). Health benefits from daylight are also observed (3).

While the benefits of daylit buildings are clear, designing high performances buildings that incorporate daylighting is in fact a complicated science and art. Many issues concerning direct sun must be taken into account when designing a building. These important issues include overheating, shadows cast by neighboring buildings, glare, and visual comfort. Since sun conditions change over the course of the day and also over the year, it is important to get an idea of this variety of circumstances during building design.

Many different tools are available today for daylight and sunlight analysis. These tools range from simple methods such as the use of sun path diagrams, daylight factor charts and simple rules of thumb, software packages of varying degrees of accuracy and physical model studies with artificial skies and/or heliodons.

Despite the variety of tools available, their use is often not covered in a building design budget and is considered the realm of specialists (4). Additionally, students of architecture are not always encouraged or taught how to perform these studies as part of their design studios.

Heliodons are often thought of as an excellent teaching tool because they are easy to understand and fun to use for students just beginning to learn about sun issues (5). A heliodon is an architectural design tool that physically simulates sun angles in reference to a horizontal surface. This horizontal surface, marked with cardinal directions, serves as a base to support a building scale model. By altering the position of a light source relative to the surface, any global latitude, date, and time can be simulated. Students of architecture can often use scale models they already have, though special daylighting scale model building procedures should be followed for more detailed studies (6).

Many different heliodon setups exist at various universities, companies, and other research centers. The purpose of this work is to provide versions of this tool with expanded capabilities for use by students at MIT, as well as to understand and assess the limitations and advantages associated with each one.

2. TWO HELIODON SETUPS

2.1 Automated Heliodon

2.1.1 Description of Setup

There are two heliodon setups currently available for research and design use at MIT. Developed by students, the indoor automated heliodon is used both for goniophotometric measurements and for observation of the effects of direct sunlight on scale models (7). This setup consists of a computer-controlled moving table and a fixed light source, which reflects off of a mirror before hitting the surface of the heliodon, to which the building model is attached (Figure 1). The 18-inch diameter spotlight has a spread of about 5 degrees, requiring maximization of the virtual beam distance by way of the mirror in order to better illuminate the surface of the heliodon. Table movement is controlled by two motors, which handle the azimuthal rotation of the table surface and table tilting for changes in altitude. A camera, which can be fitted with an endoscope or wide angle lens, is positioned using a flexible arm. Models are secured to the table using ergonomic clamps able to slide within radial table channels to accommodate models of varying sizes.

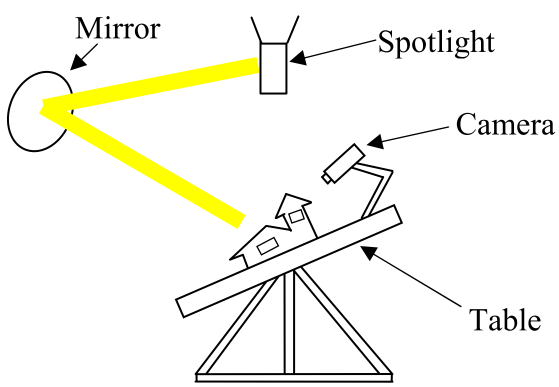

Fig. 1: The automated heliodon setup.

2.1.2 Interface Design

The interface consists of a starting screen where the user selects the testing location and building orientation (Figure 2), and then allows continuation to a display of different photo capture and display options.
Several options are available for photo capture. The first option allows photo capture of single mathematically unrelated dates and times. Second, a default set option automatically takes several images per day on four design days of the solstices and equinox; the completed set can be viewed in a matrix. Another option allows images to be taken in a series with a fixed time interval between them; for example, a user could take one image at 12 PM on the first of every month. Finally, a video option takes multiple images on a chosen day allowing them to be viewed through an interactive Flash interface as a day passing (Figure 3). These images can also be compiled into a video file.

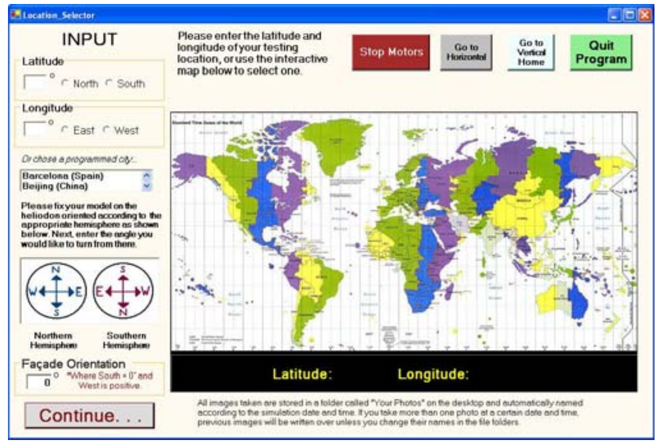

Fig.2: The opening screen from the interface.

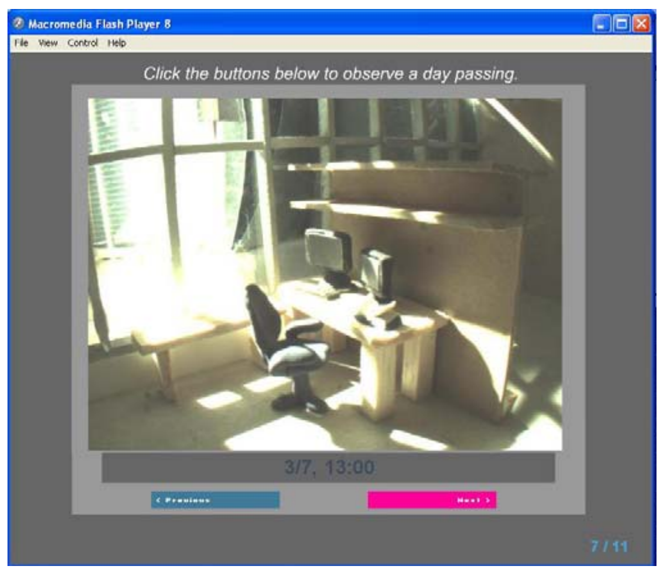

Fig. 3: The video viewing option that shows a passing day.

2.2 Portable Heliodon

2.2.1 Description of Setup

The manual heliodon is a portable device meant for outdoor experiments utilizing the real sky and sun. Designed to fit inside a rolling suitcase, its wooden components are assembled once the study location is reached. The setup is shown in Figure 4. Once assembled, the heliodon table surface has the ability to tilt and rotate to any angle and orientation. C-clamps are used to fix a scale model to the table. The entire table setup takes under 10 minutes for a first time user.

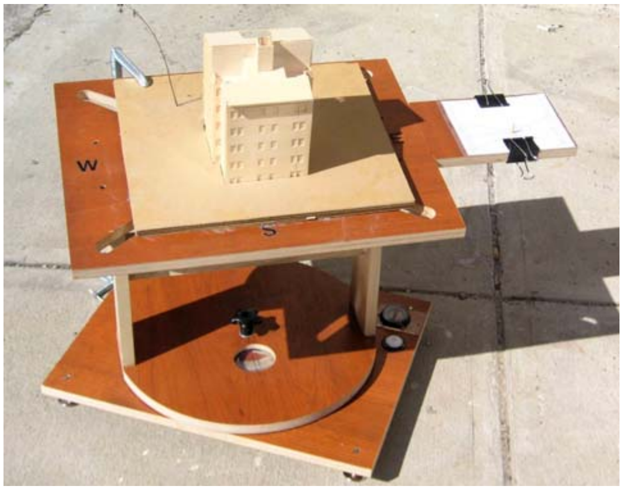

Fig.4: The portable heliodon, sunny operation.

2.2.2 Sunny or Overcast Operation

The portable heliodon has two modes of operation. During sunny weather, a sun peg diagram for the desired latitude to be simulated is chosen from a selection and fitted over a peg positioned next to the model. While watching the peg's shadow on the diagram, the user rotates and tilts the heliodon until the shadow's tip touches the marking of the date and time to be simulated. At this point the user can then take illuminance measurements or photos as desired.

On overcast days without shadows, a set of stereographic charts for different latitudes are used to look up the altitude and azimuth of both the testing conditions and the desired conditions. These four angles are then used to calculate how much the table should be moved by following angle markings on the axes of rotation without the aid of shadows.

3. PERFORMANCE ASSESSMENT

3.1 Automated Heliodon

As mentioned earlier, the indoor automated heliodon setup has a sun simulator but no sky simulator, and is thus useful for showing the effects of direct light only. However, this still makes it quite useful for a variety of studies which involve direct sunlight. For example, periods of interior glare problems and potential overheating can be assessed, and issues such as urban masking and facade orientation can be experimented with. With prepared interchangeable parts, a user can quickly try out different options such as various shading strategies or sunlight redirecting devices. The device could also be used to experiment with the placement of solar panels.

The spotlight selected has a spread of about five degrees, illuminating the surface of the heliodon in a range of 17,000 to 22,800 lux. Since the spotlight is less collimated than the real sun, the penumbra, or partially blocked area of a cast shadow, is thicker than in outdoor shadows, meaning the shadows appear less sharp. This transition region from unshaded to the umbra or darkest part of the shadow varies based on how far away the shadow casting object is from the surface; at 34 cm from the object it is 2.5 times as thick as outdoors, while at 12 cm away this is reduced to 1.6 times. Despite fuzzier shadow edges, the shadows are still easy to see and thus sufficient for the qualitative observation of where direct light and shadows fall within or outside of a model.

The motor movements of the table are accurate to within 0.5 degrees with a relatively light model and appropriate use of the table's counterweight, though this error margin can increase to three degrees with very eccentric loading. These errors may cause shadows to appear in slightly different locations than they would really be at a given moment; the significance of sun patch location errors is dependent on the scale of the model. However, the exact sun position at an individual moment is less important than understanding of the general trends through longer periods of time. Slight inaccuracies in shadow positions would only be significant in rare cases such as with a design that called for a tiny patch of sunlight to hit a certain point in a room at a precise moment of the year.

The mechanical setup is relatively easy, though basic instructions are necessary for first time users to ensure that the camera and model are positioned securely.

3.2 Simulation-Based Error Analysis for Outdoor Heliodon

Though the portable outdoor heliodon can theoretically simulate the sky conditions of any other place and time from any daylight hour at the testing site, there are some combinations of testing and theoretical times and locations that clearly give more accurate results than others. Ideally, the simulation place and time, or at least the corresponding solar altitude, should be close to that of the theoretical one. Of course, the most ideal outdoor scale model testing location is the one in which the proposed building would be constructed; the model could be tested at varying times of the day and in different weather conditions, without tilting.

Another cause of inaccuracy in these outdoor simulations is the sky vault visibility. If the heliodon needs to be tilted at a steep angle, only a portion of the model's theoretical sky dome will be comprised of real sky vault. The obstacles present in the simulated sky vault, such as buildings, concrete, or grass, also have their own optical properties which are unlikely to be similar to that of sky. The sky from the horizon will also have different brightness and color than sky that would really be overhead.

Simulations were performed to investigate the effects of these parameters on testing accuracy. The CIE standard sunny sky model was used in the tests described (8). This model was selected for its simplicity and the relative ease with which a sky can be defined. In this section, the difference between measurements obtained on a tilted scale model on a heliodon and those that would be measured in the real building are compared. The term "desired" is used to refer to the conditions one wishes to simulate; for example, a time and place on earth different from the site of the experiment. "Actual" is used to refer to the conditions where the heliodon experiment is being performed.

This replication of the outdoor testing was initially simplified to a single sensor exposed directly to the sky (not inside a scale model) and facing the same direction as the base plane of the model would for various pairs of "actual" and "desired" conditions.

The position of the sun or the particular facing direction of a sensor can be described using spherical coordinates. By subtracting a solar altitude from 90 degrees, the altitude is translated into phi (ϕ), the angle from vertical. Theta (Θ), the angle about the z axis, is equivalent to azimuth as long as azimuth values are adjusted appropriately so that $\Theta = 0$ is in the east to comply with Radiance convention (9). The angle ϕ for the sensor is calculated in equation 1.

$$\phi_{sensor} = |(90 - \beta_{desired}) - (90 - \beta_{actual})| \quad (1)$$

when $\beta_{desired} > \beta_{actual}$

$$\phi_{sensor} = |(90 - \beta_{desired}) - (90 - \beta_{actual})| + 180$$

when $\beta_{desired} < \beta_{actual}$

In order to represent these conditions simply, the azimuth of the "desired" conditions is disregarded. The calculation of these coordinates is instead dependent on the position of the "actual" solar azimuth and altitude (β), and the difference between this altitude and the "desired" one.
For this method, the value of theta used is the azimuth of the "actual" sun position.

After obtaining the appropriate values of ϕ and Θ, these are translated into Cartesian coordinates and used to define the sensor facing direction in Radiance, which gives the sensor's measured illuminance value as output. A ground reflectance of 0.2 was used. The error in illuminance, calculated by equation 2, is used to determine how closely the tilted simulation matched the conditions of the desired time and place.

% error = [("desired" illum – "actual" illum)/ ("desired" illum)]* 100 (2)

According to this method, a positive error means that the heliodon simulation of a foreign date and time would underestimate illuminance, where a negative error means that it would overestimate illuminance.

Since there are infinitely many combinations of testing location and desired conditions that one might have, the scenarios were next simplified to altitude differences between "desired" and "actual" locations for error analysis. Assuming the point of view of a heliodon user at MIT, Boston solar altitudes between 30 and 70 were examined as conditions for simulating other altitudes. Solar altitudes between 30 and 70 were used to simulate altitudes between 10 and 90. Error is calculated again as in equation 2, with the independent variable as the difference between the "actual" testing altitude and the "desired" altitude. Three sample cases are graphed in figure 5. Any of these error graphs can be consulted by a heliodon user wishing to experiment with sunny conditions at any time and place where the solar altitude is one of these values.

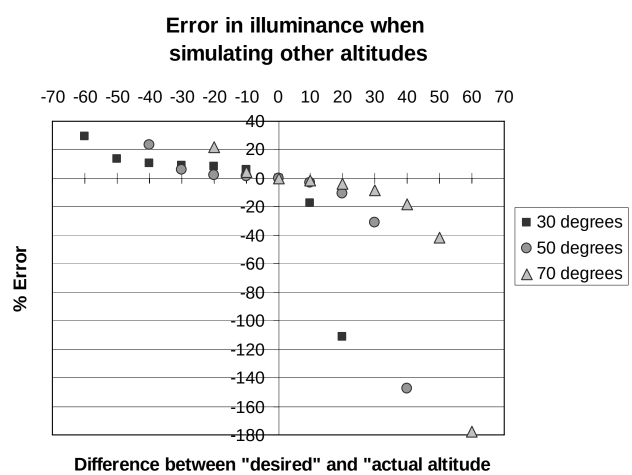

Fig. 5: Illuminance error using 30, 50, and 70 as the testing altitudes in the simulation.

The graphs suggest that using the more extreme testing altitudes (30 and 70) allows less altitude difference for the same amount of error. However, keeping the altitude difference at less than 10 degrees will keep the tilting error under 10 percent in these cases. With some forethought and luck with weather, a heliodon user can look up these altitudes before testing in order to get an altitude match that minimizes error from tilting on a sunny day. As a point of comparison, similar test sets were performed outdoors, making use of the different altitudes available throughout the day. The resulting error graphs showed the same general pattern as the Radiance results (Figure 6).

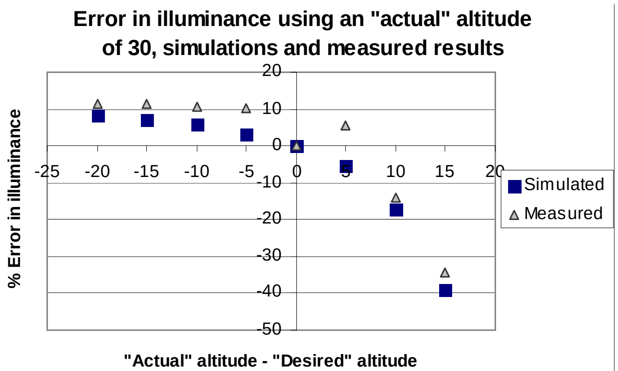

Fig. 6: Outdoor measurements compared to simulations.

According to Radiance tests with surrounding obstacles, the affect of these obstructions is quite small in comparison to that of large altitude differences, except in conditions of extremely high surroundings, though the reflectance values and placement of the obstacles affect the exact results. When a sample of surrounding obstructions consisting of three enclosing walls is less than 20 meters high, illuminance is reduced by less than 3% with an obstacle reflectance of 0.2. The number increases to 15% when the height is tripled, and decreases by several percent for each increase of 0.1 in surface reflectance. Error increases by several percent when obstacles are placed on the same side of the sensor as the sun, as they then block the brighter portion of the sky vault. In the case where an obstacle actually blocks the sun, however, error can reach over 80%.

The next stage of this study of tilting errors was to extend the simulation to whole building models. This was accomplished by performing similar Radiance simulations on a simple CAD model of a small room with several windows, containing a desk and chair. A sample of the results is shown in figures 7 and 8. The identical location of the direct sun patches in each image shows that the two cases have the same solar angle relative to the building and that the tilting method is therefore correct. In this case, the "actual" altitude on the equator is 25 degrees higher than the altitude in the "desired" conditions at 42 North during the winter. The false color maps of interior illuminance show that the "desired" illuminance is greatly overestimated, resulting in about a 40% error in illuminance for this case, which is in line with the trends predicted for the case of the bare sensor (Figure 5).

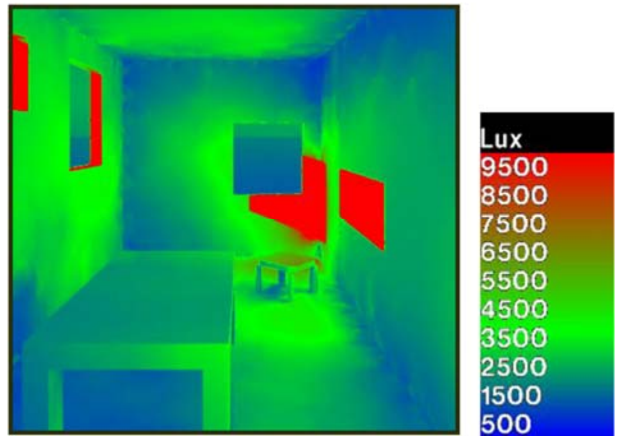

Fig. 7: 10 AM on December 21st at 42 North, no tilting.

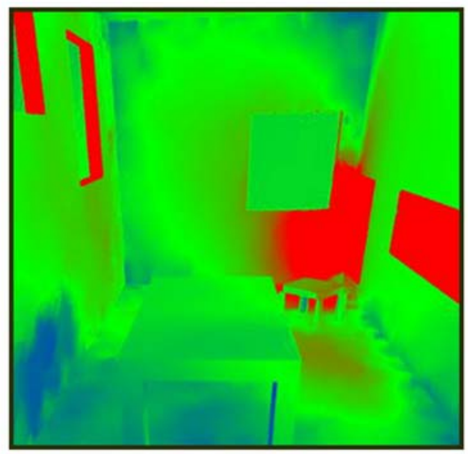

Fig. 8: Tilted simulation of 10 AM on December 21st at 42 North, using a sky at 3 PM on April 21st at zero North.

This research can be considered a supplement to studies such as Cannon-Brookes, 1997 and Thanachareonkit et al, 2005 (10, 11), which investigated the sources of model overestimation when comparisons between illuminance measured inside real buildings and corresponding outdoor scale models are made. These studies investigated cases where measurements are taken inside a building while the same measurements are taken in a corresponding model sitting next to it outdoors.
When manual heliodons are used for outdoor tilted simulations of other altitudes, there are sources of error additional to those observed in previous studies where tilting was not considered. Model overestimation without tilting appears to be consistent over various sky conditions (11) while in a case of heliodon use it can vary greatly due to the difference in "desired" and "actual" solar altitudes as shown above, as well as to very high surrounding obstructions.

4. CASE STUDY

This section presents a case study in which both available heliodons were used to perform an investigation of part of an existing building. During a review and discussion of the lab with occupants, it was discovered that the cubicles immediately adjacent to the large window were subjected to extremely uncomfortable glare conditions from a large window in the lab. Occupants had devised various strategies such as hanging up pieces of fabric, wearing sunglasses, and even designing a window-climbing robot with a collapsible shade to attempt to mitigate the glare.

Upon further investigation of the space, it was observed that the unshaded window, which faces 23.5 degrees east of south, is directly across from and next to various other reflective surfaces of the building's unusual geometry. The reflective adjacent walls, opposite window, and exterior horizontal surface are arranged in such a way that even when direct sun does not have a direct path to the lab window, as it does during early morning hours, it can have an indirect path by way of these surrounding surfaces for much longer into the day.

The goal of the project was to investigate what times this glare occurred and what reflective surfaces caused it. Additionally, methods to increase daylight penetration to the back of the room were investigated.
A model was built that could be used with both heliodons, at a scale that allowed both the inside of the office as well as the large exterior reflective surfaces to be included. Interchangeable parts were constructed in order to easily test proposed modifications of the structure, and daylighting model building guidelines were followed as strictly as possible.

First, the cause of the interior glare problems was investigated. By covering and uncovering different reflective surfaces outside of the window, it was discovered that the surface adjacent to the window was the main cause of the problem. Substituting a diffusing material instead of the shiny titanium selected would have greatly reduced the glare problem. A detachable overhang was shown to do little to help the problem. Sample photographs from these experiments are shown in figures 9 and 10.

In order to increase daylight penetration to the back of the room, two modifications were investigated. First, a miniature, detachable anidolic system was added to the window to see if it would increase daylight levels at the back of the room. This system consists of a set of parabolic mirrors able to collect diffuse daylight from a very wide portion of the sky and redistribute it inside a room (12).

Fig. 9: The inside of the lab as is, on March 21 at 10 AM. The structure visible out of the window causes high glare due to reflected light.

Fig 10: March 21 at 10 AM with a diffusing cloth covering the adjacent left exterior surface, cutting down on the reflections from the opposing structure.

The model was tested outdoors on an overcast day. For sample measurements of the interior, the average daylight factor was shown to increase with the installation. However, when hit with direct light, this system can be a major glare source, as demonstrated by experiments with the indoor heliodon (Figure 11).

The second modification to increase daylight penetration was the replacement of opaque cubicle dividers parallel to the window with translucent ones. The illuminance in the back of the room with the translucent and opaque cubicle dividers were measured on the automated heliodon for various dates and times. The comparative results clearly showed that interior illuminance increased when light was allowed to penetrate the cubicle divider.

Fig. 11: An anidolic system can be a source of glare in direct light conditions.

This investigation was considered a successful case study for many reasons. With limited training and time, a group of students was able to get hundreds of graphic representations of the causes and times of occurrence of glare problems using the automated heliodon. Clear comparisons between different options were made using interchangeable model parts with both the indoor and outdoor setups. All of the investigation was performed using only one model and allowed a time-efficient testing of several different factors.

5. USER'S PERSPECTIVE

In order to help develop the automated heliodon system in such a way that it would be used frequently by architecture design students, volunteers were recruited to test the system and interface to assess its usability.

5.1 Procedure

Students were recruited from both the undergraduate and graduate architecture programs at MIT. They were asked to bring their own models that they were interested in investigating with regards to daylight. Models were set up on the automated heliodon and participants were asked to complete a series of tasks using the computer interface. The tasks tested the students' ability to locate and use the various options available in the system; it did not test their knowledge of sun issues or the design of their particular models. The sessions were recorded and observations made about any problems the participants had completing the different tasks.

After the tasks were completed the students were asked to fill out a survey, which consisted of some questions specific to the heliodon mixed together with the ten standard questions of the widely used System Usability Scale, or SUS (13). Finally, the users were asked to comment about why and when the system would be useful for their work, and any other suggestions about the interface design they might have. Seven students performed the usability tests, which is within the 5-8 range generally preferred by usability professionals; 5 users are expected to turn up at least 80% of major usability problems (14), after which there are diminishing returns.

5.2 Results

The usability scores from the SUS questions ranged between 75 and 98 out of 100, with an average of 85, indicating a quite favorable response from the small sample size surveyed, as scores above 70 are generally considered "good." As predicted, criticisms and difficulties tended to overlap across the different participants. The common problems were that students had trouble finding certain features due to layout, didn't understand the meaning of certain options, and somewhat disliked the color choices and other graphic elements of the interface. Though this last point may seem unimportant, it is understandable when the target users are architecture students who are often very accomplished graphic artists. Additionally, it has been shown that attractive interfaces are actually perceived to work better than less attractive ones with identical functionality (15). Improvements to the interface based on these user comments will be made in future versions of the software. However, despite some initial confusion about features and how to use them without instructions, the students indicated that after completing the session they would easily be able to use any of the interface options in the future.

Additionally, the students indicated that their studio reviewers or clients would be interested in seeing this kind of photo, and that they liked the software. Opinions differed as to which stage of the design process and what kind of studies they would like to use the setup for. Five out of seven participates said that they would prefer to use the heliodon over computer simulation software, while the other two indicated that it would depend on the situation.

6. CONCLUSIONS

This paper presents the successful validation of heliodon tools meant for use by students of architecture and architects in general. The computer interface for the automated heliodon provides a large variety of image capture options that make it easier to see the effects of direct sun in different conditions. Additionally, the Radiance-based error analysis of outdoor heliodon use helps show how to minimize testing errors when quantitative results are needed. While the first priority is to keep altitude differences to a minimum, surrounding obstructions can make a significant contribution to error if the tests are performed in a dense urban setting. The case study and the results of the student survey show the heliodon's value as a tool. These very visual, physical tools promote understanding of daylight and sunlight, aiding in building design and evaluation. It is hoped that the availability and versatility of the tools will contribute to the education of architecture students in regards to natural light in building design.

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