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# Ergonomic Natural-Solar Lighting Systems in Museum of Artworks*

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## ABSTRACT

Display of artwork is the primary function of the museums of artworks and the ability to see and enjoy visiting the museum is their sublime function. Accordingly, using light, as one of the basic elements of visual perception, is one of the ways to enhance the function of the museum and make space enjoyable for humans. Therefore, studying how to use ergonomic lighting (as human-centered knowledge) in the form of natural-solar lighting systems as the most complete spectrum of light can be an effective step in improving the function of museums of artworks[1]. The main hypothesis of the present study is that ergonomics can be applied in the lighting of museums of artwork and it is also attempted to answer an applied question: how are ergonomic natural-solar lighting systems designed for these museums? The present study is qualitative-applied research in which basic studies are carried out through library research and the data are processed using content analysis. Moreover, the SWOT technique is used to more precisely examine the components discussed in the research literature section, and the related software is used to study the principles of ergonomic lighting to scrutinize the results in the findings section. Top natural lighting systems are more suitable for lighting in the museums of artworks than side lighting. A closer examination of natural lighting systems widely used in museums shows that the photovoltaic systems are the most appropriate ones for natural lighting in the museum, followed by light shield, light pipe, and light shelf. The satisfaction of visual indicators of ergonomic lighting based on the high-quality natural light provides the desirable lighting in the museums. Combining photovoltaic shades with light shields can optimally distribute the light while controlling glare, luminance, shading, and contrast in museums of artworks. In the process, it is appropriate to consider side lighting systems to provide a visual connection between the interior and exterior spaces as well as to landscape the space in the museum.

**Keywords:** Museum of Artworks, Ergonomic Lighting, Natural Lighting, Natural–Solar Lighting Systems.



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# 1. INTRODUCTION

The primary functions of a museum are to collect, display and preserve artworks. Allowing the visitors to see, understand and enjoy visiting the artworks is a more important quality that, if not generalized, not only the function of the building, as a museum, is questioned but also, the building becomes just an archive of artworks (Maghsoudi, 2009, p. 57). Above all, the ability to see and understand artworks in museums is particularly important due to the type and variety of artworks. Using light as one of the elements of space design in architecture (Pirmohammadi, Ahmadi, & Sharifi, 2014, p. 2) as well as the basic element of visual perception is one of the ways to enhance the function of the museum, to motivate and satisfy visitors and to make the space enjoyable. This is more important in spaces like museums, where the radiant destruction of some artworks due to prolonged exposure to infrared and UV rays.

Ergonomic Lighting, as a branch of environmental ergonomics, is a science dealing with the design of light for the provision of physical and mental health of the users, their optimum performance, satisfaction, and comfort. Studies show that the intensity, type, source, color, direction, and distribution of light in places can greatly influence individuals' behavior, mood, and performance (Pourdeihimi & Haji Seyedjavadi, 2008, p.67). In this regard, from an ergonomic point of view, lighting, depending on the realization of quantitative and qualitative indicators, leads to significant results. Among others, the spectrum of sunlight, as the ultimate source of light, brings the best fundamental results for users (Javani quoted from Stephenson, 2011, p. 16). Therefore, designing a lighting system and considering strategies such as natural-solar lighting systems in architecture can be considered as an effective step towards achieving ergonomic lighting conditions. Figure 1 shows the morphology and structure of the problem statement and the necessity of the present study.

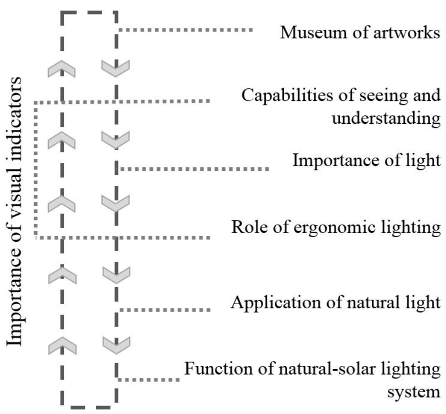



**Fig. 1. Problem Statement Morphology: Ergonomic Lighting Based on Natural-Solar Lighting Systems in Museums of Artworks**

# 2. METHOD

The present study aims to investigate the application of ergonomics in the lighting of the museums of artworks. In this paper study, it is attempted to answer the following practical question: Which natural-solar lighting systems are effective and applied in improving the display of artworks in the museums? This study is qualitative, applied research in which basic studies and information are collected using library research and the data are processed deductively, based on scientific facts to achieve rational conclusions. To this end, first, the basic keywords, based on the morphology of the problem statement, are applied as the research literature in the phase of data extraction. In the next step, the pairwise commonalities of components are studied and extracted as "research findings" according to the comparative analysis of key criteria described in the literature section. In this step, to precisely investigate the mutual use of each two components, the SWOT technique is applied. In the final step, the commonality of the three components studied is investigated and discussed to explain the use of ergonomic natural-solar lighting systems in museums. Figure 2 illustrates the study process of the present research schematically.

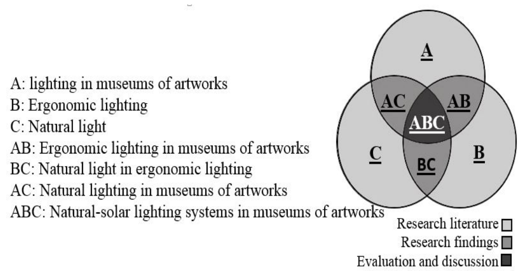



**Fig. 2. Morphology of the Study Process**

In the present study, the data are processed using descriptive-comparative content analysis, based on information obtained from data collection. In this process of processing, the considerations of optimal lighting in the museums of artworks are explained and accordingly, the ergonomic criteria applicable in the lighting of museums of artworks are extracted.

Then, given the significance of the criteria, a coefficient of impact (ranged from 1 (low) and 3 (high)) is assigned to them. Then, to achieve a suitable natural lighting pattern for the museums of artworks, based on the ergonomic principles, the studied natural-solar lighting systems, considering their advantages and disadvantages, are scored from 5 (highest score) to 1 (lowest score) based on the degree to which they are effective in the fulfillment of each criterion, and finally, the scored are averaged. In addition to the aforementioned system, Zumtobel ELI/ LENI Calculation software[2] is used to examine the data and to scrutinize the results. In the software, standard ergonomic lighting in each function (use) and space (such as a museum) is considered as a default, and then the quality of ergonomic lighting in that space is determined by answering a number of qualitative questions about the factors affecting the realization of ergonomic lighting indicators. These indicators consist of three visual and two non-visual criteria. In the present study, considering the importance of maximum visibility and a better understanding of the environment and artwork in museums, visual criteria, including performance, comfort, and visual satisfaction are considered.

## 3. RESEARCH LITERATURE

What is less seen in research on museums and similar studies is the practical way to achieve the optimal performance of a museum, especially museums of artworks, including the spatial and architectural composition, the appropriate lighting in such a space, the environmental factors suitable for such spaces and so on. Of course, several studies have been performed on light and its importance in architecture - especially with regard to its effects on humans and the energy crisis in the modern age. In recent decades, one of the effective step taken to separate space-uses to define standard quality conditions for the use and design of natural and artificial light is the book entitled "The SLL Lighting Handbook" by the Society of Light and Lighting directed by the Institute of Building Service Engineers (CIBSE, 2009). In a part of this research, which focuses on the spaces in the museums of artworks and galleries, proper display of artworks, minimization of possible damage to artworks, legibility of the space architecture, provision of a suitable bed for reaction in emergency and critical conditions are noted as the items necessary to be considered when addressing the issue of lighting in museums as audience-centered and artwork-centered space.

From an ergonomic view of point, as a human-centered knowledge applied to improve human-environment performance, lighting space brings important outcomes. Ken Parsons (2000), in some studies, such as "Environmental Ergonomics: A Review of its Principles, Types, and Procedures", attempted to explain and clarify optimal environmental ergonomic conditions including ergonomic lighting on behalf of International Organization for Standardization (ISO); in the series of studies on the environmental ergonomic effects, four major categories of human responses, individual and spatial efficiency, human health, convenience, and comfort have been emphasized. Therefore, ergonomic lighting, especially in natural-based conditions, in art galleries is expected to be considered as an important step in improving performance and efficiency, especially in natural light-based conditions due to its significant effects on human health and the improvement of visual components (Ghiabaklou, 2013). However, since ergonomics has been literally defined as a science of natural and optimal laws and principles of working and originally used in the design of equipment, up to now, its use is mainly limited to the working and educational spaces (area). Therefore, the gap in the application of this useful knowledge in research and functional designs is the use of environmental ergonomic effects in some other functional areas such as cultural spaces, museums, and galleries, that the required condition for their success is seeing and being seen under the right light. Therefore, in this section, the keywords such as lighting in museums of artworks, ergonomic lighting, natural light, and lighting are described respecting the morphologies of the problem statement and the research process and their research backgrounds are examined.

### 3.1. Lighting in Museums of Artworks

The use of light in museum design is an essential measure to make the artworks visible, which can lead to exciting sensory attractions, aesthetic reception and conceptual expression in space. Furthermore, the importance of lighting in gallery space has been increased due to the radiant destruction of some artwork. Therefore, balancing the different aspects of the design has given rise to a range of considerations in museum lighting. In other words, the lighting in the museum space has multiple functions, some of which are optimizing the display of artworks, reducing the destruction of artworks, supplying and displaying space architecture, providing security and facilitating the emergency exit (CIBSE, 2009, p. 198). In this process, the problem is not merely the provision of light. The main problem is to adjust light sources to create a proper environment and optimal visual conditions (Farzi, 2009, p.15). An architect attempts to design spaces with which the user can interact and act comfortably in optimal environmental conditions (Ghiabaklou, 2013, p. 27). In light of all the above, the challenge of lighting design in the museum includes the considerations listed in Table 2. Each challenge depends on key criteria such as illuminance (brightness intensity), luminance, shading, and other items specified in a bold form in the description column of the aforementioned table.

### 3.2. Ergonomic Lighting

The focus of ergonomics is human and its aim is to provide health and optimal comfort conditions for him (Weerdmeester & Dul, 2011, pp. 1-2). Since light is the key environmental tool in the realization of vision and perception, in the study of ergonomic lighting, it is a necessary step to consider the mechanism of vision and phenomena associated with the visual system and lighting of the environment (Table1).

**Table 1. The Basis of Examination of Ergonomic Lighting**

| Mechanism of Seeing | Phenomena Related to Visual System and Lighting of Environment |
|---|---|
| Light is a part of the electromagnetic spectrum perceived as color after colliding with the retina of eyes (Heidari, 2012, pp. 21-22). White light is composed of different wavelengths that the human eyes separate them in the process of seeing them and distinguish them as color (Ghiabaklou, 2013, p. 4); due to the different number of pigments in the retina, different wavelengths have no the same effect on human vision, and the yellow-green and red-blue wavelengths have the highest and the least effect on the vision, respectively. So, the color of the objects is meaningful when light collides them, meaning the color (Ibid, p. 4), in addition to the need for light to be seen, depends on the light itself. This is important in controlling the destruction of the light spectrum in the environment while maintaining optimum visual quality for humans. | An optimum level of visual performance is achieved when the disruptive and distracting factors are removed or controlled and the quality components are enhanced. Table 3 summarizes the important phenomena and describes effective factors. The keywords are highlighted in bold. |

Parsons (2000, pp. 589-590) believes that in the formation of humans' reaction and behavior in the environment, the benefits of ergonomic lighting conditions can be studied due to their impact on human health, user comfort, his action and performance, especially visual performance, because light is a factor directly affecting eyes, other organs, the way and amount the body operates and the behavioral reactions relying on it. On the other hand, the issue of light color affects a human's spirit and productivity, in addition to applied effect (Weerdmeester & Dul, 2011, p. 87). Accordingly, the purpose of ergonomic lighting can be examined in four major categories: safety and health, optimal performance, user comfort and satisfaction, as well as aesthetic aspects (CIBSE, 2009, pp.118-122). Accordingly, and generally, the main indicators of ergonomic lighting are including visual performance, visual comfort, visual satisfaction, vista, and empowerment (Zumtobel Staff, ELI Calculation). Meanwhile, in a space such as a museum with a focus on visual activities and the importance of seeing and being seen in the scope of lighting, in the initial step of designing, the space architecture is responsible for the three ergonomic visual indicators including visual performance, visual comfort and visual satisfaction. These three indicators depend on the factors described in Fig.3.[3] These factors, based on the requirement of achieving an optimum quality of lighting in space, were extracted depending on the control of the components causing health, mental and visual disorders, and creation and promotion of positive outcomes of lighting described in Table 3.

## 3.3. Natural light and lighting

The term "natural light" means a combination of three terms: daylight, sunlight, and skylight. (CIBSE, 2009, p. 18). Proper use of natural light requires consideration of regional climatic-environmental conditions (Heidari, 2012, pp. 31-32). For lighting in architecture, this is possible when the area has a good amount of sun hours and at least good lighting. As the ultimate light spectrum, natural light is adaptable with human body biology and his visual reactions, so it is the best source of lighting to meet visual needs (Ghiabaklou, 2013, p. 4). In addition to continuous and various effects of light contrast in space through natural light, which provide an opportunity for adaptation to the human eye and prevent eyestrain (Pourdeihimi & Haji Seyedjavadi, 2008, p. 71), such a light, due to the variable spectrum during the day, has a good uniformity, but due to the depth of its penetration into space, a proper design must be applied to cover the space with a good degree of uniformity. Additionally, the high color rendering index (CRI) of natural light is the best source for color recognition and viewing objects such as artwork (Boyce, Hunter, & Hewlett, 2003, pp. 16-18). This increases the importance of using natural light in museums. Based on the Biophilia hypothesis suggesting the affinity of human beings with the natural world, individuals tend to connect with the outdoors in some way (Boyce et al., 2003, p. 30). Introducing natural light into space, especially if combined with landscaping, is one of the most effective ways to connect indoor and outdoor. Research shows that the distribution of natural light in space results in reduced stress and temporary depression of its users (Boubekri, 2008, pp. 77-78). Dynamics of intensity and flexibility in natural light color have positive effects on human's comfort and mood in the environment (Bommel, Beld, & Ooyen, 2002, p. 5). Satisfaction is the result of a sense of general comfort and thereby, the result of the evaluation of the human senses (Ghiabaklou, 2013, p. 28). "Natural light" factor, while keeping health, provides better and more desirable conditions for individuals by creating a connection between them and the natural environment. Similarly, it provides visual comfort on one hand and increases the sense of satisfaction on the hand while enhancing visual performance (Pourdeihimi & Haji Seyedjavadi, 2008, p. 68). However, natural light has some disadvantages such as low penetration depth, reflection on some polished objects, lack of persistent and widespread uniformity, the possibility of glare (Zareiy & Ghiabaklou, 2012, p. 6; Innes, 1993, p. 2), and high UV rays (Shawn & Innes, 1993, p. 2). Since complete simulation of the quality and benefits of daylight is impossible and connection with the outside environment through natural lighting is considered an effective connection for users (Shawn, 1999, p. 4) and for other reasons, such as the economic justification and energy consumption of lighting, if protection issues permit, the daylight is preferred (Ghiabaklou, 2013, p. 295). Moreover, its possible disadvantages can be offset by the installation of appropriate lighting systems.

The optimum use of natural light depends on how it is imported and distributed, the amount of light in space, and the control of some of the disturbing factors while enhancing its potential, and this is conditional on the use of appropriate lighting systems. These systems have been designed with the three major objectives of receiving, controlling, and transmitting natural light (Ghiabaklou, 2015, p. 157) to bring natural light to a deeper depth of space, as well as quantitative and qualitative control and distribution of light in space (Littlefair, 1990, p. 1). Each system has a variety of capabilities and features that make it suitable for different purposes. Table 4 summarizes the most common natural-solar lighting systems used in artwork museums[4].

**Table 2. Considerations of Lighting in Museums**

| Considerations of Lighting in Museums | |
|---|---|
| **Radiant Destruction** | The sensitivity of the material to light, **the illuminance, intensity and type of beams emitted to the object**, the duration of light exposure to the artworks, and the type of protection of the objects affect the phenomenon of radiant destruction. About the spectrum of light beams, the visible part realizes the phenomenon of seeing, and **its ultraviolet and infrared rays** cause the destruction of artworks (Maghsoudi, 2009, p. 60). Accordingly, and based on a ten-year evaluation, the works are classified into three categories in terms of sensitivity to light: a.Works with high sensitivity, including paper, cloth, carpet, objects containing vegetable or animal components; b. Works with moderate sensitivity, including oil paintings on canvas, most wooden works with natural color, bone and ivory; and c. Works with no sensitivity, including metals, stone objects, ceramics, glass, and wooden objects with no natural color (Shawn, 1999, p. 5). In the museums of artworks and according to the history of the galleries in these museums, the works mainly fall into the second and third categories. |
| **Illuminance** | In general, low **illuminance (brightness intensity)** in a space results in disturbed seeing and detection and high brightness intensity causes radiant destruction (CIBSE, 2009, p. 199). Proper brightness in a museum's galleries is measured by how sensitive its objects are to light and the duration of exposure to radiation. |
| **Distribution of Brightness and Luminance** | Distribution of brightness in museums should be tailored to the type of display of objects. Accordingly, for objects displayed on walls, according to the designer’s purpose, lighting can be applied either locally or in a scattered mode, linearly or on the artwork surface (Zumtobel Staff, 2004, p. 84). On the other hand, in this group of artworks, it is necessary to avoid shading and **veiling reflection**, as well as provide the **proper uniformity** of light on the surface of the wall, including the artworks (CIBSE, 2009, p. 201). While 3D artworks and sculpture should be lighted from several directions and with a combination of rod light and local light to provide an appropriate degree of penumbra (lighting and shading) for detecting the details of the artwork by **avoiding flickers** (CIBSE, 2009, p. 202; Zumtobel Staff, 2004, p. 86). About the distribution of brightness, **the lighting of artworks must be in balance with the space lighting**. |
| **Color Rendering Index of Light Source** | This index should be high for the display of artworks, i.e. between 80 and 100 (CIBSE, 2009, p. 199). Daylight with an index of about 100 is the most appropriate light source in this area; among the sources of artificial light, LED lamps have the highest value of this index, followed by traditional and energy-efficient incandescent lamps (Zumtobel Staff, 2004, p. 10). Due to the importance of colors in museum artworks and the need to correctly identify them, **high color rendering index** is one of the most important factors of lighting in museum space. |
| **Eyes’ Ability of Adaptation** | In the human visual system, the ability to adapt or, in other words, adjust the sensitivity of the eye to the light conditions of the environment and its adaptation time are of particular importance; if these changes are sudden and severe, more time is needed to adapt the eye to the environment (Heidari, 2012, p. 25). For this purpose, it is recommended that the museum **be zoned in terms of lighting**, based on its artworks, and to place intermediate layers with **appropriate, flexible and gradual brightness** between main layers with different brightness to allow users to adapt their eyes to the light conditions (Shawn, 1999, p. 6). Accordingly, the distribution of light in space should be in a **uniform** manner. |

| | |
|---|---|
| **Reflection of Light** | The **combination** of direct and reflected lights in space improves visibility (Smith, 2009, p. 151). On the other hand, the **position of the light source** should be such as to prevent the light reflection to the user's eyes and to avoid *shading and veiling reflection*, so the light source must be placed above or around the object (Weerdmeester & Dul, 2011, p. 91). |
| **Glare** | This phenomenon disrupts sensory concentration and therefore the visual function and comfort, so avoiding it is essential to optimize the display of artworks in the museum. **Avoidance of glare and flicker** is achieved by controlling the **radiation of light source** (Zumtobel Staff, 2004, p. 61) - whether natural or artificial - through filtering or diffusing it in space. Another solution is to control the **flicker of the light source**. Natural light is a light source with the least fluctuations. |
| **Shading** | Appropriate **shading and contrast** and **proportional uniformity** are effective in helping to identify the shape and details of 3D objects; on the other hand, improper shading disturbs the detection of objects (CIBSE, 2009, p. 200). In general, a highly reflective background and a **rod light source** do not create a shadow, while a low reflective background and a narrow strip of light can create a great shadow. The range between these two bounds should be taken according to the designer's purposen. |
| **Ease of Navigation** | Ease of navigation can be achieved by providing a **favorable level of illuminancev**. Zoning the spaces in a museum by lighting and **proper light distribution** can be an important step to provide greater legibility and easier navigation in a museum. |
| **Provision of Landscape** | Providing **proper landscape** when **lighting the space** provides visual comfort and novelty in thinking for the user (Ghiabaklou, 2013, p. 297). The design of this part is particularly effective in unrestricted display spaces as well as in passing spaces, providing users' comfort and satisfaction. |
| **Flexibility** | Temporary galleries in museums emphasize the need for flexible lighting conditions such as **the amount of light, the distribution of light, the position of the light source, and even the light color** (CIBSE, 2000, p. 201; Shawn & Innes, 1993, p. 5). In addition, it is necessary to provide adequate light at this time (CIBSE, 2009, p. 200) in order to perform the cleaning and maintenance activities. On the other hand, the possibility of blocking light and removing light from museum objects outside the scope of museum activity can help reduce the radiant destruction. |
| **Safety and Emergency** | At least 20 lux **illumination** is required for safe movement in the museum space (Ibid, p. 201). The valuable and precious objects of the museum make it necessary to consider light sources and light fixtures **with special safety considerations**. |
| **Repair and Maintenance** | When installing **a variety of light sources** and designing museum lighting, it is necessary to take into account the time required for cleaning and inspection as well as the ease of access to light sources for periodic cleaning and repairs (Ibid, p. 201), so that the light source chosen should not impose double trouble and cost on the museum. |

**Table 3. The Phenomena Associated with the Human Vision System and Environment Lighting**

| **Components of phenomena associated with the human vision system and environment lighting** | |
|---|---|
| **Tissue Damage** | This disorder (which is often seen in the skin tissue and the eye tissue) occurs under light conditions **mainly through high-energy, short-wavelength beams** that are largely outside the visible spectrum. To avoid this disorder, it is required to control the purple and blue spectra in the visible range. Temporary corneal inflammation and the risk of blue light are such cases (Boyce, Hunter, & Hewlett, 2009, pp.2 - 3). **Reducing, filtering or removing UV rays and controlling the source causing the intrusive factor** are the most important steps in reducing the adverse effects of this disorder. |
| **Eyestrain** | This disorder is physiologically caused by the excessive use of control muscles of eyes to adapt to environmental conditions, and perceptually by the conditions disturbing proper vision and distraction. Its symptoms are eye irritation, vision impairment, and even headache and dizziness (Ibid., pp. 7 - 8). **Environment brightness, the color of objects and vision range** are environmental conditions affecting subjective conditions and eyestrain (Smith, 2009, p. 134) so that poor light, **unbalanced luminance**, unpleasant and **severe reflections, flickering** light sources, **very low/ high level of uniformity** in space as well as inappropriate light color in space and range of vision can cause or exacerbate this phenomenon (Bommel, Beld, & Ooyen, 2002, p. 6; Parsons, 2000, p. 589). |
| **Glare** | It is a phenomenon caused by the **excessive and unwanted amount of light** coming from a surface to the eye or the **sharp contrast of luminance** in a field of view that can cause impaired object recognition, visual discomfort, distraction or even inability to see (Smith, 2009, p. 44 - 45). The **control of the source luminosity**, the **distribution of luminance** and **contrast**, the **position of the light source and the object,** as well as the duration of exposure to the field of view, play a key role in examining this disorder (CIBSE, 2000, p. 38-39). |

| | |
|---|---|
| **Flicker** | Flicker is a disorder meaning to percept an image discretely that is one of the main causes of discomfort (Smith, 2009, p. 45) and is caused by **fluctuations in the light source** (the frequency of being off and on of the light source) or flickering. It is possible to encounter this phenomenon by **removing the fluctuation or using two light sources with different phases in the immediate vicinity of one another**; daylight is considered an ultimate flicker-free light source (Ibid, p. 145). |
| **Metamerism** | Metamerism occurs when an object looks different from its true color under a light source (Ibid, p. 63). This phenomenon is most closely dependent on the **color rendering index of the light source** (meaning the quality of the light source in the representation of the objects' true color) as well as the **illuminance**. Among the light sources commonly used in architectural spaces, daylight has the highest color rendering index, followed by a variety of LED lamps, some incandescent lamps, energy-efficient incandescent lamps, and then luminous lamps (Zumtobel Staff, 2004, p. 10). |
| **The Effect of Light Color on Space Perception** | The spectrum of visible light is understood as **color**; on the other hand, color and phenomenon of seeing have a psychological dimension in addition to physical or physiological dimensions. This means the psychological and sensory perception of the color of space and thus its spiritual qualities, including the sense of place, are also function of factors, such as culture, social factors, and personal experiences. Accordingly, color has **perceptual and thermal effects** (Ghiabaklou, 2013, pp. 7-11). |

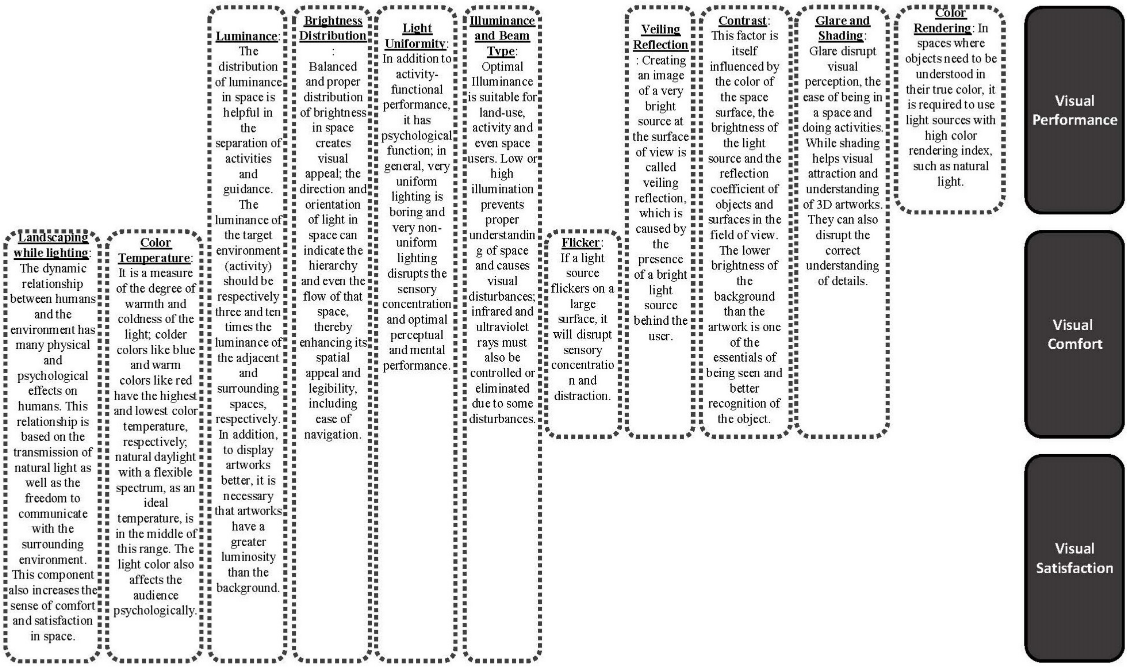
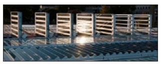



**Fig. 3. Indicators of Ergonomic Lighting in the Museum and their Components**

**Table 4. Examination of Widely Used Natural-solar Lighting Systems**

| Natural-Solar Lighting Systems | Type of System | Advantages | Disadvantages | Optimum Conditions |
|---|---|---|---|---|
| Light Shelf (Ghiabaklou, 2013, pp. 70, 75, 84, & 87; Zareiy & Ghiabaklou, 2012, p. 2; Boubekri, 2008, pp. 114-115; Littlefair, 1990, pp. 10-11; Karlen & Benya, 2004, p. 34) | Combined with window, light controller and diffuser  | • Increase the penetration depth<br>• Reduce annoying light and shading near the window<br>• Control glare<br>•Distribute light more widely and uniformly<br>• Reduce the thermal load of space<br>• Cost-effective design and implementation<br>• Not disturb the visual connection with the outside | • Have a relatively low performance under cloudy conditions<br>• Need for periodic and continuous cleaning | • South, east and west fronts<br>• Light and opaque or semi-mirror upper surface<br>• Being installed at the height of the upper third of the window<br>• Depth of inner and outer parts are 65 and 80 cm, respectively<br>• High altitude of space<br>• Gable or curved roof |

| | | | | |
|---|---|---|---|---|
| Light Shield (Pirmohammadi, Ahmadi, & Sharifi, 2014, p. 12; Ghiabaklou, 2013, pp. 100-101; Smith, 2009, pp 9, 140- 142; Park, Joo, & Yang, 2007, p. 4) | Combined with a skylight, light controller and diffuser<br> | • Distribute light more widely and uniformly<br>• Eliminate glare<br>• Control incoming spectrum intensity and radiant destruction<br>• Avoid veiling reflection<br>• Lack of unfavorable contrast in the layers near the skylight | • An obstacle to the view of the sky | • Aluminum-like material<br>• Consist of two curved wings<br>• Small pores on the wings<br>• Curved roof<br>• Light materials of the interior walls for better reflection and diffusion of light |
| Photovoltaic Shade (Movable on Roof) (Ghiabaklou, 2013, pp. 159 -160; Vafaei, 2009, pp. 74, 76-77; Ghiabaklou, 2015, pp. 230, 239, & 242; Bagheri Rad & Mofidi Shemirani, 2015, pp. 3-5) | Combined with roof, facade, window and shades, light receiver and controller, electricity generation<br><br> | • Have proper performance in all seasons and at different radiation levels<br>• Generate and store energy<br>• Reduce electricity consumption<br>• Reduce environmental pollution<br>• Have a high shelf life<br>• Have the ability to remove harmful wavelengths of light<br>• Reduce heat absorption intensity<br>• Provide various degrees of light and shade<br>• Control contrast and glare<br>• Distribute light widely<br>• Have high security<br>• The possibility of automatic washing by the rain<br>• Lack of the interference of design with the building structure | • Cost of installation (which, of course, is returned in the short run due to system efficiency in energy generation). | • Zero to 45° movable window shades and zero to 90° movable panels<br>• On roof and tilting south<br>• Main structure made of aluminum or stainless steel<br>• Transparent photovoltaic glass with the capability of controlling ultraviolet and infrared spectra<br>• Building orientation in accordance with climate considerations for obtaining the maximum amount of solar energy and radiation<br>• A ventilator on the back layer of the system<br>• A longer plan |
| Light Pipe (Ghiabaklou, 2013, pp. 177, 188-189, 193, 215, 218, 221, & 224; Zareiy & Ghiabaklou, 2012, pp. 3-4; Pirmohammadi, Ahmadi, & Sharifi, 2014, p. 13; CIBSE, 2009, pp.136-137; Boubekri, 2008, p. 125; Littlefair, 1990, pp. 1-3) | Receiver and Transmitter of light<br><br> | • Direct and transmit light in buildings with a deep plan and lower floors<br>• Have high security<br>• Has the ability to remove or reduce infrared spectrum<br>• Reduce power consumption<br>• Reduce thermal load and heat transfer<br>• Uniform light distribution<br>• Control glare | • Decrease incoming light as the number of floors increases<br>• Have low efficiency under mostly cloudy conditions<br>• Have high cost of installation and maintenance<br>• The relatively large size of the equipment<br>• Absorb some of the light into the carrier tube<br>• Affect the structure and architecture of the building | • Laser-cut light collector with two layers<br>• Fixed pyramid or axial rotational<br>• The prismatic carrier tube with the lowest bending<br>• Laminated multilayer distributor with minimum light absorption<br>• Double carrier tube<br>• Equipped with light shields to increase the uniformity of light distribution |

## 4. RESEARCH FINDINGS

As mentioned in the morphology of the study process, at this stage, the pairwise commonalities of components, namely ergonomic lighting, natural light, and lighting in museums of artworks, are examined and extracted based on comparative analysis of the key criteria discussed in the research literature section. In this step, to precisely examine the mutual relationship between the aforementioned components, the SWOT technique, and the comparative analogy were applied.

### 4.1. Ergonomic Lighting in Museums of Artworks

Among human senses, vision is more powerful than other senses in providing information about the environment and realizing the perceptual process; realization of this process also requires good lighting so that people can obtain information from the environment and analyze and understand all environmental images, in addition to the recognition of them. Therefore, it is necessary to address the issue of lighting as one of the fundamental pillars of seeing and providing favorable visual conditions for human beings in the museum as an artwork-centered space as well as audience-centered space. Since ergonomic lighting is based on the optimization of conditions for the user and space-use (function) with visual components, it is expected that the realization of ergonomic lighting conditions in the museum is considered an effective step in improving the efficiency of the museum. For a detailed comparative study of the function of ergonomic lighting in the museum, Figure 4 illustrates the important considerations of lighting in museums of artworks as well as ergonomic lighting indicators and their components. To study their alignment and adaptation, a comparative analysis was performed. According to the comparative analysis of Fig. 4, the realization of ergonomic lighting conditions is an effective factor in achieving museum lighting considerations in order to enhance the quality of the display of artworks. In general, it can be stated that applying ergonomics is effective in the realization of lighting considerations physically, perceptually and psychologically. It should be noted that the realization of these visual components is primarily conditional on providing a safe environment ensuring the health of users.

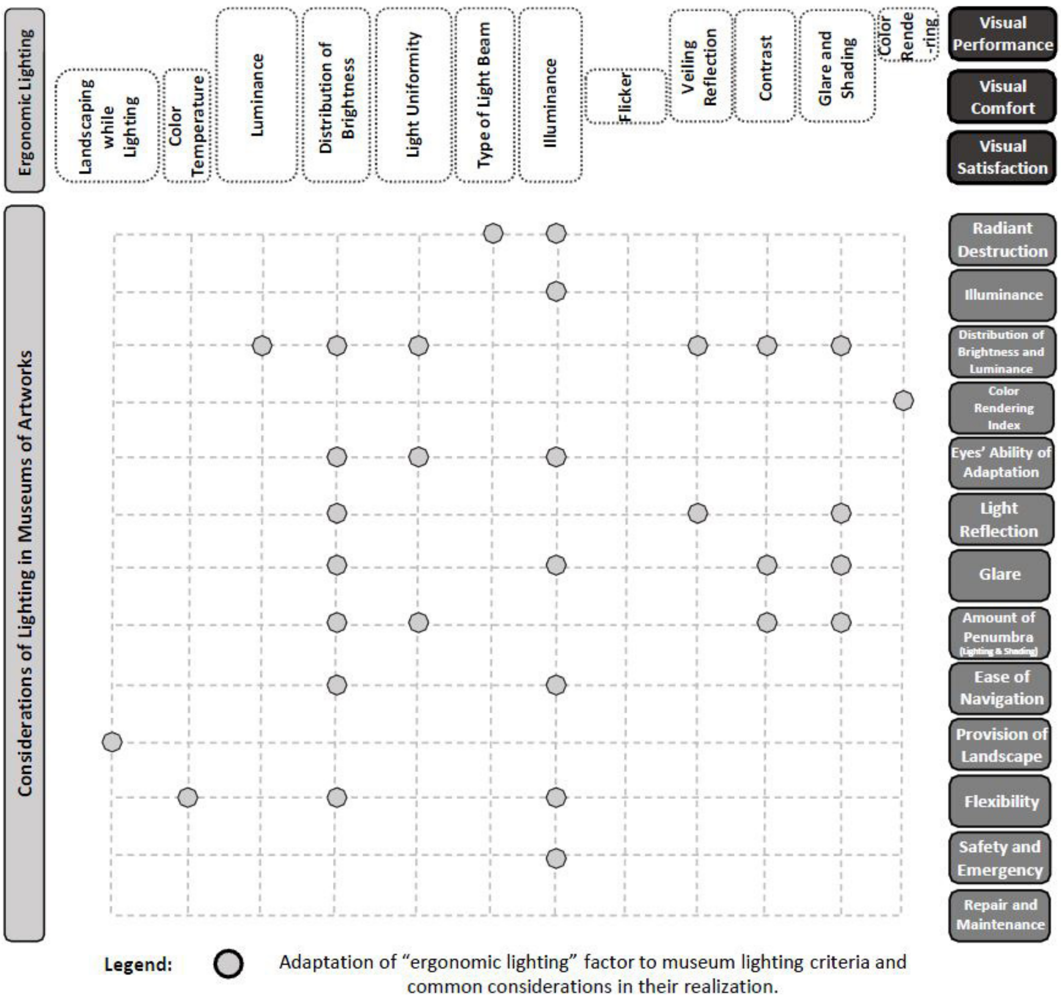



**Fig. 4. Analytical-comparative Chart of Applications of Ergonomic Lighting in Museums**

## 4.2. Natural Light in Ergonomic Lighting

Studies show that light, depending on its quantity and quality in terms of different aspects, can significantly affect human performance, comfort and morale in different settings. As mentioned earlier, natural light, as an ultimate source of the light spectrum, is able to provide an important part of the need of the environment and the user to light, while also being most consistent with the visual reactions of human beings. Therefore, given the importance of visual components in the realization of ergonomic lighting, natural light is expected to be an important element in ergonomic lighting.

In order to examine precisely the application of natural light in the realization of ergonomic lighting, the adaptation of this light to the components of ergonomic lighting is examined in the five categories of strengths, opportunities, threats, weaknesses and being ineffective in Fig.5 and the reasons are explained under each component. Accordingly, natural light can be effective in realizing of ergonomic lighting by providing the right bed for most of the ergonomic lighting criteria, although some limitations and disadvantages of this light confirm the necessity of using appropriate lighting systems to achieve the maximum of optimum conditions.

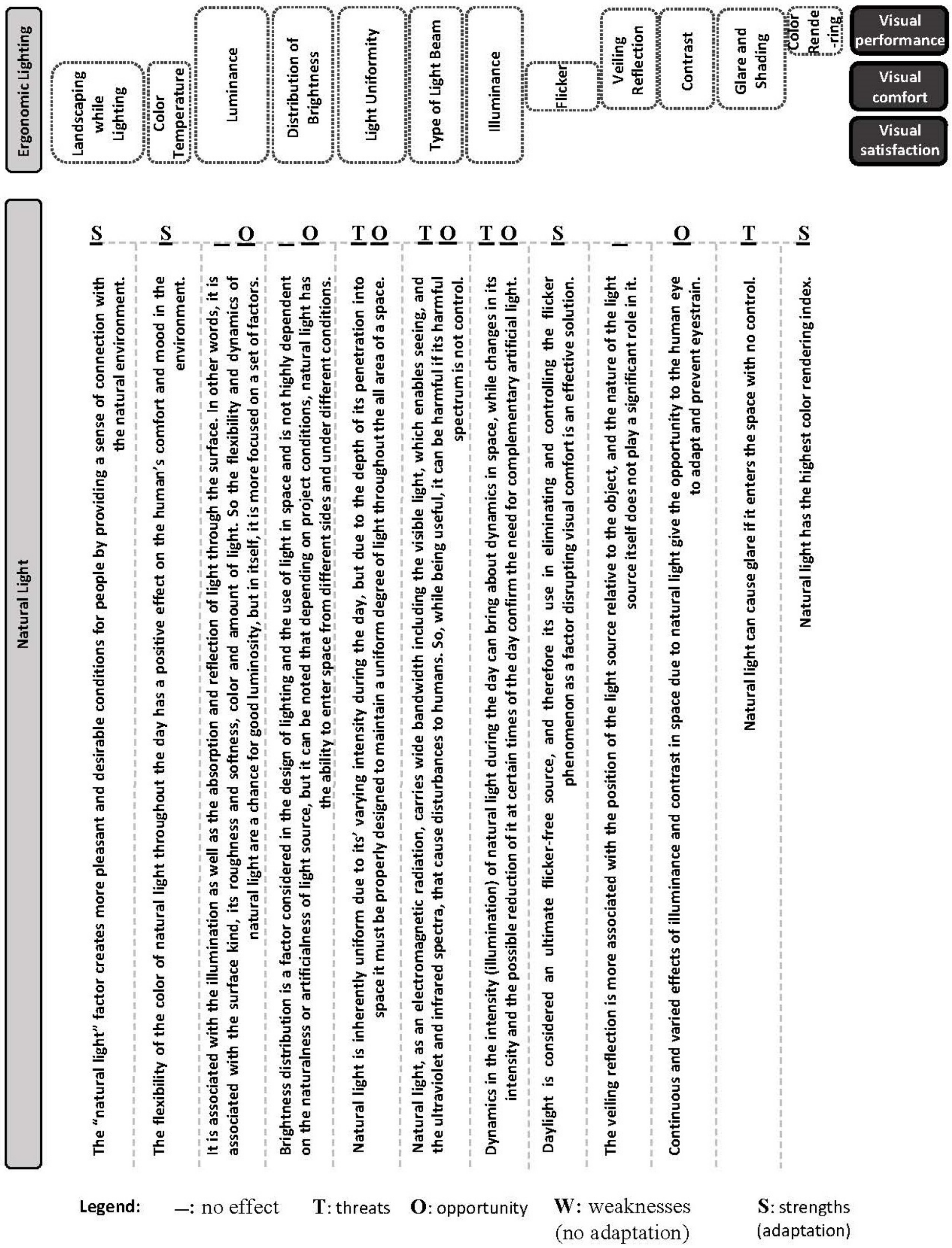



**Fig. 5. Analytical-comparative Chart of Applications of Natural Light in Ergonomic Lighting**

### 4.3. Natural Light in Lighting Museums of Artworks

Due to the high adaptation of natural light to visual reactions, this light can be a top priority for visual activities and those environments with the focus on seeing and being seen, provided that security-protection issues are met.

To more precisely examine the adaptation, Figure 6 illustrates the adaptation of natural light with each criterion of lighting in the museum. According to this graph, natural light is able to cover the most important lighting considerations in museums of artworks although the presence of infrared and ultraviolet rays is its major disadvantage causing the destruction of some artworks in the museum.

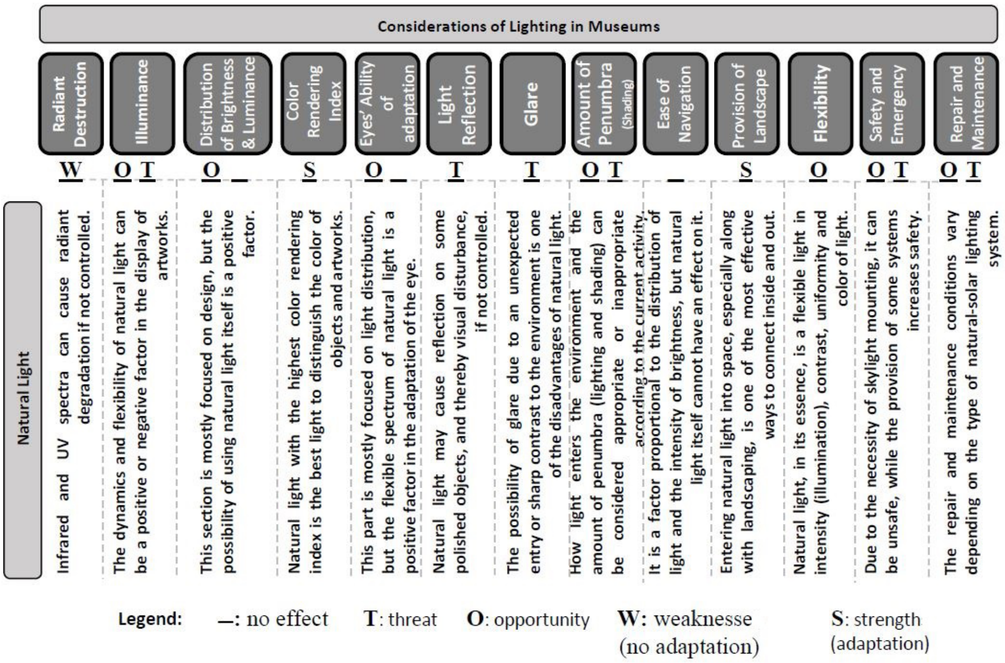



**Fig. 6. Analytical-comparative Graph of Application of Natural Light in Museums Lighting**

## 5. EVALUATION AND DISCUSSION

Based on the research findings, creating space (place) using light is a challenge of ergonomics in lighting in museums of artworks while realizing visual performance, visual comfort, and visual satisfaction. In the meantime, natural light, in addition to meeting the criteria of ergonomics, is able to meet the lighting needs of museums focused on displaying artworks, while removing its limitations and deficiencies requires the use of natural-solar lighting systems. Therefore, in this step of the research, the common and widely used natural-solar lighting systems used in museums, as earlier studied, are evaluated to the degree to which they satisfy ergonomic lighting conditions in museums.

### 5.1. Ergonomic Natural-solar Lighting Systems in Museums of Artworks

To obtain a suitable model in the process of evaluating the systems studied, a set of criteria were extracted according to Table 2 and Figure 4, and each of them was given a coefficient of impact ranging from one to three. In the process, if the visual performance is defined as visibility and the ability to perform visual activities perfectly, visual comfort as performing visual activities in comfort conditions and with no disturbance, and visual satisfying as performing visual activities with satisfaction and a tendency to re-attend that space, visual performance and its factors are a prerequisite for achieving optimum museum efficiency, (coefficient of impact of 3). On the next level, relieving the boringness of the museum by providing visual comfort is of importance (coefficient of impact of 2). On the last level, making space attractive and the audience's tendency to experience the space for several times are of importance, that are realized by the factors related to visual satisfaction and the possibility of a flexible experience of artworks in the museum (coefficient of impact of 1). In addition, the possibility of radiation destruction of artworks should also be considered. Since the objects in such museums have no or moderate sensitivity to light, the "radiation destruction" criterion is considered a moderate criterion (coefficient of impact of 2) in terms of importance in lighting museums of artwork. Accordingly, the criteria of ergonomic lighting in the museum can be explained according to the coefficient of impact as follows:

• Coefficient of impact of three (Most important): illuminance and amount of incoming light, uniformity of light, control of glare, luminance, shading and contrast, wide distribution of brightness and high penetration depth, high color rendering index, control of intrusive reflections such as veiling reflection and security of light source.

• Coefficient of impact of two: color temperature and, in other words, the appropriate light color, landscaping along with lighting, the possibility of eliminating or reducing infrared and ultraviolet rays and the non-fluctuation of the light source (source with lower flicker).

• Coefficient of impact of one: flexibility in the amount of incoming light and flexibility in the color of light distributed in space.

In Table 5, the aforementioned systems are evaluated based on the criteria of lighting in the museum by coefficient of impact and Figure 7 shows the evaluation of the studied systems in graph (right: criteria of A to M in the order of criteria listed in Table 5) as well as the computerized evaluation of them through Zumtobel ELI/ LENI Calculation (left). The systems were scored at the scale mentioned for each criterion according to the role of each system in realizing that criterion. For example, studies (Table 4) show that certain types of photovoltaic systems are capable of using infrared and ultraviolet spectra to generate electricity, thereby eliminating its penetration into the interior, while light shields, depending on the kind of their materials, can adjust and control the spectra of incoming infrared and ultraviolet rays. It should be noted that since the performance of all these systems is based on natural light, the "light color" and the "non-fluctuation of the light source" criteria have been measured in them identically. On the other hand, the color rendering index is also generally measured based on the type of light source that is natural light here. But the uniform distribution of light and the lack of undesirable and disruptive shading are considered to be the most advantageous potential of natural light. That is why they were considered in the evaluation of the studied systems.

Investigating the effect of natural light, in the form of natural-solar light systems, on the achievement of ergonomic conditions in order to enhance the quality of display of artworks and improve the way to display artworks in museums, due to extent and complexity, first of all, requires extensive study on processes forming optimum lighting in museums of artworks and in the final step, it is necessary to properly summarize, evaluate and present a suitable model based on comparative analytical studies. Evaluations conducted in this study show that top lighting systems stems are better suited to light museums with a focus on displaying artworks because they can spread and diffuse more uniform light in the space while distributing light even more widely. In addition, there is less possibility of glare and less eyestrain compared to side lighting systems. Due to the penumbral spectrum and contrast on the space surface, these systems allow for better seeing and understanding of 3D artworks. A close examination of the systems commonly used in museums shows that the photovoltaic shade is the most suitable natural lighting system in these museums, followed by light shields, light pipes, and light shelfs, respectively. Due to the relative complexity of design and implementation, light pipes are only appropriate when the purpose is to provide natural brightness for spaces far away from natural light. In the process of using these systems, attention is also given to their type and function; for example, the optimum performance of photovoltaic shades is obtained when they are movable or the optimum performance of optical pipes in museums of artworks is conditional on having two layers.

**Table 5. Evaluation of the Effect of Natural-Solar Lighting System in the Realization of Ergonomic Lighting and Optimum Display of Artworks in the Museum**

| Criterion (coefficient of impact / Natural-solar lighting systems | Illuminance (3) | Uniformity of Light (3) | Control of Glare, Luminance, Shading and Contrast (3) | Extensive Distribution of Light and high penetration depth (3) | Color Rendering (3) | Control of Intrusive Reflections (3) | Security of the Light Source (3) | Color Temperature (Light Color) (2) | Landscaping while Lighting (2) | Elimination or Reduction of UV and Infrared rays (2) | Light Source without Flicker (2) | Flexibility of Incoming Light Amount (1) | Flexibility of the Color of the Light Distributed in Space (1) | Average |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Light Shelf** | 3 | 3 | 4 | 4 | 4 | 3 | 2 | 4 | 5 | 1 | 5 | 2 | 2 | 3.32 |
| **Light Shield** | 4 | 5 | 5 | 5 | 5 | 4 | 4 | 4 | 1 | 4 | 5 | 2 | 3 | 4.16 |
| **Photovoltaic Shade** | 5 | 4 | 4 | 5 | 5 | 4 | 4 | 4 | 2 | 5 | 5 | 5 | 3 | 4.30 |
| **Light Pipe** | 4 | 4 | 3 | 5 | 4 | 3 | 5 | 4 | 1 | 4 | 5 | 3 | 3 | 3.80 |

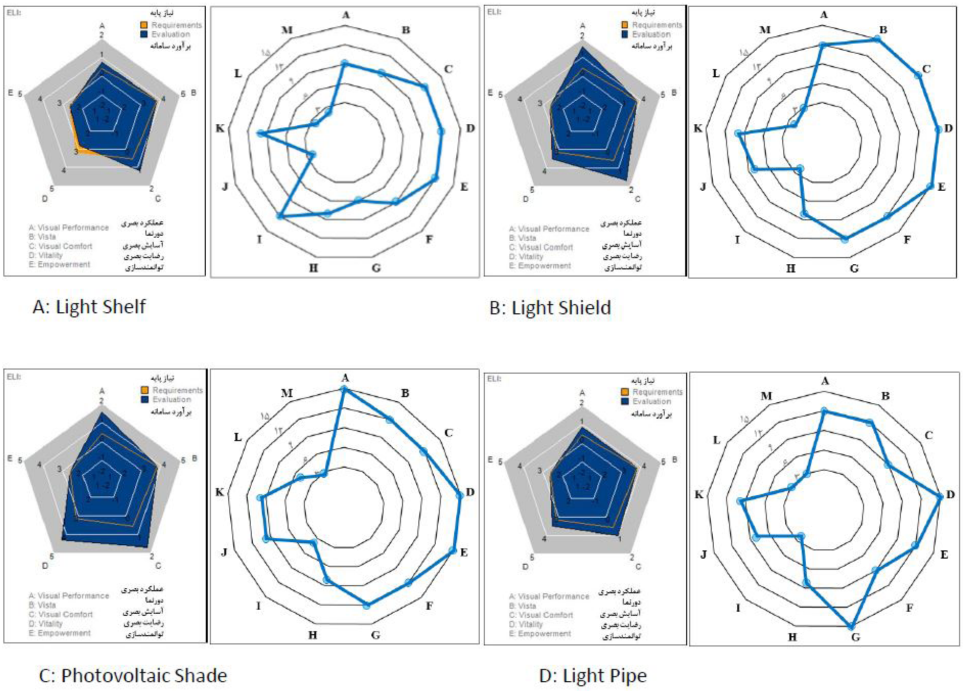



**Fig. 7. Analytical-comparative Graph of Application of Ergonomic Lighting in Museums**

## 6. CONCLUSION

The realization of visual indicators of ergonomic lighting relies on the high quality of natural light as a desirable quality for seeing artworks. Creating space using light is a challenge of ergonomics in lighting in museums of artworks while realizing visual performance, visual comfort, and visual satisfaction. Natural light, that full simulation of its quality and benefits is impossible, is very important in meeting this challenge, due to its high quality, color spectrum, variety and variability, the ability to experience some of the environmental stimuli and to provide proper visibility. But it also has disadvantages such as low penetration depth, possibility of glare, intrusive reflections, and non-uniformity. These disadvantages can be remedied by using appropriate lighting systems. Each of these systems has a variety of capabilities and features that make them suitable for different purposes in the museums of artworks. In general, top natural lighting systems are better suited for lighting in the museum space because they have greater depth of penetration while controlling glare and intrusive reflections. In addition, due to having flexible contrast spectrum, they allow for better seeing and understanding of the artworks. However, it should be noted that the possibility of destroying some artworks sensitive to infrared and UV rays of natural light in long term is considered a threat that requires to be controlled and met by applying appropriate lighting systems. In addition to generation and supplying part of the electricity through solar energy, movable photovoltaic shades are capable of providing the suitable illumination for museum spaces by changing the amount of incoming natural light, while distributing it widely. On the other hand, among the commonly known natural lighting systems, this system can provide the greatest amount of control and even the elimination of the destructive spectrum of natural light, including UV and infrared rays. Combining this system with a light shield can allow for a more even distribution of light while better controlling glare, luminance, shading and contrast in the museum. The combination of these two systems is capable of meeting the most criteria of ergonomic lighting in the museums of artworks desirably, while “landscaping while lighting” criterion is not desirably satisfied with top lighting systems; therefore, side lighting systems is considered an appropriate option to provide visual connection between inside and out. It is recalled that it is necessary to properly combine natural lighting with artificial light (if required) to achieve the proper lighting in the museums of artworks (especially those artworks presented in showcases and conservatories).

**END NOTE**

1. Since museums, according to their themes) are divided into artworks, eco-museums, sciences, archeology, etc., and their design challenges, including lighting, vary according to their needs, to study the effect of ergonomic lighting and evaluate natural-solar lighting systems, it is required to determine the type of museum. So, in the present study, the needs and conditions of museums of artworks were considered. In addition, it is noted that natural lighting systems in this article refer to public environmental lighting systems for the display of artworks exhibited in the museum space and outside the showcases and conservatories.
2. Zumtobel ELI/ LENI Calculation (Manufactured by Zoomtabel Lighting Research Group in Austria): This software is considered as the default standard for ergonomic lighting in each space, then the quality of ergonomic lighting in that space is determined by answering a number of qualitative questions about the factors affecting the realization of ergonomic lighting indicators such as visual performance, visual comfort, visual satisfaction, vista, and empowerment. In the present research, given the more importance of better visibility and better understanding of the environment and artworks in museums, three indicators of visual performance, visual comfort and visual satisfaction were considered and two other factors, i.e. vista (means lighting with the purpose of separation of activity zones while addressing the maintenance of lighting tools) and empowerment (referring to lighting management issues) were considered at the default level defined by the software.
3. The components listed in Table 3 were extracted from the following references, which were not separately mentioned due to their multiplicity:

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4. Among the lighting systems, according to the detailed studies, the most common systems, that have been applied to the museums, were also selected and evaluated.

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