Article

Smart Design of Portable Indoor Shading Device for Visual Comfort—A Case Study of a College Library

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Abstract: With the development of architectural technology, the use of floor-to-ceiling windows has emerged widely. The ensuing problem is that more and more students and office workers are suffering from direct sunlight while working in specific areas. Based on the pain points of the working process, this study designed a portable product for improving visual comfort through field research and environment simulation. It provided a new personalized design for blocking direct sunlight from the working area using a portable and liftable sunshade curtain, allowing the users to control the height and angle of the sunshade curtain through a mobile phone application. It can also adjust itself according to environmental parameters collected by sensors, so as to block sunlight in certain areas. A simulation based on the design features and the light environment of a library is run, proving the model effective in improving these aspects. The study aimed to provide solutions for indoor visual comfort and suggestions for future indoor household designs.

Keywords: visual comfort; smart product design; interaction design; user research; living environment improvement

1. Introduction

Visual comfort is a subjective evaluation of satisfaction with the surrounding environment [1,2]. Today, people are increasingly pursuing satisfaction, especially satisfaction with the environment. Therefore, it is of practical significance to improve the ambient light condition [3]. As representatives of modern urban buildings, many libraries use full-transparent floor-to-ceiling windows, which allow people to observe from both inside and outside. While ensuring the aesthetic qualities of the building, this structure is relatively less considerate of visual comfort in the indoor environment. Individuals are more likely to suffer from extra glare [4].

Based on current research, two main conclusions were derived from existing indoor lighting research. First, our research has shown that natural light technology can save 64% more energy compared to other institutions, so making full use of natural light can help protect the natural environment by making full use of natural energy [5,6]. According to the available data, changes in library lighting conditions can affect users’ reading, mood, comfort, and behavior in the library. Satisfaction and residence time are also affected by the light. With better sunlight, readers show more positive behaviour and favour lightened areas. Secondly, most of the current research has focused only on macro level concepts, such as form, function, space, the streamlined design of libraries and the form of future digital libraries. There have also been some related achievements in energy conservation research. Most of them are simple, producing findings on a macro level but have not conducted any specific spatial experience research. Most current studies are strategic analyses of natural light through simulation using a traditional calculating system. There is far less research that has conducted simulation analysis and collected quantitative data to propose improvements aiming at a more flexible light and climate environment. There are also relatively few studies on new shading devices and shading strategies based on light...
discomfort in college libraries. Thirdly, several studies have discussed the potential smart devices and automatic solutions for high-performance or efficient lighting environments, which inspired this research to take smart and automatic into consideration [7–10]. The library is an important place for college students to carry out learning activities. Creating a comfortable indoor environment here is conducive to improving the overall experience and learning efficiency of students [11]. At present, this area of research, especially that focusing on design and practice, is relatively sparse worldwide [9].

This project set Shanghai Jiao Tong University’s main library as the research object. The college library we chose to study is one of the most frequently used learning spaces for teachers and students on the campus. The current library reading environment features obvious pain points in terms of visual comfort. Students and teachers bring their own umbrellas to block out strong sunlight, and seats close to the window are avoided due to strong direct sunlight. These forced actions obviously affect users’ experience negatively. By focusing on the existing light environment of the library and the subjective experiences of users, this study pursues insights into existing pain points and real user needs and proposes corresponding design strategies that can improve the quality of the indoor environment of the library.

2. Existing Shading Designs

We firstly focused on the existing shading features. There are several ways to improve the existing indoor visual comfort level. We analysed the advantages as well as the flaws of the existing designs. This enabled us to propose a better shading solution.

2.1. Curtain Shaped Shading Device

The most widely used solution is curtains. Curtains are simple, mainly made from cloth, and with the development of technology, they are now being made from special materials designed to cut off sunlight, thus preventing the heating up of indoor environments and improving the building’s energy performance. A curtain is a piece of tailored fabric hung on the wall that can be moved over a window. Traditional curtains achieve very good and consistent results. They are now widely used in most indoor sites [12]. However, curtains block the view, which further reduces the benefits of full-transparent floor-to-ceiling windows.

2.2. Louver Shaped Shading Device

The louver is a better version of the curtain. It has the same purpose as the traditional curtain, which blocks sunlight from a window to ensure indoor visual comfort. The louver has been proven useful in improving light performance in modern buildings. Studies have shown that the integration of louver shading devices into buildings leads to comfortable indoor light conditions, and may lead to significant energy savings, compared to a building without shading devices [13,14]. The louver occupies part of the window space, which affects the width of the windows of a house. The concave and convex directions of the blades block the outside view. When used for lighting, it blocks the line of sight from top to bottom. At night, if the convex surface of the blades faces indoors, shadows will not be visible outside, and it is clean, safe, and easy to use.

A material with good heat insulation is used for the blades to effectively maintain the indoor temperature and achieve energy saving. The easy angle adjustment of the blades can control the incident light. Compared with curtains, blinds, which can be flexibly adjusted, have abilities that are rare in curtains. In terms of sunshade, in addition to resisting ultraviolet radiation, blinds can adjust indoor light. In terms of ventilation, the fixed installation of blinds and their thick texture ensure stability. The cascading design of the blinds ensures the privacy of the home. In addition, by combining a designer’s capacity to create louver shapes and window patterns with a generic algorithm, louvers can now be designed with more effective forms.
3. Research Procedure

We specifically chose the library in Shanghai Jiao Tong University as the research area, as it is the most used area in the university. The library contains a large number of floor-to-ceiling windows that lack efficient shading devices. A questionnaire focusing on occupants’ personal attitudes towards visual comfort was distributed in the library to collect subjective data. Basic personal information, including gender, age, clothing, and activity level, was collected. Subjective preferences related to light comfort was recorded. Visual comfort was rated on a five-point scale: comfortable, slightly uncomfortable, uncomfortable, very uncomfortable, and intolerable. A total of 239 samples were obtained in the field survey.

3.1. Preliminary Analysis of the Research Data

Because the major objective of this research was to assess the influence of direct sunlight and the interviewees’ opinions on the light environment of the library, we addressed the subjects’ locations in the library. By analysing whether their locations are near the windows or in direct sunlight, we are able to reach more precise conclusions in subsequent analyses. The locations are summarized in Figure 1. According to the survey results, the number of interviewees choosing to stay by the window (111) is slightly lower than the number of interviewees choosing not to stay by the window (128).

![Figure 1. An overview of the basic information: by a window or not.](image)

3.2. General Description of Visual Comfort

In Table 1, an overview of our survey results on the interviewees’ personal assessment of the light environment is provided. In Table 1a, the data on the light and dark preferences of the interviewees and light environmental satisfaction are listed. Generally, interviewees felt positive about the library’s light environment. As shown in Table 1b, more than half of the interviewees found the library’s light environment satisfying, but some interviewees still thought that the environment was too dark or harsh and were not satisfied with the current light environment. In addition to individual differences of perception, the main reason for this may be that the light environment at different seats is inconsistent.
Table 1. An overview of the basic information: light environmental satisfaction.

<table>
<thead>
<tr>
<th>Light and Dark Feel</th>
<th>Frequency</th>
<th>Percentage (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dark</td>
<td>1</td>
<td>0.4</td>
</tr>
<tr>
<td>Dim</td>
<td>7</td>
<td>2.9</td>
</tr>
<tr>
<td>Neutral</td>
<td>79</td>
<td>33.1</td>
</tr>
<tr>
<td>Bright</td>
<td>121</td>
<td>50.6</td>
</tr>
<tr>
<td>Dazzling</td>
<td>27</td>
<td>11.3</td>
</tr>
<tr>
<td>Very Dazzling</td>
<td>3</td>
<td>1.3</td>
</tr>
<tr>
<td>All</td>
<td>238</td>
<td>99.6</td>
</tr>
</tbody>
</table>

(b) Light Environmental Satisfaction

<table>
<thead>
<tr>
<th></th>
<th>Frequency</th>
<th>Percentage (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dissatisfied</td>
<td>14</td>
<td>5.9</td>
</tr>
<tr>
<td>Neutral</td>
<td>62</td>
<td>25.9</td>
</tr>
<tr>
<td>Satisfied</td>
<td>137</td>
<td>57.3</td>
</tr>
<tr>
<td>Very satisfied</td>
<td>26</td>
<td>10.9</td>
</tr>
<tr>
<td>All</td>
<td>239</td>
<td>100</td>
</tr>
</tbody>
</table>

3.3. Advanced Analysis of Research Data

An advanced analysis of the data collected was conducted to statistically prove the former conclusions. In the advanced analysis, the influence being by a window and being subjected to direct sunlight was specifically focused on. As shown in Table 2, we applied a $t$-test to investigate the group statistics related to direct sunlight. All of the values of significance are below 0.05, which statistically means that direct sunlight has a critical effect on the users’ experience.

Table 2. Group statistics regarding whether in direct sunlight or not.

<table>
<thead>
<tr>
<th></th>
<th>Levene’s Test for Equality of Variances</th>
<th>$t$-Test for Equality of Means</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>F</td>
<td>Sig.</td>
</tr>
<tr>
<td>Light and dark feel</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Equal variances assumed</td>
<td>2.295</td>
<td>0.131</td>
</tr>
<tr>
<td>Equal variances not assumed</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Light environmental satisfaction</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Equal variances assumed</td>
<td>12.374</td>
<td>0.001</td>
</tr>
<tr>
<td>Equal variances not assumed</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Overall comfort</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Equal variances assumed</td>
<td>19.636</td>
<td>0.000</td>
</tr>
<tr>
<td>Equal variances not assumed</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

In Table 3, the user’s satisfaction with the optical environment and the light environment, and their overall comfort, all showed higher scores when without direct sunlight, meaning direct sunlight mostly has a negative impact on user experience.

In Table 4, we see that there are significant differences between the users’ feelings towards light and dark, and their satisfaction with the light environment, between the window groups. However, the value of significance of overall comfort is above 0.05, which means, in a statistical sense, that being by the window is not critical to users’ satisfaction.
Table 3. Group statistical comparison of direct sunlight vs. not.

<table>
<thead>
<tr>
<th></th>
<th>Whether with Direct Sunlight</th>
<th>N</th>
<th>Mean</th>
<th>Std. Deviation</th>
<th>Std. Error Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light and dark feel</td>
<td>No</td>
<td>150</td>
<td>4.59</td>
<td>0.744</td>
<td>0.061</td>
</tr>
<tr>
<td></td>
<td>Yes</td>
<td>85</td>
<td>4.98</td>
<td>0.740</td>
<td>0.080</td>
</tr>
<tr>
<td>Light environmental satisfaction</td>
<td>No</td>
<td>150</td>
<td>3.87</td>
<td>0.662</td>
<td>0.054</td>
</tr>
<tr>
<td></td>
<td>Yes</td>
<td>85</td>
<td>3.48</td>
<td>0.781</td>
<td>0.085</td>
</tr>
<tr>
<td>Overall comfort</td>
<td>No</td>
<td>150</td>
<td>3.95</td>
<td>0.535</td>
<td>0.044</td>
</tr>
<tr>
<td></td>
<td>Yes</td>
<td>85</td>
<td>3.73</td>
<td>0.679</td>
<td>0.074</td>
</tr>
</tbody>
</table>

Table 4. Group statistical comparison of being by the window or not.

<table>
<thead>
<tr>
<th></th>
<th>Levene's Test for Equality of Variances</th>
<th>t-Test for Equality of Means</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>F</td>
<td>Sig.</td>
</tr>
<tr>
<td>Light and dark feel</td>
<td>Equal variances assumed</td>
<td>2.634</td>
</tr>
<tr>
<td></td>
<td>Equal variances not assumed</td>
<td></td>
</tr>
<tr>
<td>Light environmental satisfaction</td>
<td>Equal variances assumed</td>
<td>10.728</td>
</tr>
<tr>
<td></td>
<td>Equal variances not assumed</td>
<td></td>
</tr>
<tr>
<td>Overall comfort</td>
<td>Equal variances assumed</td>
<td>7.258</td>
</tr>
<tr>
<td></td>
<td>Equal variances not assumed</td>
<td></td>
</tr>
</tbody>
</table>

3.4. Research Conclusion

For library users, the light environment is generally warm and bright, and the overall satisfaction is relatively high. However, the data reflect that some readers still have a poor experience under the current conditions of the library.

The problem of direct sunlight has a serious negative impact on the reader’s experience, which is mainly related to the light environment. Direct sunlight can cause glare, reflections on the computer screen, a high ambient temperature, and many other uncomfortable light conditions. These are the current main problems in the library’s photo light environment. In addition to objective conditions such as direct sunlight and regional environmental differences, the individual conditions of different readers, such as studying habits, personal attire, and subjective feelings, also affect the overall comfort with the photo light environment.

4. Design and Implementation

In this section, we evaluate the pain points derived from the research. The Value Flow Model presents the supply and communication between an organization and its users, as well as the value flow among multiple members in the whole system. Therefore, we built a Value Flow Model for the operation of this project in the early stage as shown in Figure 2, incorporating readers, the design studio, APP, and products. These construct a four-core value proposition. Librarians, staff on duty, equipment managers, and security staff are complementary value points. Maintenance workers, manufacturers, and the network service compose the supply chain. The construction of the value stream model in this phase helps establish the overall direction of product and strategy design in the actual operation system.

We also used an affinity diagram to derive design insights. This places designer insights and observations on paper, facilitating the aggregation of information. Figure 3 is based on specific observations of the project and information derived from an affinity dia-
3.4. Research Conclusion

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The problem of direct sunlight has a serious negative impact on the reader's experience, which is mainly related to the light environment. Direct sunlight can cause glare, which reduces the picture quality. Thus, we need to adjust according to specific areas. The use scenario is an offline working environment in a company or a school. The target users are office workers or students suffering from direct sunlight.

The light environment is warm and bright, and there is a lack of shade. The solution to the snowball problem is to create an offline environment. Taking the library as an example, the main problem is the direct sunlight. The design is a portable product for improving visual comfort, thus constructing a sun-responsive shade. The shape of the device when closed makes it easy to carry, and it can be placed anywhere the user wants.

The research based on specific observations of the project and information derived from an affinity diagram. The information obtained is divided into three parts: user feeling, actual conditions, user needs.

4. Design and Implementation

4.1. Design Expectations

Based on the pain points derived from the research, this study sought to design a portable product for improving visual comfort, thus constructing a sun-responsive shade. The shape of the device when closed makes it easy to carry, and it can be placed anywhere the user wants.

The device should be of a portable size. The appearance of the product is a cuboid. The sunshade curtain is hidden inside the device when it is not activated. The cuboid operation system.

The main functional expectations are listed below.

- The product consists of a photosensitive sensor, a temperature and humidity sensor, a total solar radiation intensity sensor, a data recorder, a connector, a single-chip microcomputer, an LED display screen, and a shading film (Figure 4).

- The product and the mobile phone application work together to implement information collection and communication. When a relatively high number of sunshades are used in a specific area, such as a library, sensors in the sunshades can collect data automatically change the lifted height of the sunshade curtain according to environmental parameters, such as temperature and humidity, and publish the data on the application, keeping the user informed of the latest information related to the building’s environment.

- The design studio is an integral part of the feedback cycle. The product is continuously improved according to the users’ personal needs, the device can be switched on or off on the mobile phone application.

- The device can be controlled by either the mobile phone application or the IP address. The mobile phone application helps us establish the overall direction of product and strategy design in the actual operation system. The main functional expectations are listed below.

- Equipment Supply Service
- Maintenance Worker
- Manufacturer Equipment Supplier
- Network Service

4.2. Product Design Workflow

The value flow model. The value flow model presents the supply and communication between an organization and its users, as well as the value flow among multiple members in the whole system. Therefore, we built a value flow model for the operation of this project in the early stage as shown in Figure 2.

4.3. Affinity Diagram

Affinity Diagram. The affinity diagram. Based on the pain points derived from the research, this study sought to design a portable product for improving visual comfort, thus constructing a sun-responsive shade. The shape of the device when closed makes it easy to carry, and it can be placed anywhere the user wants.

Figure 2. The value flow model.

Figure 3. The affinity diagram.
4.1. Design Expectations

Based on the pain points derived from the research, this study sought to design a portable product for improving visual comfort, thus constructing a sun-responsive shading system. The main functional expectations are listed below.

First, the device should be of a portable size. The appearance of the product is a cuboid. The sunshade curtain is hidden inside the device when it is not activated. The cuboid shape of the device when closed makes it easy to carry, and it can be placed anywhere the user wants.

Secondly, the process of controlling this device should be simple. The main target users of this device are students and office workers, so we designed a mobile phone application to control the sunshade.

Thirdly, with the sensors we put inside the device, it can automatically adjust the height of the sunshade curtain to ensure shading effectiveness. The design can automatically change the lifted height of the sunshade curtain according to environment parameters collected by sensors inside the device, helping it to keep a specific area covered. According to the users’ personal needs, the device can be switched on or off on the mobile phone application.

Fourthly, the product and the mobile phone application work together to implement information collection and communication. When a relatively high number of sunshades are used in a specific area, such as a library, sensors in the sunshades can collect data relating to environmental parameters, such as temperature and humidity, and publish them on the application, keeping the user informed of the latest information related to the building’s environment.

4.2. Product Design Workflow

Based on design expectations and existing designs, this study developed a portable intelligent indoor liftable shade, called ‘SUNSHADE’. The SUNSHADE allows users to shade specific areas. The use scenario is an offline working environment in a company or school. The target users are office workers or students suffering from direct sunlight.

The product consists of a photosensitive sensor, a temperature and humidity sensor, a total solar radiation intensity sensor, a data recorder, a connector, a single-chip microcomputer, an LED display screen, and a shading film (Figure 4).
A customized shell comprises the main part, which can be raised and lowered, and has a small volume and a light weight. The photosensitive sensor, temperature and humidity sensor, and total solar radiation intensity sensor are integrated into the 3D-printed shell of the lifting part and connected to a single-chip microcomputer through a connecting rod.

The single-chip microcomputer is integrated in the shell of the 3D-printed main body and electrically connected to an LED screen to display the information. The main body is placed on a surface that needs to be shaded. As the sensor senses the light environment, the light environmental data will be displayed on the LED screen. The program written in the single-chip microcomputer processes the light environment data and controls the movement of the motor, so that the shading film and the flexible OLED screen rise together to achieve the shading effect. The light environment data are synchronously transmitted by the single-chip microcomputer to the LAN for processing storage. All sensors are highly integrated in the housing to ensure the uniformity of the product’s appearance. Each part is customized by 3D printing, which has high applicability and adaptability. The product is light and easy to carry. The intelligent control of each sensor ensures adaptation to different areas. This means that the product can be applied to different light environments and change automatically according to the specific characteristics.

We have determined the following four requirements for our product: it must be convenient, easy to operate and intelligent, and it must be capable of environmental collection. First, according to the requirements of convenience, the shape of the product is rectangular, with the lower parts being slightly larger, and the upper part a little smaller. The regular shape can enhance the overall stability of the structure. When modelling, the lightweight design of the product is enclosed to reduce the wall thickness as much as possible. Regarding the steering gear, the shaft requires some bearing parts, such as an improved support structure and a stiffener. After stress analysis, the topology of the structure is optimized, and to make the structure stable, the weight is optimized. In order to make the form simple and facilitate the folding of the part of the structure used for shading, we chose a hinge structure. This structure can not only guarantee the scaling of the sunshade, but it can also endure much usage, ensuring its stability and long-term usage (Figure 5).
To make our products more sustainable, we hope to use environmentally friendly materials for shell construction. Some large enterprises, such as Nike and Adidas, collect marine garbage, plastic bottles, woven nets, and other materials, and then recycle them into the soles of their shoes, which have a good supporting performance and can meet production requirements. In order to make the product more intelligent, as well as reduce the user’s use burden and learning cost, we have added a variety of sensors into the product. The top of the product is equipped with a number of photosensitive sensors, humidity sensors, temperature sensors, carbon dioxide sensors, PM2.5 detection devices and illuminance detection devices. The MCU receives sensor information to adjust the height of the sunshade. In addition to receiving sensor information, each device itself can determine the local environment model according to its location, incorporating year-round sun trajectory and temperature and humidity information, to adjust the device. These devices also do not operate independently; they can form an information collection and communication network. Several nearby devices can collect environmental information in the region, ensuring the accuracy of the mutually authenticated data. After a long period of environmental information collection, they can use these data to further optimize the environment.

4.3. Corresponding APP Design

To build the mobile phone application corresponding to the SUNSHADE device, we designed a prototype user interface in Figma. The process is divided into the following parts.

First, users of SUNSHADE can register an account in the initial page. Users can use their school accounts or telephone numbers to register.

As shown in Figure 6, After registering, the location of the user will be shown on a map of the area where the SUNSHADE is available. Sliding up from the bottom, detailed information of the environmental parameters and user distribution are shown, including the current humidity, temperature, carbon dioxide concentration and particulate matter 2.5 concentration.

Figure 6. App information page.

If the user has decided to use one of the SUNSHADE devices, he or she can choose to either scan the QR code on the device or enter the number of the device to unlock it. After successfully unlocking one of the devices, the controlling interface shows the device information (Figure 7), which includes the number and location. Considering that the light environment in different areas varies significantly, and different individuals have different personal feelings about the environment, a specific function is incorporated. The users can choose between auto adjustments and manual adjustments. When choosing the auto follow mode, the SUNSHADE will adjust the height of the curtain itself, keeping
its user shaded. Alternatively, the user can turn on the manual adjustment mode, which allows them to choose from a range of options between completely closed and completely open by sliding a slide block. If the users find any problems with the device, such as mechanical malfunctions, they can use the report button in the top right corner. Staff will work on the feedback.

After the user has finished using SUNSHADE and plans to lock the device, he or she can click the “stop using” button at the bottom of the screen and enter the finishing interface. The finishing interface shows the exact locking time and the period of use.

As shown in Figure 8a, the user’s personal information interface is divided into four parts: “My credit”, “usage record”, “feedback record” and “settings”. We have also designed a real-name qualification section. Users can qualify themselves by entering their real name and identity number.

In the “My credit” part (see Figure 8b), we have designed a credit system, including a 12-point credit record. When the user exhibits unfavourable behaviour, such as forgetting to lock the SUNSHADE after using it, one point will be removed. When the credit score is below zero, the user is qualified as unruly, and will be banned from using the SUNSHADE. After a certain period of time with unfavourable behaviour, the credit will naturally recover. In the “usage record” section, every time the user has used the SUNSHADE will be recorded and shown. The usage record includes the using location and duration. In the “feedback record” section, a feedback record is listed. Users’ feedback is shown. In the “settings” part (see Figure 8c), five columns are shown, including “account and security”, “legal terms”, “manage personalized recommendations”, “about us” and “version update”. The version update section shows the latest version of the application and reminds the user to update the application whenever a new version is uploaded. The “about us” section shows details of the application and provides the contact number of the developers.

The user’s personal information interface is hidden on the left side of the screen, so it will not bother users during regular use. When the user needs to check his or her personal information or credit, a leftwards slide will call up the personal information interface. 

Figure 7. Product controlling page.

Figure 8. Cont.
5. Design Evaluation

5.1. Lighting Simulation

The most uncomfortable aspect of the library’s light environment is glare, and some of the simulations we have performed to verify the effectiveness of the designed device have been conducted from the perspective of whether it can solve the glare problem [15,16].

Glare is a condition that causes visual discomfort and reduces the visibility of objects via inappropriate luminance distribution in the visual field [17,18]. The glare in the library under study is mainly caused by excessive luminosity outside the window. The degree of uncomfortable glare is assessed on the glare index, which indicates the contrast between a glare source (characterized by its size, luminance, and position inside the field of view) and the average luminance of the background [19,20].

The indoor glare comfort evaluation index used in this study is Daylight Glare Probability (DGP), which is an index used for evaluating the degree of glare caused by strong solar insolation in the room and is obtained by analysing the difference in brightness in the line of sight, the orientation of light in the line of sight, and the subjective level of human comfort. Compared with older glare indicators (e.g., UGR, DGI, CGI, VCP), DGP

In the “My credit” part (see Figure 8b), we have designed a credit system, including a 12-point credit record. When the user exhibits unfavourable behaviour, such as forgetting to lock the SUNSHADE after using it, one point will be removed. When the credit score is below zero, the user is qualified as unruly, and will be banned from using the SUNSHADE. After a certain period of time without unfavourable behaviour, the credit will naturally recover. In the “usage record” section, every time the user has used the SUNSHADE will be recorded and shown. The usage record includes the using location and duration. In the “feedback record” section, a feedback record is listed. Users’ feedback is shown. In the “settings” part (see Figure 8c), five columns are shown, including “account and security”, “legal terms”, “manage personalized recommendations”, “about us” and “version update”. The version update section shows the latest version of the application and reminds the user to update the application whenever a new version is uploaded. The “about us” section shows details of the application and provides the contact number of the developers.

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The most uncomfortable aspect of the library’s light environment is glare, and some of the simulations we have performed to verify the effectiveness of the designed device have been conducted from the perspective of whether it can solve the glare problem [15,16].

Glare is a condition that causes visual discomfort and reduces the visibility of objects via inappropriate luminance distribution in the visual field [17,18]. The glare in the library under study is mainly caused by excessive luminosity outside the window. The degree of uncomfortable glare is assessed on the glare index, which indicates the contrast between a glare source (characterized by its size, luminance, and position inside the field of view) and the average luminance of the background [19,20].

The indoor glare comfort evaluation index used in this study is Daylight Glare Probability (DGP), which is an index used for evaluating the degree of glare caused by strong solar insolation in the room and is obtained by analysing the difference in brightness in the line of sight, the orientation of light in the line of sight, and the subjective level of human comfort. Compared with older glare indicators (e.g., UGR, DGI, CGI, VCP), DGP is the most up to date index used to evaluate glare derived from daylight. The calculation formula (Figure 9) and evaluation process of DGP (Table 5) are as follows [3,21].

![Figure 9. Evaluation formula of DGP.](image)

**Figure 9.** Evaluation formula of DGP.

**Table 5.** DGP evaluation level and range.

<table>
<thead>
<tr>
<th>Glare Level</th>
<th>DGP Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intolerable Glare</td>
<td>0.45 &lt; DGP</td>
</tr>
<tr>
<td>Disturbing Glare</td>
<td>0.4 &lt; DGP &lt; 0.45</td>
</tr>
<tr>
<td>Perceptible Glare</td>
<td>0.35 &lt; DGP &lt; 0.4</td>
</tr>
<tr>
<td>Imperceptible Glare</td>
<td>DGP &lt; 0.35</td>
</tr>
</tbody>
</table>

For this model and simulation, the Ladybug and Honeybee platform is used in Rhino’s parametric plug-in Grasshopper, a parametric lighting performance analysis plug-in group based on the Grasshopper platform [22–24]. Honeybee combines Grasshopper with other building performance analysis software, such as Radiance, Energy Plus, Daysim and Open Studio, to simulate building interior glare using specific cell sets, see Figure 10.

Regarding the creation of the library model, since the building plan is E-shaped and the three reading rooms, A, B and C, are similar in layout, only one model (of reading room A, as shown in Figure 11) is created for simulation. In the simulation, the model is given materials and local climate data, and sky data are imported. As for the viewing angle, in our analysis, the DGP index is measured at the “eye level” (Figure 12) of a green mannequin sitting at a desk near the west window, with its line of sight parallel to the...
side wall (the mannequin’s eye view angle used for the glare check). The eye level of the mannequin was set at 1.1 m from the floor [25].

Figure 10. DGP simulation of calculated battery packs in Grasshopper.

Figure 11. The model of reading room A.

Figure 12. The mannequin’s eye view angle.
In our simulation, based on the results of field research performed in the library reading room and data from a student questionnaire, we selected typical days at typical times, and conducted an analysis of glare data before and after the installation of the designed SUNSHADE device, so as to verify the effectiveness of this device. We selected the typical times of 6:00 p.m. on 20 February, 6:00 p.m. on 31 April and 5:00 p.m. on 30 December, and measured the DGP index of the A400 reading room before and after the installation of the SUNSHADE device by simulation.

According to the results of this simulation (Figure 13), before the installation of the SUNSHADE device, the glare problem at the selected specific time was more serious, and the DGP index scores all exceeded 0.45, reaching unbearable glare levels, and even reaching a maximum value of 1 at 5:00 p.m. on 30 December. After the addition of the SUNSHADE device, the DGP index dropped significantly, with all scores less than 0.35, denoting imperceptible glare, showing that the light environment reached a more comfortable state.

![Figure 13. DGP index and data images.](image)

### 5.2. Design Evaluation Results

From the simulation results, it can be seen that the designed shading device solves the glare problem on a typical day with comparative effectiveness and reduces the glare index to a level below imperceptible glare. Since we selected the typical time of day at which the glare problem is more prominent for the preliminary research, these results are still more illustrative, and can prove the effectiveness of the device when used for shading. Although there were some specific times at which the shading effect was not as good as expected, the device is still able to solve the problem in general.

### 6. Conclusions

According to former studies, as well as research conducted on the library environment and its users, we propose a smart design for a portable indoor shading device, used for light comfort. We make two major contributions in this work, as follows:

We conducted research based on the library’s light environment and users’ information, analysing via simulation and quantitative data, which has rarely been carried out before. As a result, we derived the exact pain points and deduced solutions.

We proposed a solution to the pain points by designing a new physical product. The product is designed in a new mechanical form. It uses internal sensors and a single-chip...
microcomputer to collect and process data, so it can adjust the shading mode itself. The corresponding mobile phone application provides a full system of use.

The simulation related to glaze shows that the proposed design obviously improved the light environment of the library. Furthermore, this design is able to build a network by sharing the collected data, meaning it can provide more insight for further optimization. There are still some issues that require further research. First, availability tests could be conducted on the proposed design. Proper availability testing can identify more potential problems of the design, enabling it to be optimized. In addition, the further usability of the data collected by the proposed design remains to be assessed.

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